

Embedded Systems: An Introduction using the Renesas RX63N Microcontroller

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Preface

This book is the results of a long relationship the author has enjoyed with Renesas Electronics America, Inc. (and one of its predecessors, Mitsubishi Electronics). I originally worked with this company because of their commitment to providing a low-cost evaluation board and free development software that students could purchase and use in classes and senior design projects. Over the years the boards have remained as affordable (and popular) as ever, and the software development tools available have added more functionality while still remaining available for free to our students.

I have been teaching embedded systems courses for over fourteen years (and working in the field even longer). I had not been able to find a book suitable for using in an undergraduate course that would lend itself to the theoretical and applied nature of embedded systems design. Renesas had been asking me to create a book for several years, and the introduction of the new RX63N microcontroller offered a wonderful opportunity to work with this powerful device and integrate it into classes.

This book also has a radical feature not seen in many books currently on the market (if any). It is freely available for download and is also provided with the Renesas RX63N evaluation board. It is also available for purchase in hardcopy form for a modest price.

This book can be used on its own for an Introduction to Embedded Systems class or an Introduction to Microprocessors/Microcontrollers. It can also be used as a supplement in many different types of classes. The book also has supplemental materials available through Renesas Electronics America's University program. These materials include homework solutions (sorry, faculty only!), PowerPoint presentations, lab exercises, and a test bank. Video lectures can be found on YouTube under the channel stiquitojmconrad.

This book would not have been possible had it not been for the assistance of numerous people. Several students and educators contributed to some of the chapters in the RX63N (original) version of the book, including: Adam Harris (1, 2), Suganya Jebasingh (2, 6), Vikram Gill (3,4), Archana Subramanian (4), Onkar Raut (5, 7), Steven Erdmanczyk (8,9), Sunil Gurram (8), Vivek Srikantan (10), and Paul Mohan Das (10). Alex Dean of North Carolina State University heavily edited the original book and was it's co-author. Stephanie Conrad heavily edited versions of the chapters. Michael McLain and Sam Shue helped create the solutions for the homework assignments. Kunal Bagewadi, Robin Davidsson, and Amogh Gokhale went through the original RX62N book and made corrections to text and code examples to convert it to the RX63N microcontroller and evaluation board. Thanks go to the compositor, Linda Foegen, and especially to June Hay-Harris, Rob Dautel, and Todd DeBoer of Renesas for their help in getting this book produced and published (and for their patience!). Many, many thanks go to the reviewers who offered valuable suggestions to

make this book better, especially David Brown, Jerry Zacharias, Mitch Ferguson, Mike Wilkinson, John A. Onuska, Mark Radley, Barry Williams, and students from my UNC Charlotte Embedded Systems courses.

I would like to personally thank my parents, the Conrads, and my in-laws, the Warrens, for their continued assistance and guidance through the years while I worked on this and other books. Also, I would especially like to thank my children, Jay, Mary Beth, and Caroline, and my wife Stephanie, for their understanding when I needed to spend more time on the book than I spent with them.

James M. Conrad
September 2013

Foreword

The world of MCU-based embedded designs can be divided into those that take advantage of existing code and MCUs, and those that require leading edge MCU architectures and implementations. Dr. Conrad spent more than a year internalizing the inner workings and surrounding ecosystem of the newly-developed RX architecture, and has generated a book showcasing the RX line which has a level of peripheral integration that has not been seen before. Indeed, by taking the best DNA of both CISC and RISC architectures, and combining them into a new breed of MCU, the RX line enables design approaches that were previously spread across the CISC and RISC camps and inaccessible in one device line.

The author leverages the capabilities of the RX and demonstrates his own expert grasp of all the dynamics that differentiate successful end solutions from those of the “me-too” variety. He recognizes that successful embedded systems require more than just good hardware and software engineering. Jim has masterfully applied RX capabilities to real world challenges using examples, applications, and approaches that will surely empower individuals and teams of designers.

Readers aspire to find books that have the right balance between depth and breadth. Where there is too much detail, the relevance can be obscured; while a broad brush approach may trivialize the essence of key topics. This is especially true of books relating to embedded designs that must achieve a utilitarian purpose. Here, Jim skillfully navigates from topic to topic, knowing exactly when to throttle for maximum utility.

Whether you are a university student preparing for the real world, a design engineer looking for leading edge approaches to time-critical processes, or a manager attempting to further your risk management techniques, you will find his approach to embedded systems to be stimulating and compelling.

Ali Sebt
Renesas
September 19, 2013

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Introduction to Embedded Systems

1.1 LEARNING OBJECTIVES

In this chapter the reader will learn:

- What an embedded system is
- Why to embed a computer
- What functions and attributes embedded systems need to provide
- What constraints embedded systems have

1.2 CONCEPTS

An embedded system is an application-specific computer system which is built into a larger system or device. Using a computer system rather than other control methods (such as non-programmable logic circuits, electro-mechanical controls, and hydraulic control) offers many benefits such as sophisticated control, precise timing, low unit cost, low development cost, high flexibility, small size, and low weight. These basic characteristics can be used to improve the overall system or device in various ways:

- Improved performance
- More functions and features
- Reduced cost
- Increased dependability

Because of these benefits, billions of microcontrollers are sold each year to create embedded systems for a wide range of products.

1.2.1 Economics and Microcontrollers

Microcontrollers are remarkably inexpensive yet offer tremendous performance. The microprocessor for a personal computer may cost \$100 or more, while microcontrollers typically cost far less, starting at under \$0.25. Why is this so?

Microcontrollers provide extremely inexpensive processing because they can leverage **economies of scale**. MCUs are programmable in software, so a chipmaker can design a single type of MCU which will satisfy the needs of many customers (when combined with their application-specific software). This reduces the per-chip cost by amortizing the design costs over many millions of units.

The cost of an integrated circuit (such as a microcontroller or a microprocessor) depends on two factors: non-recurring engineering (**NRE**) cost and **recurring** cost. The **NRE** cost includes paying engineers to design the integrated circuit (IC) and verify through simulation and prototyping that it will work properly. The **recurring cost** is incurred by making each additional IC, and includes raw materials, processing, testing, and packaging.

The IC's area is the major factor determining this recurring cost. The smaller the IC, the more will fit onto a silicon wafer and the lower the recurring cost. Microcontrollers are much smaller than microprocessors for personal computers, so they will cost less (given the same number of ICs sold). The NRE cost must be divided across each IC sold. As the number of ICs sold rises, the NRE adder falls, and so each IC's price falls as well. Low-volume chips are more expensive than high-volume chips.

1.2.2 Embedded Networks

Some embedded systems consist of **multiple embedded computers** communicating across an **embedded network**, and offer further benefits. Each computer on the network uses a communication protocol to share the same set of wires to communicate, rather than dedicating one set for each possible communication route. Several advantages come from having fewer wires:

- Lower parts cost, as fewer wires are needed
- Lower labor costs, as it is faster to assemble
- Greater reliability, as it has fewer connections to fail

Other advantages come from allowing separate nodes to share information. New features may be possible, or the system efficiency may be improved through better coordination of activities among different nodes.

1.3 TYPICAL BENEFITS OF EMBEDDED SYSTEMS

As an example, let's examine how embedded systems have affected automobiles. A typical modern car has dozens of microcontrollers embedded within it. Let's see why.

1.3.1 Greater Performance and Efficiency

Computer control of automobile engines lowers pollution and increases fuel efficiency, reducing operating costs.

Burning gasoline with air in spark ignition engines is a tricky business if we want to maximize efficiency, yet minimize pollution. The main factor affecting emissions is the ratio of air mass to fuel mass. The ideal ratio is 14.7 to 1, and the catalytic converter is designed to operate most efficiently at this ratio. If there is too little air (a rich mix), then excessive carbon monoxide (CO) and hydrocarbons (HC) will be produced. If there is too much air (a lean mix), then large amounts of oxides of nitrogen (called NO_x) will be created. So we would like for each fuel injector to add just the right amount of fuel. This depends on the mass of the air inside the cylinder, which depends on factors such as air temperature and air pressure. These in turn depend on altitude and weather, as well as whether the engine is warmed up or not.

Another factor is the timing of the sparkplug firing. If it fires early, then there is more time for combustion within the cylinder before the exhaust valve opens. This raises the average temperature within the cylinder and changes the combustion process, affecting CO, HC, and NO_x concentrations.

It would be quite impractical to design a mechanical control system to consider all of these factors and squirt the fuel injectors at just the right instant for the right amount of time. Thankfully, an inexpensive microcontroller is quite effective at these kinds of calculations and control.

1.3.2 Lower Costs

There are various ways in which an embedded system can reduce the costs associated with a device.

- **Component costs:** Embedded software can compensate for poor signal quality, allowing the use of less-expensive components. For example, a low-cost pressure sensor may be very temperature-dependent. If ambient temperature information is already available, then it is a simple matter to compensate for the temperature-induced error.
- **Manufacturing costs:** Many vehicles use the Control Area Network (CAN) protocol to communicate across an in-car network. The embedded network reduces assembly and parts costs because of the simpler wiring harness.
- **Operating costs:** As mentioned above, an embedded system enables automobile engines to operate more efficiently, reducing the amount of gasoline needed and hence lowering operating costs.
- **Maintenance costs:** Some vehicles predict oil life by monitoring engine use history, notifying the driver when an oil change is needed.

1.3.3 More Features

An MCU running application-specific software offers tremendous opportunities for features and customization. These features can make your company's products stand out from the competition.

- **Cruise control** keeps the car running at the same speed regardless of hills, wind, and other external factors.
- **Smart airbags** reduce injuries by adjusting inflation speed based on passenger weight.
- **Power seats** move to each driver's preferred position automatically, based on whose keyless entry fob was used to open the car.
- **Headlights and interior lights** shut off automatically after a time delay if the car is not running and prevents the lights from draining the battery.

1.3.4 Better Dependability

Embedded systems and networks offer many opportunities to improve dependability.

- An engine controller (and other controllers) can provide various "limp-home modes" to keep the car running even if one or more sensors or other devices fail.
- A warning of an impending failure can be provided.
- Diagnostic information can be provided to the driver or service personnel, saving valuable trouble-shooting time.

1.4 EMBEDDED SYSTEM FUNCTIONS

There are several common functions which embedded systems typically provide.

- **Control systems** monitor a process and adjust an output variable to keep the process running at the desired set point. For example, a cruise control system may increase the throttle setting if the car's speed is lower than the desired speed, and reduce it if the car is too fast.
- There is often **sequencing** among multiple states. For example, a car engine goes through multiple states or control modes when started. During **Crank and Start**, the fuel/air mix is rich and depends on the engine coolant temperature. Once the engine has started, the controller switches to the **Warm-Up** mode, in order to raise the engine and exhaust system temperatures to their ideal levels. Here the fuel/air

mixture and ignition timing are adjusted, again based in part on the engine coolant temperature. When the engine has warmed up it can switch into **Idle** mode. In this mode the controller seeks to minimize the engine's speed, yet still run smoothly and efficiently despite changes in loads due to air conditioning, power steering, and the electrical system.

- **Signal processing** modifies input signals to eliminate noise, emphasize signal components of interest, and compensate for other factors. For example, a hands-free speakerphone interface may use multiple microphones, beam-forming, and active noise cancellation to filter out low-frequency road noise. Other sensors may have spark-plug noise filtered out.
- **Communications and networking** enable different devices on the same network to exchange information. For example, the engine controller may need to send a message indicating speed. To do this, the speed value must be formatted according to the communication protocol and then loaded into the network interface peripheral for transmission.

1.5 ATTRIBUTES OF EMBEDDED SYSTEMS

Embedded systems are designed so that the resulting device behaves in certain desirable ways.

- Embedded systems need to **respond to events** which occur in the environment, whether a user presses a button or a motor overheats. A system which is not sufficiently responsive is not likely to be a successful product. For example, when we press a channel select button for the radio, we would like for it to respond within some reasonable time.
- For **real-time systems**, the timing of the responses is **critical** because late answers are wrong answers. Igniting the fuel in a cylinder is time-critical because bad timing can damage or destroy engine components (to say nothing of reducing power, or the efficiency and pollution concerns mentioned previously).
- Embedded systems typically require sophisticated **fault handling and diagnostics** to enable safe and reliable operation. Often the fault handling code is larger and more complex than the normal operation code. It is easy to design for the “everything goes right and works fine” case. It is far more difficult to determine methods to handle the exceptional cases. What is likely to fail? Which failures can lead to dangerous conditions? How should the system handle failures? How will you test that the system handles the failures correctly?
- Embedded systems may be expected to **operate independently** for years without operator attention such as adjustment or resetting. The system is expected to

operate robustly and always work. Given that it is very difficult and expensive to write perfect, bug-free software, developers build in mechanisms to detect faulty behavior and respond, perhaps by restarting the system.

1.6 CONSTRAINTS ON EMBEDDED SYSTEMS ---

Embedded systems often have **constraints** which limit the designer's options, and can lead to creative and elegant solutions. These constraints are typically different from those for general-purpose computers.

- **Cost** is a common constraint. Many applications which use embedded systems are sold in very competitive markets, in which price is a major factor. Often a manufacturer will hire subcontractors to design and build individual sub-systems. This allows the manufacturer to pit potential subcontractors against each other, keeping prices down.
- There may be **size** and **weight** limits for portable and mobile applications. An embedded system for an automotive remote keyless entry transmitter must fit into a small fob on a key ring which fits easily into a pocket. Similarly, the receiver must not be too heavy. A heavier car will have worse acceleration, braking, cornering, and fuel efficiency. Aircraft and spacecraft are especially sensitive to weight since a heavier craft requires more fuel to achieve the same range.
- There may be limited **power** or **energy** available. For example, a battery has a limited amount of energy, while a solar cell generates a limited amount of power. High temperatures may limit the amount of cooling available, which will limit the power which can be used.
- The **environment** may be harsh. Automotive electronics under the hood of a car need to operate across a wide range of temperatures (-40°C to 125°C , or -40°F to 193°F), while withstanding vibrations, physical impact, and corroding salt spray. Spark plugs generate broadband radio frequency energy which can interfere with electronics.

1.7 DESIGNING AND MANUFACTURING EMBEDDED SYSTEMS ---

Embedded systems are designed with a central microcontroller and other supporting electronic components mounted on a printed circuit board (PCB). PCBs provide the means to connect these integrated circuits to each other to make an operational system. The PCB provides structural support and the wiring of the circuit. The individual wires on the PCB are called traces and are made from a flat copper foil. While many circuit designs may use the same standard components, the PCB is often a custom component for a given design.

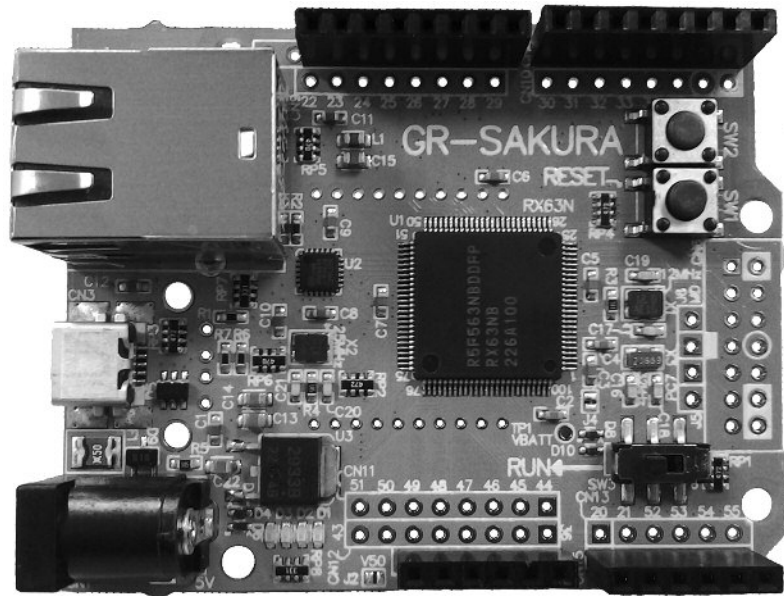


Figure 1.1 Renesas Sakura Board.

Designing a PCB requires a completed schematic for the circuit. This schematic is sometimes different than the schematic seen in textbooks. It often contains extra information about the components and construction of the board. For example, a textbook schematic may only show a battery for the power supply, while the production schematic would show the battery case, the number of cells, the rating of the battery, and the manufacturers of the components.

From the schematic, a designer will use their computer-aided design tools to identify the size of the PCB, and then place the electronic components on their board drawing. The designer will also place the wiring between the components on the PCB.

The physical PCB is manufactured from a fiberglass-resin material that is lightweight and inexpensive. A manufacturer will add copper wiring traces to the surfaces of the board and the appropriate insulation and white silk screening. The final manufacturing steps are applying solder, placing the components, and heating/cooling the solder. Figure 1.1 shows an example of a finished board.

The completed boards are electrically tested for functionality. Any board failing the test is inspected in more detail to find the problems. These boards are repaired to increase the passing rate acceptable to the manufacturer. The boards are wrapped in anti-static materials and shipped to the next location for the next stage of production, or immediately installed in a mechanical enclosure (like the mechanical shell of a mobile phone).

1.8 AN EXAMPLE OF AN EMBEDDED SYSTEM: THE RENESAS SAKURA BOARD

The Renesas Sakura Board (Figure 1.1) is one example of a Renesas MCU-based embedded system. This device has fifty-five digital I/O lines that are controlled by the Renesas microcontroller. [1]

Some of the main components to note are the 100/10 Mbps Ethernet port in the upper left, a micro USB port right beneath the Ethernet port which is used to program the built-in flash memory, and at the bottom left a 5 V DC power jack. The Sakura also has a micro SD card slot located on the underside of the board.

The large chip in the center is a Renesas R5F563NBDDFP microcontroller from the RX Family of chips with 1024 K of flash memory, 128 Kbytes of RAM, and 32 Kbytes of data flash. Fifty-five I/O pins are used to interface with external pins on the module. This processor runs at 96 MHz [2].

1.9 SUMMARY OF BOOK CONTENTS

This book is structured as follows:

- Chapters 2 and 3 present basic microcontroller concepts and the specifics of the RX63N.
- Chapters 4 and 5 show how software is built. At the low level they show how programs are compiled and downloaded. At the high level they show software engineering concepts and practices.
- Chapters 6 through 8 present how to use peripherals to interface with the environment and simplify programs.
- Chapter 9 presents how to use interrupts to improve response times and program structure.
- Chapter 10 presents how to structure multi-threaded software so the resulting system is predictably responsive.

1.10 RECAP

An embedded system is an application-specific computer system which is built into a larger system or device. Using a computer system enables improved performance, more functions and features, lower cost, and greater dependability. With embedded computer systems, manufacturers can add sophisticated control and monitoring to devices and other systems, while leveraging the low-cost microcontrollers running custom software.

1.11 REFERENCES

- [1] Renesas. Gadget Renesas. Renesas Electronics America, Inc. 2013. Web. Accessed at <http://www.renesas.com/products/promotion/gr/index.jsp#board>
- [2] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013.

Concepts of Microcontrollers

2.1 LEARNING OBJECTIVES

Embedded systems consist of computers embedded in larger systems. Additional circuitry such as power supplies, clock generators, and reset circuits, is required for the computer to work. Transducers (devices that convert one type of energy into another) are also used to connect microcontrollers to the outside world. There are two classes of transducers: inputs and outputs. Inputs are also known as “sensors” and contain such things as switches, keypads, and buttons. Output transducers include devices such as LEDs, motors, and coils.

In this chapter the reader will learn general information about:

- Connecting LEDs
- Connecting motors and coils
- Connecting switches and buttons
- Connecting keypads
- Analog to digital conversion
- Digital to analog conversion
- Power supplies for embedded systems
- Clock generation options
- Reset circuitry

2.2 INTERFACING WITH DIGITAL SIGNALS

2.2.1 General Purpose Digital I/O

Embedded systems consist of computers embedded in larger systems. The processor needs to sense the state of the larger system and environment, and control output devices. The most basic way to do this is through one or more discrete signals, each of which can be in one of two states (on or off). General purpose digital I/O **ports** are the hardware which can be used to read from or write to the system outside the microcontroller.

The RX63N has eighteen I/O ports (Port 0 to 9, A to G, J). Each port has eight pins, except for ports 0 and F which have 6 pins, and port J which has 2 pins, and on most ports all pins can be selected as inputs or outputs. However, on some ports some pins are reserved. The reserved pins cannot be configured as I/O pins. Each port has a Port Direction Register (PDR), Port Output Data Register (PODR), Port Input Register (PIDR), Open Drain Control Registers (ODRy, y = 0, 1), Pull-up Resistor Control Register (PCR), Drive Capacity Control Register (DSCR), and Port Mode Register (PMR). The pins of a port may serve several purposes; for example, Port 4 pin 0 can be used as a general purpose I/O pin, as an A/D converter input, or as an interrupt input. Depending on the purposes these pins serve, they might have extra registers.

Port Direction Register (PDR)

This register, as the name suggests, is used to set the data direction (input or output) of a pin. PDR is a read/write register. Each bit of the Port Direction Register represents a pin.

	B7	B6	B5	B4	B3	B2	B1	B0
Value after reset:	0	0	0	0	0	0	0	0

Figure 2.1 Port Direction Register [1], page 661.

The ‘iodefine.h’ file has C code constructs that make it easy to access each port with C code. Each port is defined as a *structure* and each register of the port is defined as a *union* of variables within that structure. An example of how the PDR is defined inside a port *structure* follows:

```

1. struct st_port4 {
2.     union {
3.         unsigned char BYTE;
4.         struct {
5.             unsigned char B7:1;
6.             unsigned char B6:1;
7.             unsigned char B5:1;
8.             unsigned char B4:1;
9.             unsigned char B3:1;
10.            unsigned char B2:1;
11.            unsigned char B1:1;
12.            unsigned char B0:1;
13.        } BIT;
14.    } PDR;
15. }
```


Line 1 shows that Port 0 has been defined as a *structure*. Lines 2 to 14 suggest that the Port Direction Register (PDR) has been defined as a *union* with the variable BYTE and a structure called BIT. This organization helps in easy access of the bits of the PDR. Unsigned char $B_n:1$ ($n = 0$ to 7) indicates that the character variable is assigned 1 bit.

To select a particular pin as the input pin, the corresponding bit of the PDR has to be set to '0'; and to select a pin as output, the corresponding bit of the PDR has to be set to '1.' The general syntax to set a bit of the PDR is `PORTx.PDR.BIT.Bn` ($x = 0$ to 9 , A to G, J; and $n = 0$ to 7) since ports are defined as *structures* and accessing structure *members* is done so this way. To configure multiple pins at the same time, the *char* variable BYTE can be used. All pins are configured as inputs at reset, by default.

EXAMPLE 1

Set Switch 1 (Port 4 bit 0) as Input

```
PORT4.PDR.BIT.B1 = 0;
```

When a pin is selected as an input from a peripheral, the Port Mode Register (PMR) has to be enabled. The PMR will be explained a little later.

Selecting a pin as an output involves setting the Port Output Data Register (PODR) and the Port Direction Register (PDR).

Port Output Data Register (PODR)

The Port Output Data Register is used to store data for pins that have been configured as output pins. This register is similar to the PDR in that each bit of the register represents a pin and certain bits of certain ports are reserved.

	B7	B6	B5	B4	B3	B2	B1	B0
Value after reset:	0	0	0	0	0	0	0	0

Figure 2.2 Port Output Data Register [1], page 662.

The Port Output Data Register (PODR) is also defined as a *union* of variables inside the port *structure*, in the 'iodefine.h' file. It is presented just like the PDR. Unsigned char: 1 is used to represent reserved pins.

The syntax to access the bits of the Port Output Data Register (PODR) is `PORTx.PODR.BIT.Bn` ($x = 0$ to 9, A to G, J; and $n = 0$ to 7). To select a pin as an output pin, first set the Port Output Data Register (PODR) to a known value, preferably 0, so that changes in the output can be easily observed. The *char* variable `BYTE` can be used to set multiple pins as output at the same time.

EXAMPLE 2

Set LED1 (Port D bit 0) as Output

1. `PORTD.PDR.BIT.B0 = 1;`
2. `PORTD.PODR.BIT.B0 = 0;`

Line 1 sets LED1 as an output and line 2 switches on the LED.

Sets LEDs 1, 2, and 3 (Port D bit 0, 1, and 2) as Outputs

1. `PORTD.PDR.BYTE = 0x07;`
2. `PORTD.PODR.BYTE = 0xF8;`

Line 1 sets LED1, 2, and 3 as outputs and line 2 switches on the LEDs.

Port Input Data Register (PIDR)

Port register is also defined as a *union* of variables inside the port *structure* in the 'iodefine.h' file. `PORTx.PIDR.BIT.Bn` ($x = 0$ to 9, A to G, J; and $n = 0$ to 7) is used to read the state of a pin and the state is stored in the Port Input Register regardless of the value in the Port Mode Register (PMR). This register also has some reserved bits. These bits are read as 1 and cannot be modified.

	B7	B6	B5	B4	B3	B2	B1	B0
Value after reset:	x	x	x	x	x	x	x	x

Figure 2.3 Port Input Data Register.

Check State of Switch1 (Port 4 bit 0) and Turn On LED1 (Port D bit 0)

```

1. if (PORT4.PIDR.BIT.B0 == 1) {
2.     PORTD.PODR.BIT.B0 = 1;
3. }

```

Port Mode Register (PMR)

This register is used to buffer the input values for pins that have been configured as input from peripheral modules.

	B7	B6	B5	B4	B3	B2	B1	B0
Value after reset:	0	0	0	0	0	0	0	0

Figure 2.4 Port Mode Register [1], page 664.

Before configuring a pin as an input from a peripheral, the PMR must be enabled. To enable the PMR set $PORTx.PMR.BIT.Bn$ ($x = 0$ to 9, A to G, J; and $n = 0$ to 7) to 1. If a pin has to be configured as an output pin, set $PORTx.PMR.BIT.Bn$ ($x = 0$ to 9, A to G, J; and $n = 0$ to 7) to 0. Setting PMR to 0 disables the PMR. While setting the PMR, make sure that the corresponding pin is not in use. For example, when setting $IRQi$ ($i = 0$ to 15) as input, first disable the interrupts, next enable PMR and then enable interrupts. It is necessary to follow the above steps to avoid unintended operations from taking place.

Open Drain Control Registers (ODR0/ODR1)

Most output pins function as CMOS but some output pins can operate as CMOS or NMOS open-drain pins. Since NMOS circuits are faster compared to the CMOS circuits, which consist of the slower p-channel transistors, using NMOS open-drain pins as outputs would be similar to a wired-OR connection. All of the pins of all ports are capable of functioning as NMOS open-drain output pins. Setting $PORTx.ODRy.BIT.Bn$ ($x = 0$ to 9, A to G, J; and $y = 0$ or 1; to 1, selects the pin as an NMOS open-drain pin.

Pull-Up Resistor Control Register (PCR)

Some devices have limited signal swing. When such a device is interfaced with the RX63N board, the signal from the device has to be pulled up so that it is in the valid voltage range of the board (this is not the typical usage, the typical usage is the external device is only capable of pulling down; or there is nothing attached and you do not want the port to float). To simplify this kind of interfacing, pull-up MOS circuitry is available for all

ports. To enable pull-up MOS for a particular pin of a port, set `PORTx.PCR.BIT.Bn` ($x = 0$ to 9, A to G J; and $n = 0$ to 7) to 1. To disable pull-up MOS, set `PORTx.PCR.BIT.Bn` ($x = 0$ to 9, A to G, J; and $n = 0$ to 7) to 0. The PCR is automatically disabled for pins configured as outputs. To enable or disable pull-up MOS for multiple pins use `PORTx.PCR.BYTE` command. The value of the PCR after reset is 0x00.

Drive Capacity Control Register (DSCR)

This register is used to switch the drive capacity of a port. The default value of 0 sets the pin as normal-drive output. Setting `PORTx.DSCR.BIT.B0` ($x = 0$ to 5, A to E, H and J) or `PORTx.DSCR.BIT.Bn` ($x = 0, 2, 5, 9, A$ to E, and G; and $n = 1$ to 7) to 1, selects the pin as high-drive output.

2.2.2 Example 1: Reading Switches to Control LEDs

Using LEDs as Outputs

LEDs require a current-limiting resistor so that they do not draw too much current from the I/O pin to which they are connected. Most microcontrollers can sink more current than they can supply, so generally LEDs are connected with the cathode to the microcontroller pin, and a current-limiting resistor between the anode and supply voltage. Formula 2.1 shows how to calculate the value of the current limiting resistor. Figure 2.5 shows the two ways of connecting LEDs to a microprocessor.

$$R = (V_{\text{Output}} - V_{\text{LED}}) / I_{\text{LED}} \quad \text{Formula 2.1}$$

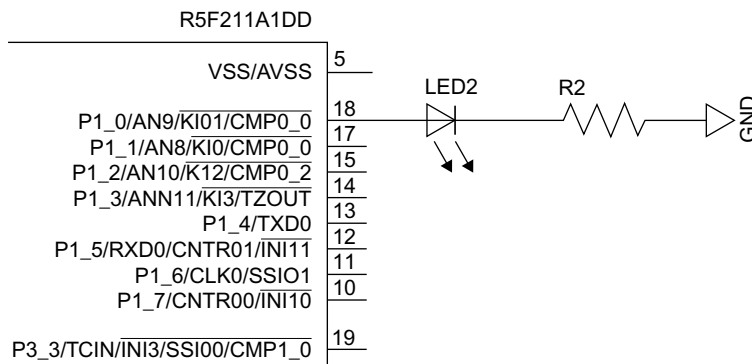


Figure 2.5A The microprocessor is sourcing current to an LED. Turning on this LED requires a logical high signal on the output pin. If the LED is attached to Port D, Pin 0, and that pin is set to an output; then the code needed to turn the LED on would be: `PORTD.PDR.BIT.B0 = 1;`

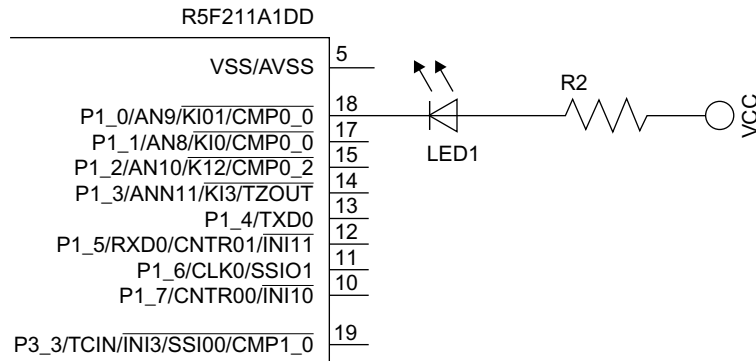


Figure 2.5B The microprocessor is sinking current from the LED. Turning on the LED requires a logical low on the output pin. If the LED is attached to Port D, Pin 0, and that pin is set to an output; then the code needed to turn the LED on would be: `PORTD.PDR.BIT.B0 = 0;`

Using Switches as Inputs

A simple interfacing design can include using a pull-up resistor on a pin that is also connected to ground through a button or switch. The resistor will pull the voltage on that pin to logical high until the button connects to ground. When the button is pressed, the voltage at that pin will drop to zero (logical low). Figure 2.6 shows a schematic of this approach. If the switch in Figure 2.6 is connected to Port D pin 0, the code to check this switch would be:

```

1. if (PORTD.PIDR.BIT.B0 == 0) {
2.     //Conditional code goes here
3. }

```

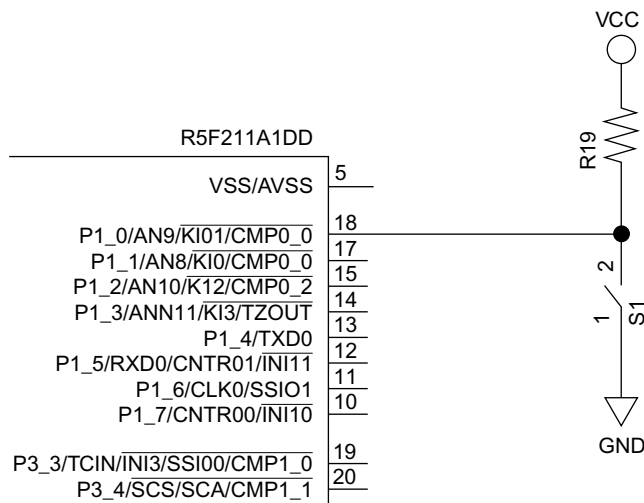


Figure 2.6 Basic button connection to a microprocessor input pin.

Contact bounce is a worry with any mechanical switch. When the switch is closed, the mechanical properties of the metals in the switch cause the contacts to literally bounce off of one another. This can cause false signals to be read as inputs. Your design should take this into account with either a hardware or software *debouncing* solution. Hardware debouncing circuits often require digital logic as well as some resistors and capacitors. Hardware debouncing circuits are very useful for interrupt pins. Software debouncing is accomplished by setting up a timer to check the state of the switch at a set interval, such as every 1 ms. If the value of the input has been the same for the duration of the timer (1 ms in this case) the input can be considered valid. This method helps to ignore false input values.

To better understand configuring I/O pins let us look at an example. The RX63N board has three push buttons and twelve LEDs (six red and six green). Switches and LEDs are simple I/Os and in the following program we will see how to set up switches as inputs and LEDs as outputs. According to this program, when switch1 is pressed, green LEDs will glow, when switch2 is pressed, red LEDs will glow, and when switch3 is pressed, all the LEDs will glow.

```
1. #include "iodef.h"
2. #ifdef YRD_RX63N
3. #define LED1    PORTD.PODR.BIT.B0
4. #define LED2    PORTD.PODR.BIT.B1
5. #define LED3    PORTD.PODR.BIT.B2
6. #define LED4    PORTD.PODR.BIT.B3
7. #define LED5    PORTD.PODR.BIT.B4
8. #define LED6    PORTD.PODR.BIT.B5
9. #define LED7    PORTD.PODR.BIT.B6
10. #define LED8    PORTD.PODR.BIT.B7
11. #define LED9    PORTE.PODR.BIT.B0
12. #define LED10   PORTE.PODR.BIT.B1
13. #define LED11   PORTE.PODR.BIT.B2
14. #define LED12   PORTE.PODR.BIT.B3
15. #define LED1_PDR  PORTD.PDR.BIT.B0
16. #define LED2_PDR  PORTD.PDR.BIT.B1
17. #define LED3_PDR  PORTD.PDR.BIT.B2
18. #define LED4_PDR  PORTD.PDR.BIT.B3
19. #define LED5_PDR  PORTD.PDR.BIT.B4
20. #define LED6_PDR  PORTD.PDR.BIT.B5
21. #define LED7_PDR  PORTD.PDR.BIT.B6
22. #define LED8_PDR  PORTD.PDR.BIT.B7
23. #define LED9_PDR  PORTE.PDR.BIT.B0
24. #define LED10_PDR  PORTE.PDR.BIT.B1
```

```
25. #define LED11_PDR    PORTE.PDR.BIT.B2
26. #define LED12_PDR    PORTE.PDR.BIT.B3
27. #define LED_ON      1
28. #define LED_OFF     0
29. #define ALL_LEDS_ON  {LED1 = LED2 = LED3 = LED4 = LED5 = LED6 =
    LED7 = LED8 = LED9 = LED10 = LED11 = LED12 = LED_ON;}
30. #define ALL_LEDS_OFF {LED1 = LED2 = LED3 = LED4 = LED5 = LED6 =
    LED7 = LED8 = LED9 = LED10 = LED11 = LED12 = LED_OFF;}
31. #define ENABLE_LEDS  {LED1_PDR = LED2_PDR = LED3_PDR = LED4_PDR =
    LED5_PDR = LED6_PDR = LED7_PDR = LED8_PDR = LED9_PDR =
    LED10_PDR = LED11_PDR = LED12_PDR = 1;}
32. #endif
33. #define SW1    PORT4.PIDR.BIT.B0
34. #define SW2    PORT4.PIDR.BIT.B1
35. #define SW3    PORT4.PIDR.BIT.B4
36. #define ENABLE_SWITCHES {PORT4.PDR.BIT.B0 = PORT4.PDR.BIT.B1 =
    PORT4.PDR.BIT.B4 = 0;}
37. void main(void){
38.     ENABLE_LEDS;
39.     ENABLE_SWITCHES;
40.     while(1){
41.         if(SW1 == 0){
42.             LED12 = LED11 = LED10 = LED6 = LED5 = LED4 = LED_ON;
43.         } else if(SW2 == 0){
44.             LED9 = LED8 = LED7 = LED3 = LED2 = LED1 = LED_ON;
45.         } else if(SW3 == 0){
46.             ALL_LEDS_ON;
47.         } else {
48.             ALL_LEDS_OFF;
49.         }
50.     }
51. }
```

In line 1, the file ‘iodefine.h’ has been included. It is a custom header file created by Renesas for easy access and manipulation of data. The RX63N board has two sets of LEDs: RSK_RX63N LEDs which are used to indicate basic functions like power on, and YRD RX63N LEDs which are used to simulate a motor. This program uses the YRD RX63N LEDs to demonstrate the use of digital I/O pins. Line 2 and line 32 are used to indicate that the statements between them should be executed only for YRD RX63N LEDs. All pins of Port D and pins 0 to 3 of Port E are the LED pins. The three switches are at Port 4 bits 0, 1, and 4.

In main, first the LEDs have been enabled (line 38). `ENABLE_LEDS` is a macro defined earlier in the program (line 31) to set the Port Direction Register (PDR) of the LEDs to 1; i.e., set up the LED pins as output pins.

Next, the switches have been enabled (line 39). `ENABLE_SWITCHES` is another macro defined earlier (line 36) to set the Port Direction Register (PDR) of the switches to 0; i.e., set up the switch pins as output pins.

The next part of the program is an important part of many embedded systems—the while (1) loop (line 40). This loop makes the microcontroller execute all the statements within the loop repeatedly until the microcontroller is stopped by an external force (e.g., power off). In this program, the conditions for LED operation are given within the while (1) loop using if-else statements (lines 41 to 47). Even though use of the switch statement will result in much better code, the if-else statement has been used for easy understanding.

- If switch 1 is pressed (state of switch 1 is low), all the green LEDs are turned on (line 42). The state of the switch is checked using the macro defined in line 33 using the PDR register. From the schematic of the board it can be seen that green LEDs are LED 12, 11, 10, 6, 5, and 4. They are turned on by setting the Port Output Data Register (PODR) of the LED pins to 1 (active high) which has been defined using the macro `LED_ON` in line 27.
- If switch 2 is pressed (state of switch 2 is low), all the red LEDs are turned on (line 44). The state of the switch is checked using the macro defined in line 34 using the PDR register. From the schematic of the board it can be seen that red LEDs are LED 9, 8, 7, 3, 2, and 1. They are turned on by setting the Port Output Data Register (PODR) of the LED pins to 1 (active high) which has been defined using the macro `LED_ON`.
- If switch 3 is pressed (state of switch 3 is low), all the LEDs are turned on (line 46) using the macro `LED_ON`.
- If none of the switches are pressed (line 47) all the LEDs are turned off using the macro `LED_OFF` (line 48).

2.2.3 Driving Motors and Coils

Input/Output (I/O) pins on a microcontroller have specific limits to the amount of current each pin can sink or source. These limits are found in the datasheet. Voltage levels can also be different between sensors and the microcontroller. Both of these constraints must be taken into account when designing interfaces for the actuator.

Because of their large coils, motors draw a lot of current. For Direct Current (DC) motors, simple transistor drivers or H-bridges (shown in Figure 2.7) can be used to interface

them with a microcontroller. If the left input of the circuit in Figure 2.7 is connected to Port D pin 0 and the right input of this circuit is connected to Port D pin 1, the code to turn the motor one direction would be:

1. `PORTD.PDR.BYTE = 0x03;` //Sets pins 0 and 1 on Port D as outputs
2. `PORTD.PODR.BYTE = 0x02;` //Sets one pin as HIGH and the other as LOW

Stepper motors can use transistors or stepper motor driver ICs. Some ICs such as the L293 or the 754410 are specifically designed to drive the DC motors and interface directly with a microcontroller. Servos are gearboxes that have motor control circuitry built in. These devices can often connect their control pins directly to a microprocessor as their internal circuitry handles driving the motor itself. Other large coils such as relay coils should be treated similarly to motors. Figure 2.8 shows a basic coil driving circuit. Code to drive the coil is the same as it is to drive an LED.

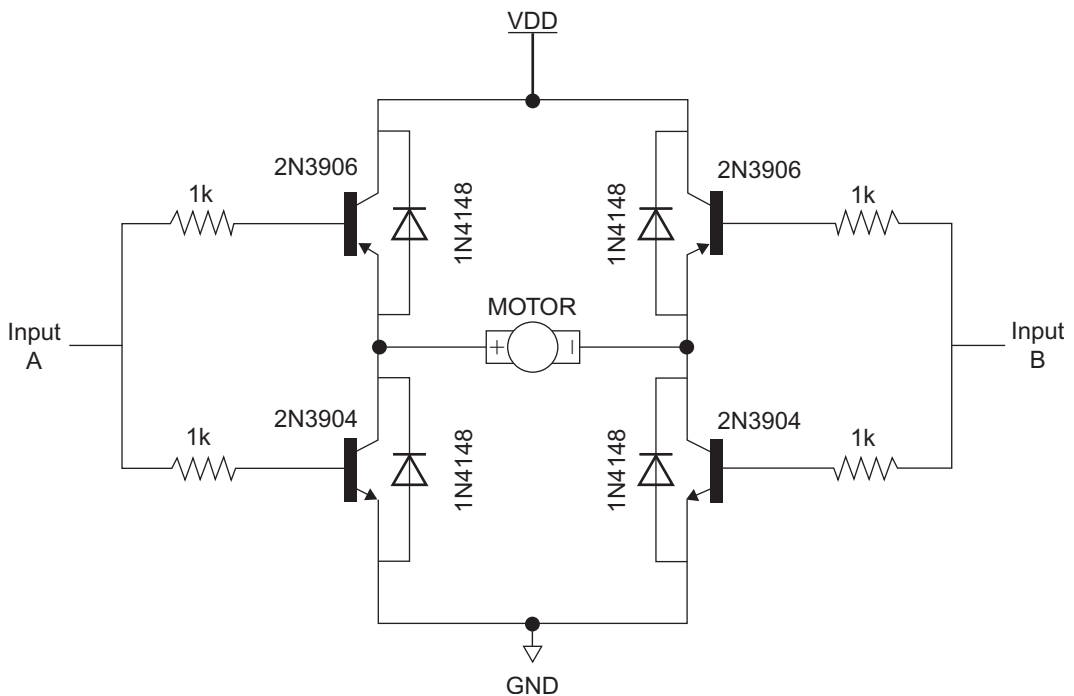


Figure 2.7 H-bridge motor driver. Two of the microprocessor's outputs are connected to the resistors. *Note: Both inputs should not be the same value for the motor to turn.*

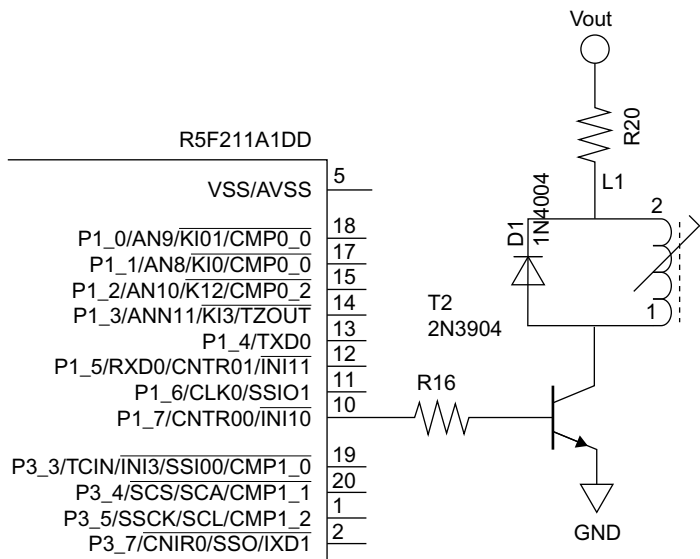


Figure 2.8 A simple coil driver.

There are other methods of controlling large loads with a microprocessor, such as using relays or triacs. The overall concept with all load driving circuits is to keep the source and sink currents of the microprocessor within the manufacturer's recommendations.

Some sensors may require different voltages than what the microprocessor requires. Care should be taken when interfacing these sensors. If the microprocessor runs at 5 V and the sensor runs at 1.8 V, the microprocessor will not be able to read a HIGH logic signal on the sensor output. Circuits for interfacing with higher voltage sensors can be designed using transistors or by using level converter ICs, which convert the signals between the microcontroller and the sensor either uni-directionally or bi-directionally (in case the microprocessor needs to communicate to the sensor.) The use of a flyback diode is very important when interfacing inductive loads, to safely dissipate the voltage spike when the voltage to the load is removed.

2.2.4 Scanning Matrix Keypads

Keypads work as a matrix of buttons. For instance, Figure 2.9 shows an example keypad matrix. The top three output pins are used as the columns of the matrix. The three pins connected as the rows of the matrix are all input pins. A button is placed in the circuit at each intersection of a column and row. One at a time, the output pins turn on and each of the input pins is read. If an input is detected, the microprocessor can determine which button on the keypad had been pressed. For example, if the microprocessor noted an input on the

middle row pin at the time in which the middle output was logical high, then the center button must have been pressed. If the columns in Figure 2.9 are connected to Port D bits 0, 1, and 2 respectively, and the rows are connected to Port E bits 0, 1, and 2 respectively; code to read the keypad values of the first column would be:

```

1. PORTD.PODR.BIT.B0 = 1; //Set the output of the first column to 1
2. PORTD.PODR.BIT.B1 = 0; //Set the output of the second column to 0
3. PORTD.PODR.BIT.B2 = 0; //Set the output of the third column to 0
4.
5. if(PORTE.PIDR.BIT.B0 == 0){
6.     //Conditional code for Row 0
7. }
8.
9. if(PORTE.PIDR.BIT.B1 == 0){
10.    //Conditional code for Row 1
11. }
12.
13. if(PORTE.PIDR.BIT.B2 == 0){
14.    //Conditional code for Row 2
15. }

```

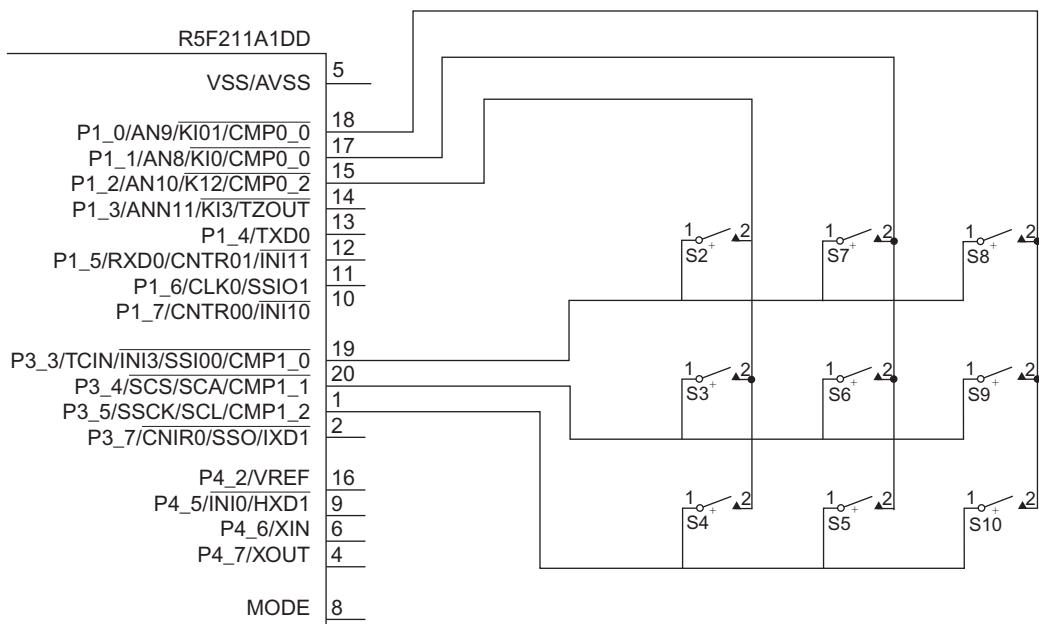


Figure 2.9 Keypad button matrix.

2.3 INTERFACING WITH ANALOG SIGNALS

The world is not digital; it is analog. Microphones, thermometers, speakers, light sensors, and even video cameras are all analog sensors. As a result, the signals from these sensors must be converted to digital values so that the microcontrollers can process them.

2.3.1 Analog to Digital Converters

To read the value of an analog sensor, *Analog to Digital Converters* (also referred to as ADC, A/D, A-to-D, and A2D) are used. This circuit produces a multi-bit binary number based on a voltage scale. The number of bits in the multi-bit binary number helps determine the resolution or precision of the reading; 8-bit, 10-bit, and 12-bit converters are commonly used. ADCs also require a reference voltage. This is a stable voltage to which the current reading will be compared to produce the binary output. The analog reference voltage is scaled by the resolution. Most ADCs use linear scales, so converting the values is straightforward. Figure 2.10 shows the transfer function which is used to convert an analog voltage (measured on the horizontal axis) to its digital output code representation (on the vertical axis). Each step on the transfer function represents one least significant bit (LSB). Figure 2.11 shows an example input analog voltage which is sampled over time.

The resolution of the conversion is determined by Formula 2.2.

$$\text{Resolution} = V_{\text{LSB}} = V_{\text{ref}}/2^{N_{\text{bits}}}$$

Formula 2.2

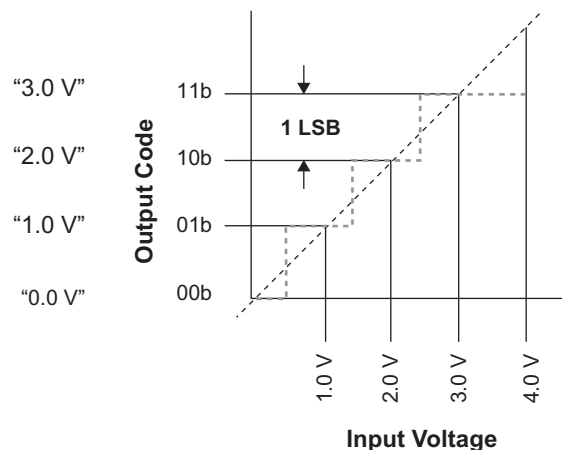


Figure 2.10 2-bit ADC conversion chart. The stair step line shows the ADC's output code.

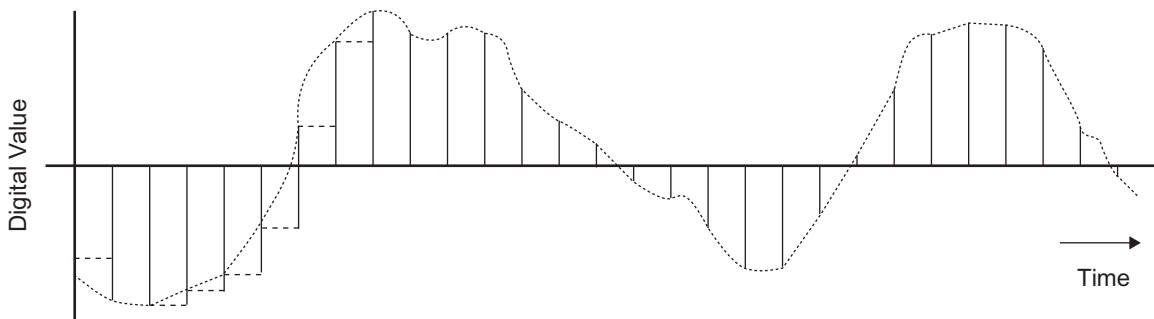


Figure 2.11 ADC readings over time.

If $V_{\text{ref}} = 5 \text{ V}$, and there is an 8-bit resolution, the volts per ADC raw value step = $5 \text{ V}/256 = 0.01953 \text{ V/step}$.

To determine the value of the conversion, Formula 2.3 can be used:

$$\text{ADC output code} = \text{int}(((2^{N_{\text{bits}}} - 1) * (V_{\text{in}}/V_{\text{ref}})) + 1/2) \quad \text{Formula 2.3}$$

For example:

$$V_{\text{ref}} = 5 \text{ V}, V_{\text{in}} = 2.26295 \text{ V}, \text{ with a 10-bit resolution;} \\ \text{int}((1023 * (2.26295 \text{ V}/5 \text{ V})) + 1/2) = 463 \text{ ADC raw value steps.}$$

Once the raw ADC value is known, the application software should reverse the formula to calculate the actual voltage on that pin. Since the datasheet for most sensors provides a formula for converting the voltage to the unit the sensor is measuring (be it degrees Celsius, distance in centimeters, pressure in kilopascals, etc.), this formula can be inserted into the firmware to make sense of the data.

More advanced sensors use a communication protocol such as RS-232, RS-485, I²C, and SPI. These sensors generally take an analog value, convert it to digital, and then send it to the microcontroller for processing using a communication protocol. These protocols sometimes allow for multiple sensors to be connected to the same pins of the microcontroller.

2.3.2 Analog Comparator

Some microcontrollers may contain one or more comparator circuits. This circuit can be thought of as a simple 1-bit ADC. It compares an analog voltage input with an analog reference voltage, and then determines which is larger.

2.3.3 Digital to Analog Conversion

Just as we must convert analog signals to digital to process them, sometimes there is a need to convert digital signals to analog. In systems that control audio, speed, or even light levels; digital output from a microprocessor must be converted into an analog signal. There are several different methods for converting digital signals to analog.

Resistor Networks

Resistor networks allow a very simple solution for converting digital signals to analog. There are many methods of using resistor networks for DACs, but two designs are predominantly used.

Binary Weighted DACs

Resistor networks are another simple method for DAC conversion. Several different methods are available for using resistor networks, and again it is up to the designer to

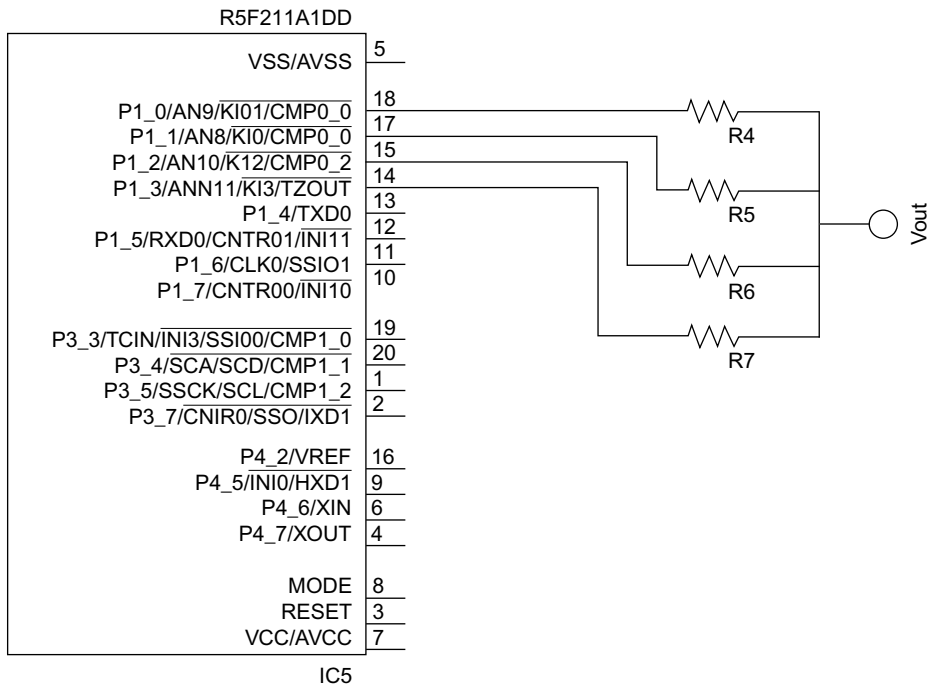


Figure 2.12 4-bit binary weighted network DAC design [2], pages 153–159.

decide which method is best for a particular design. *Voltage-Mode Binary Weighted DACs* are commonly used with microcontroller circuits. In this design, resistors are connected together on one end (the analog output), and the other ends are connected directly to the pins of a microcontroller port. The values of the resistors are based on binary bit place-values (R , $2R$, $4R$, $8R$, etc.; with R being the least significant bit or LSB). When the pins of the microcontroller are set to HIGH, then the sum voltage of the analog output are related to the value on that port. Figure 2.12 shows an example of a 4-bit Binary Weighted DAC.

R-2R DAC

Another method of using resistor networks to design a DAC is called the *R-2R* or *R/2-R Network*. It consists of resistors of only two values. One value is twice the value of the other. For instance, if the R resistors are one kilo-ohm, then the $2R$ resistors must equal two kilo-ohms. Figure 2.13 shows an example R-2R network (Kuphaldt, T. R., “The R2-R”).

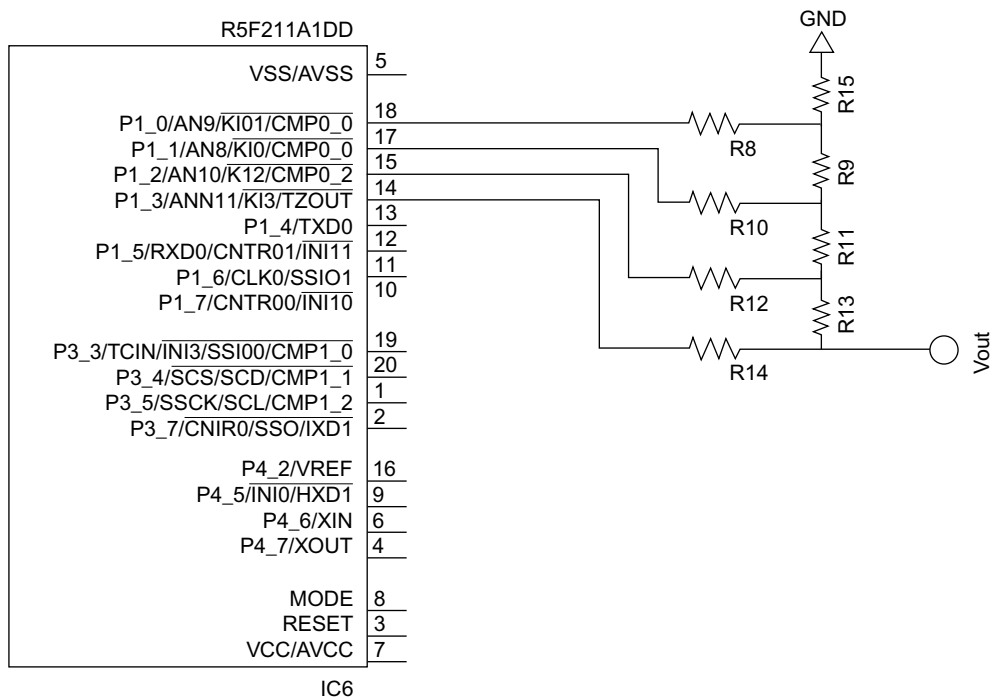


Figure 2.13 R-2R network. R9, R11, and R13 are considered “R” resistors and all = 1k ohm while R8, R10, R12, R14, and R15 are considered “2R” and all = 2k ohm [3].

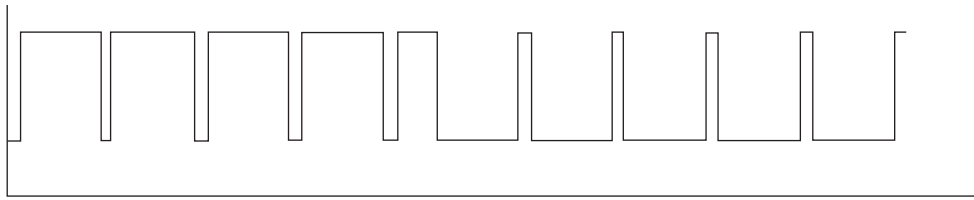


Figure 2.14 An example PWM signal. If this were controlling an active-high LED, the LED would be brighter during the first half of the graph, and dimmer over the second half.

As with the binary weighted DAC, the output voltage corresponds to the binary value on the port. The following example is valid for both R-2R as well as Binary Weighted DACs:

If the V_{ref} is 5 V and there is a 4-bit binary value 1001 (decimal number 9) on the microcontroller pins, we would expect the output voltage to be:

$$V_{out} = (V_{ref}/(2^N)) * (\text{binary value of microcontroller output}) \quad \textbf{Formula 2.4}$$

For example:

$$(5 \text{ V} / 16 \text{ bits}) * (9) = 2.8125 \text{ V.}$$

Pulse Width Modulation

A common method for controlling the speed of a simple DC motor or the brightness of an LED is *Pulse Width Modulation*. Pulse Width Modulation works as a DAC by changing the duty cycle of an oscillating digital output as shown in Figure 2.14. In the case of an LED, the more time the duty cycle is HIGH, the brighter the LED. This method works in cases where the oscillating frequency is so fast that the resulting output seems smooth. The LED is actually turning on and off several times per second; however, the human eye cannot detect the independent flashes of the LED due to their speed. Motor speed can be controlled this way because the inertia of the spinning armature carries the motor forward through the moments when no power is applied.

2.4 INFRASTRUCTURE: POWER, CLOCK, AND RESET

2.4.1 Power Supply

When designing the power supply for an embedded system, the designer must determine how to power peripherals and whether or not they will use a separate supply. This decision will affect the overall design requirements of the power supply. This chapter only addresses the power supply for the microprocessor itself.

Voltage and current ratings for the microprocessor can be found in the manufacturer's datasheet for the chip, often under the title of *Recommended Operating Conditions* or *Electrical Characteristics*. Another section in the datasheet also shows *Absolute Maximum Ratings*, which should be considered but not confused with the *recommended values*. To be assured that the chip will operate as expected, a system should never be designed to operate too close to the absolute maximum or minimum power ratings. Fluctuations in the power supply may cause the values to go over the absolute maximum ratings of the chip, which can damage the microprocessor. The power supply should be designed with a safety factor to account for these fluctuations, hence the recommended values.

Once the requirements are determined, the source of the power must be determined. Whether the design plugs into the wall or if it uses batteries will determine the type of power supply circuit.

If the design uses mains power, then a standard design method for a power supply circuit can be used. This design will require a transformer to drop the voltage to an acceptable range for a voltage regulator chip. Capacitors will be required to smooth out any ripple or noise.

If batteries are to be used, then the type of battery (NiCad, NiMH, LiPo, etc.) must be selected based on the current rating each battery type can supply, and whether the design will need to be rechargeable.

The length of time a battery will last can be calculated based on the capacity of the battery and the amount of current the circuit uses using Formula 2.5.

$$\text{Battery Life (hours)} = \text{Capacity (amp-hours)} / \text{current (amps)} \quad \textbf{Formula 2.5}$$

An 800 mAh battery will power a device that draws 200 mA for;

$$800 \text{ mAh} / 200 \text{ mA} = \mathbf{4 \text{ hours}}$$

Putting batteries in parallel adds their current capacities. Putting them in series adds their voltages.

For two batteries with each 1.5 V and 2000 mAh:

$$\text{Series: } 1.5 \text{ V} + 1.5 \text{ V} = \mathbf{3.0 \text{ V}} \text{ at } 2000 \text{ mAh}$$

$$\text{Parallel: } 2000 \text{ mAh} + 2000 \text{ mAh} = 1.5 \text{ V at } \mathbf{4000 \text{ mAh}}$$

If the batteries need to be recharged, then a battery charging circuit as well as battery level monitor will also need to be designed.

Regardless of which batteries are chosen, a voltage regulator of some type is generally required. The use of linear or switch-mode voltage regulator integrated circuits (ICs) is a standard practice.

2.4.2 Clock Signal Generation

Microprocessors are synchronous circuits that require a clock to work. This clock allows data to be pushed through the stages of the instruction pipeline and helps the microprocessor coordinate tasks. When selecting a clock generator, the microcontroller datasheet must be used. This datasheet gives the values of the different clocks that a particular microprocessor can accept.

There are two major types of clock signal generators: those that work on purely electrical principles, and those that work on mechanical vibration (resonance of a quartz element). The signal generators for the electrical driven clock can be simple resistor-capacitor (RC) or inductor-capacitor (LC) circuits. Generally, these clocks aren't very accurate on their own, and their design can become quite complicated when precision is required. Many microprocessors offer signal generators with an internal clock that consists of an RC circuit inside the chip, which can be configured. These clocks should not be used when precision is required. Figure 2.15 shows the connection of an RC oscillator to the clock input of a microprocessor.

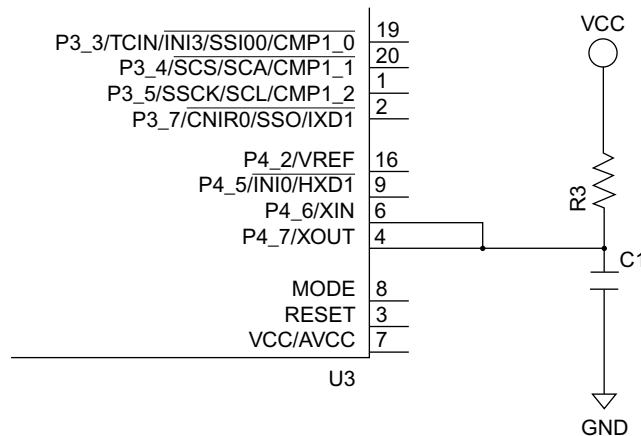


Figure 2.15 RC clock generator.

Clock signal generators that are mechanically driven use a quartz crystal to produce a steady signal. These oscillators rely on the piezoelectric effect of the crystal. This method of clocking is accurate (around 30 parts per million or about 0.003% error), cheap, and widely available. Generally, two small load capacitors are required between each lead of the crystal and ground. The values of these capacitors are based on the crystal characteristics and are listed in the crystal's datasheet.

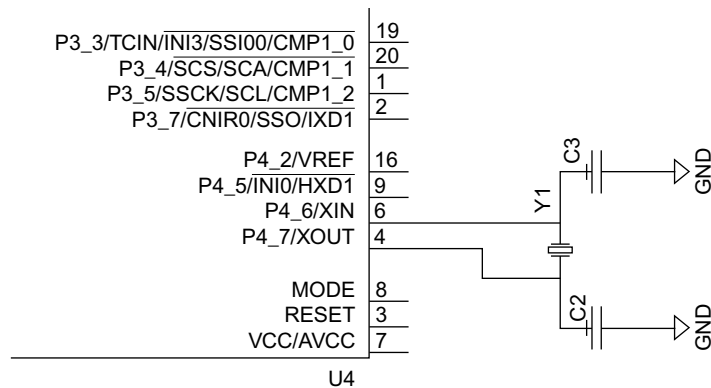


Figure 2.16 Connection of a crystal clock generator chip.

Ceramic resonators are growing in popularity for use as a clock generator. The resonators use a piezoelectric ceramic element that is not as accurate as quartz, yet more accurate than RC circuits. They also contain the appropriate load capacitors built in so they do not require any additional components to work.

External clock generator integrated circuit chips can also be used. These clocks use a quartz or RC circuit as a resonant oscillator, but also contain an amplifier. The frequency can be changed by reprogramming the clock generator. The duty cycle is also selectable for use in cases where a 50% duty cycle cannot be used. These circuits are usually more expensive when compared to other oscillators.

2.4.3 Reset Circuit

Resetting a microprocessor starts the processor off in a predictable state. When a reset is detected, the microprocessor loads predefined values into the system control registers. These registers are useful in case of a catastrophic event, such as if the power supply were to drop below a certain threshold. All microprocessors designate a pin that is solely used for resetting the chip. A reset circuit controls this pin to assure a reset is valid if it is used. The requirements of a reset circuit is specific to the microprocessor being used and can be found in the manufacturer's datasheet. Some microcontrollers contain reset logic internally; however, the manufacturer's datasheet should be consulted to make sure it meets the specifications for your application. Alternatively, reset controller chips can be used which contain all the parts necessary for the circuit. Even though they are generally more expensive, in some cases such as low-volume productions, it may be best to use reset controller chips.

2.5 RECAP

It should now be easier to understand how the embedded systems you encounter in your everyday life actually operate and communicate with the outside world. It should also be easier to break some of these systems down into their component parts, given the knowledge of sensor and actuator interfacing presented in this chapter.

2.6 REFERENCES

- [1] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013.
- [2] Kester, W. A., and Analog Devices, Inc. *Data Conversion Handbook*. Lawrence, KS: Newnes, 2005: pp. 153–159. Print.
- [3] “The R2-R,” in Kuphaldt, T. R., *All about Circuits*. Electronic publication. Web. Accessed at http://www.allaboutcircuits.com/vol_4/chpt_13/3.html

2.7 EXERCISES

1. Name ten devices that use an embedded system.
2. Write the C code to set port 4, bits 0 through 3 to be input pins, and port 4, bits 4 through 7 to be output pins.
3. Write the C code to read the data on port 4, bits 0 through 3 and write the read data to port 4, bits 4 through 7.
4. How long will a 2500 mAh battery last if the circuit using it runs at 600 mA?
5. You have a wireless sensor node whose current drain is 50 mA for one minute every one hour and 0.001 mA the rest of the time. I am using a single 5000 mAh cell as the power supply for this device. How long will my device run in hours, days, and years?
6. What are the different kinds of clock generators? Define their base technologies.
7. What resistor value should be used to connect an LED with a forward voltage of 3.1 volts and a forward current of 20 mA to the input pin of a microcontroller that outputs 5 volts?
8. Is it generally safe to connect a coil or motor directly to a microcontroller I/O pin? Why or why not?
9. Is it generally safe to connect a servo control input directly to a microcontroller I/O pin? Why or why not?

10. How many volts per ADC step are in a system with an ADC resolution of 10-bits, and a reference voltage of 3.3 V?
11. How many volts per ADC step are in a system with an ADC resolution of 12-bits, and a reference of 5 V?
12. An analog input has a voltage of 1.37860. What value will the ADC return if it has an 8-bit resolution and a reference of 4.25 volts?
13. An analog input has a voltage of 7.61245. What value will the ADC return if it has a 12-bit resolution and a reference of 10 volts?
14. Using a binary-weighted DAC, using 8 bits and a reference of 4.35 volts, what is the voltage of the output if the 8-bit value is 01011010?

Organization and Architecture of the Renesas RX63N Microcontroller Board

3.1 LEARNING OBJECTIVES

In this chapter the reader will learn about:

- Basic organization of computers
- Architecture of the Renesas RX63N board
- Endianness, data arrangement, and bus specification in RX63N CPU
- Date types, operating modes, and memory map of RX63N CPU

3.2 BASIC CONCEPTS

3.2.1 Introduction to Computer Organization & Architecture

A computer is a complex digital system. The best way to look at it is by looking at its hierarchical nature. Hierarchical systems are best described as a series of subsystems that are interconnected at various levels to form a complete computer system. At each level is a set of components whose behavior depends on the characteristics and functions of the next lower level. A designer focuses on structure and function within each level. The computer has four basic functions to perform (see Figure 3.1):

1. Data processing
2. Data storage
3. Data movement
4. Data control

Computers process data with the help of the data processing facility. During and after processing, storage is required for this data. During processing, the data needs a temporary or short term storage area. After processing, the data will be stored in a long-term storage area. The Data Movement Block provides a data path between the outside environment and the computer. This block is also responsible for the data flow between various subcomponents

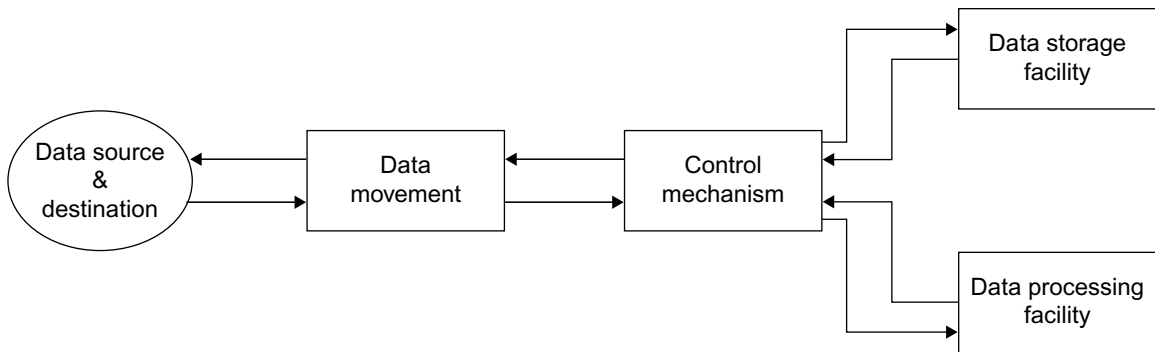


Figure 3.1 A generalized view: Building blocks of a computer.

within the computer. The Control Mechanism takes care of controlling and managing various subcomponents and their interactions with each other.

Computers have four basic structural components (See Figure 3.2):

1. CPU: Processes the data and controls the operation of computer.
2. Memory: Stores data.
3. I/O: Moves the data between the computer and the external environment.
4. System Interconnection: Provides a mechanism for transferring data or communicating between components such as the CPU, main memory, and I/O.

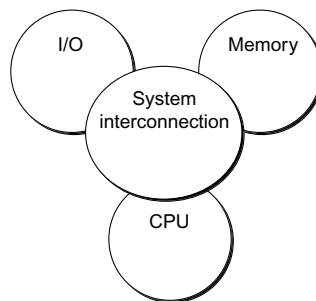


Figure 3.2 A top level view of a computer.

The Central Processing Unit (CPU) is the most complex component out of the four basic components. The structure of the CPU is illustrated in Figure 3.3. The components that make up a CPU are:

1. Control Unit: Controls the operation of the CPU.
2. Arithmetic and Logic Unit (ALU): Performs the computer's data processing functions.
3. Registers: Provides internal storage for the CPU. They store ALU operands.
4. Interconnections: Provides a mechanism for transferring data or communicating between components such as the Control Unit, ALU, and registers.

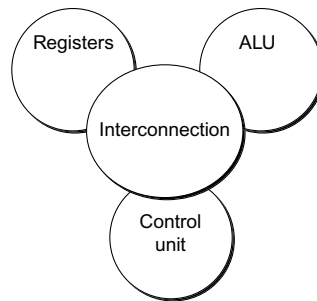


Figure 3.3 A top level view of a CPU.

The IAS* computer, which is a prototype of general-purpose computers, is based on the stored-program concept. This idea was developed by John von Neumann and is known as the von Neumann Machine. As shown in Figure 3.4, the von Neumann machine has a main memory for storing the instructions and data the same as an IAS computer. It also has an ALU, which processes the binary data. A control unit decodes the instructions and forwards them to the ALU for execution. The Input/Output unit interacts with the external environment and is controlled by the Control Unit.

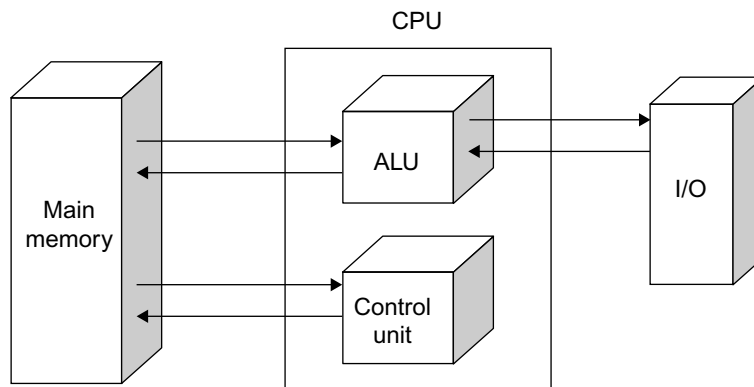


Figure 3.4 Structure of a von Neumann machine.

* Institute for Advanced Study, Princeton, NJ

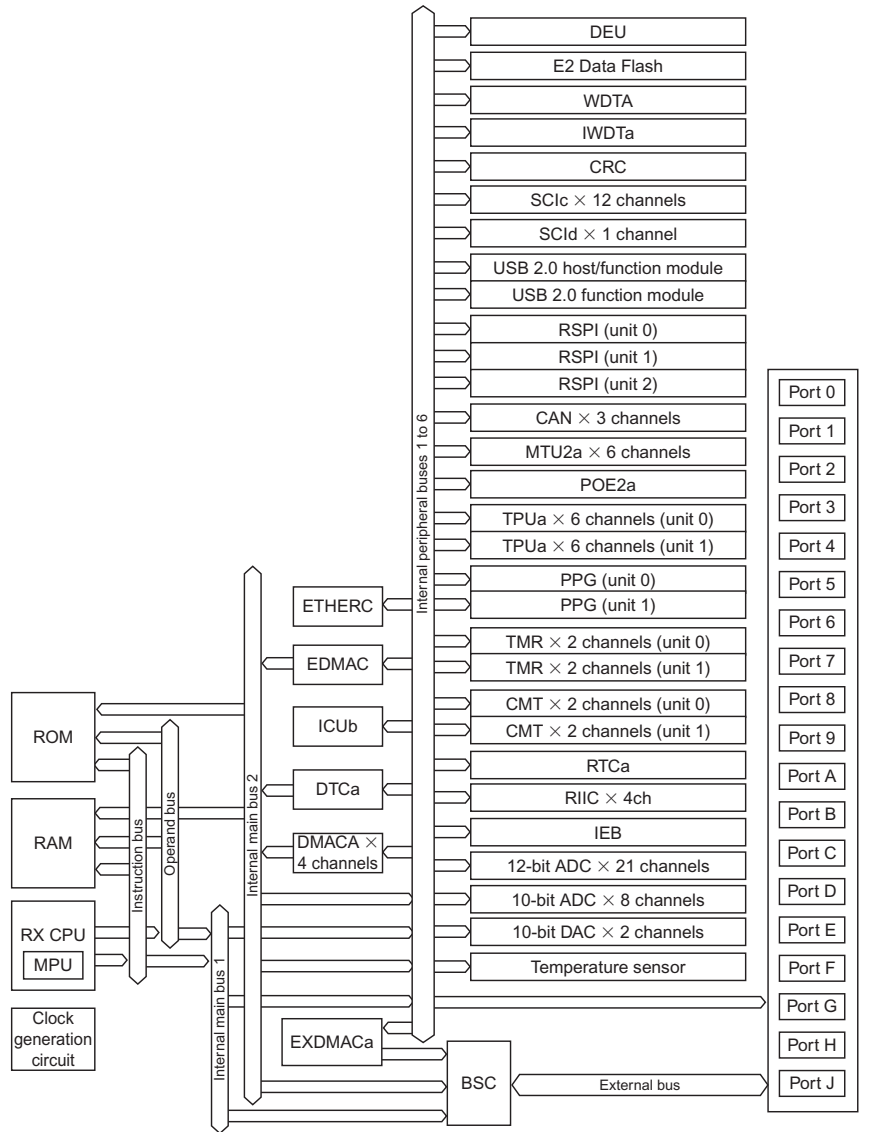
3.2.2 Architecture of the Renesas RX63N

The RX63N microcontroller architecture has the following components:

1. **CPU:** The CPU contains two main modules or functions:
 - CPU: It is a 32-bit RX CPU with maximum operating frequency of 100 MHz.
 - Floating Point Unit (FPU): This unit is a single precision (32-bit) floating point unit which supports data types and floating-point exceptions in conformance with IEEE 754 standard.
2. **Memory:** The memory contains three main modules:
 - ROM: RX63N variants have the following ROM capacities: ROMless, 256 Kbytes, 384 Kbytes, 512 Kbytes, 768 Kbytes, 1 Mbyte, 1.5, Mbytes, 2 Mbytes; the RX63N supports four on-board programming modes and one off-chip parallel programmer mode.
 - RAM: Its variants have the following capacities: 64 Kbytes, 128 Kbytes, 192 Kbytes, 256 Kbytes.
 - E2 Data Flash: Its capacity is 32 Kbytes.
3. **Clock generation circuit:** The clock generation circuit consists of two circuits, namely a main clock oscillator and a sub clock oscillator. The CPU and other bus masters run in synchronization with the system clock (ICLK): up to 100 MHz; the peripheral modules run in synchronization with the peripheral module clock (PCLK): up to 50 MHz; while devices connected to the external bus run in synchronization with the external bus clock (BCLK): up to 50 MHz.
4. **Reset:** There are various reset sources available for different modules in the MCU such as pin reset, power-on reset, voltage-monitoring reset, watchdog timer reset, independent watchdog timer reset, and deep software standby reset.
5. **Voltage detection circuit:** When the voltage available on VCC falls below the voltage detection level (V_{det}), an internal reset or internal interrupt is generated.
6. **External bus extension:** The external address space is divided into nine areas: CS0 to CS7 and SDCS. The capacity of each area from CS0 to CS7 is 16 Mbytes, and for SDCS the capacity is 128 Mbytes. A chip-select signal (CS0# to CS7#, SDCS#) can be output for each area. Each area is specifiable as an 8-, 16-, or 32-bit bus space.
7. **Direct Memory Access (DMA):** The DMA system consists of three different controllers which are explained below. The activation sources for all three controllers are software trigger, external interrupts, and interrupt requests from peripheral functions:
 - DMA controller: It has four channels and three transfer modes. These modes are normal transfer, repeat transfer, and block transfer.
 - EXDMA controller: It has two channels and four transfer modes. These modes are normal transfer, repeat transfer, block transfer, and cluster transfer.
 - Data transfer controller: It has three transfer modes. These modes are normal transfer, repeat transfer, and block transfer.
8. **I/O ports:** The main modules of I/O ports are programmable I/O ports. There are several I/O ports available on the 177-pin TFLGA, 176-pin LFBGA and 176-pin

LQFP,145-pin TFLGA and 144-pin LQFP, 100-pin TFLGA,64-pin LQFP and 48-pin LQFP packages.

9. **Timers:** There are seven timer units available for controlling the sequence of an events or processes.
 - 16-bit timer pulse unit: It has two units of 6 channels each. It supports cascaded connection to provide 32-bit timers (2 channels). It can be used for PPG output trigger, A/D conversion trigger and for clock frequency measuring method.
 - Multi-function timer pulse unit: It has two units each supporting six channels and each channel has 16 bits. It provides time bases for the twelve 16-bit timer channels by way of up to 32 pulse-input/output lines and six pulse-input lines.
 - Port output enable: It controls the high-impedance state of the MTU's waveform output pins.
 - Programmable pulse generator: It has two units, each supporting four groups and each group has 4 bits. It outputs an MTU pulse as a trigger. The maximum output possible is 32-bit pulse output.
 - Frequency measuring a method: The MTU or unit 0 TPU module can be used to monitor the main clock, subclock, HOCO clock, LOCO clock, and PLL clock for abnormal frequencies.
 - 8-bit timers: It has two units, each supporting two channels and each channel has 8 bits. The clock signal can be selected from seven internal clock signals (PCLK, PCLK/2, PCLK/8, PCLK/32, PCLK/64, PCLK/1024, and PCLK/8192) and one external clock signal. These are capable of outputting pulse trains with desired duty cycles or of PWM signals.
 - Compare-match timer: It has two units, each supporting two channels and each channel has 16 bits.
 - The clock signal can be selected from four internal clock signals (PCLK/8, PCLK/32, PCLK/128, and PCLK/512).
 - Watchdog timer: It has one channel of 14 bits. The clock signal can be selected from eight counter-input clock signals (PCLK/4, PCLK/64, PCLK/128, PCLK/512, PCLK/2048, PCLK/8192). It is switchable between watchdog timer mode and interval timer mode.
 - Independent watchdog timer: It has one channel of 14 bits. It requires a counter-input clock (which is available from the dedicated on chip oscillator) of IWDTCLK, IWDTCLK/16, IWDTCLK/32, IWDTCLK/64, IWDTCLK/128, or IWDTCLK/256.
10. **Communication function:** For communicating with the outside world, the MCU provides several controllers:
 - Ethernet controller: The data rate it supports is either 10 or 100 Mbps. It supports both full and half duplex modes.
 - IEBus: It supports protocol control for IEBus (IEB) with two selectable modes, differentiated by transfer rate.



- | | | | |
|------------|---|-------|------------------------------------|
| ETHERC | :Ethernet controller | RSP1 | :Serial peripheral interface |
| EDMAC | :DMA controller for Ethernet controller | CAN | :CAN module |
| ICUb | :Interrupt controller | MTU2a | :Multi-function timer pulse unit 2 |
| DTCa | :Data transfer controller | POE2a | :Port output enable 2 |
| DMACA | :DMA controller | TPUa | :16-bit timer pulse unit |
| EXDMACa | :EXDMA controller | PPG | :Programmable pulse generator |
| BSC | :Bus controller | TMR | :8-bit timer |
| WDTA | :Watchdog timer | CMT | :Compare match timer |
| IWDTa | :Independent watchdog timer | RTCa | :Realtime clock |
| CRC | :CRC (cyclic redundancy check) calculator | RIIC | :I ² C bus interface |
| SCIC, SCID | :Serial communications interface | IEB | :IEBus controller |
| MPU | :Memory protection unit | DEU | :Data encryption unit |

Figure 3.5 Block diagram [1], Figure 1.2, page 66.

- Half-duplex asynchronous transfer and Multi-master operation are supported.
 - DMA controller for Ethernet: It supports transmission and reception FIFO of 2 Kbytes each.
 - USB 2.0 host/function module: It includes a USB device controller and transceiver for USB 2.0. It incorporates 2 Kbytes of RAM as a transfer buffer and supports data rate of 12 Mbps.
 - Serial communication interfaces: 13 channels (SCiC: 12 channels + SCId: 1 channel) and supports several serial communication modes such as asynchronous, clock synchronous, and smart-card interface. The desired baud rate is selected by on-chip baud rate generator.
 - I²C bus interfaces: It has four channels, one of which is FM+. The communication formats supported are I²C bus format/SMBus format and master/slave selectable. It Supports the multi-master. Maximum possible transfer rate is 1 Mbps (channel 0)
 - CAN module: It supports one channel and 32 mailboxes.
 - Serial peripheral interfaces: It supports up to three channels and MOSI (master out, slave in), MISO (master in, slave out), SSL (slave select), and RSPI clock (RSPCK) signals. They enable serial transfer through SPI operation (four lines) or clock-synchronous operation (three lines). It is capable of handling serial transfer as a master or slave.
11. **A/D converter:** MCU supports two types of A/D converters, specifically 12-bit and 10-bit. The conversion time is 1.0 μ s per channel (in operation with Peripheral Clock at 50 MHz). The selectable operating modes are single scan mode and continuous scan mode.
 12. **D/A converter:** It supports two channels and 10-bit resolution. The output voltage ranges from 0V to V_{ref} .
 13. **CRC calculator:** CRC code generator generates code for arbitrary amount of data in 8-bit units. It is capable of selecting any of three generating polynomials:

$$X^8 + X^2 + X + 1, X^{16} + X^{15} + X^2 + 1, \text{ or } X^{16} + X^{12} + X^5 + 1.$$

One can also generate CRC codes for use with either LSB-first or MSB-first communications.

14. **Low power consumption:** RX63N has module stop function, four low power consumption modes (sleep mode, all-module clock stop mode, software standby mode and deep software standby mode) and battery backup function.
15. **Interrupt:** RX63N has 187 sources of peripheral function interrupts, 16 external interrupts pins (IRQ0 to IRQ15), 1 software interrupt source and 6 non-maskable interrupts. 16 levels of interrupt priority can be specified.
16. **Temperature sensor:** It has an on-chip temperature sensor with 1 channel and precision of $\pm 1^\circ\text{C}$.
17. **Data encryption unit:** It has AES encryption and decryption functions with 128/192/256-bit key lengths.

DEFINITION OF TERMS:			
ETHERC:	Ethernet Controller	WDT:	Watchdog timer
EDMAC:	DMA controller for Ethernet controller	IWDT:	Independent watchdog timer
ICU:	Interrupt control unit	CRC:	Cyclic redundancy check calculator
DTC:	Data transfer controller	MPU:	Memory-protection unit
DMACA:	DMA controller	SCI:	Serial communications interface
EXDMAC:	EXDMA controller	USB:	USB 2.0 host/function module
BSC:	Bus controller	RSPI:	Serial peripheral interfaces
CAN:	CAN module	TMR:	8-bit timer
MTU:	Multi-function timer pulse unit	CMT:	Compare match timer
POE:	Port output enable	RTC:	Realtime clock
PPG:	Programmable pulse generator	RIIC:	I ² C bus interface

CPU

The RX CPU being used in RX63N/RX631 Group of MCU's supports high-speed and high-performance.

The instruction set architecture (ISA) of RX CPU has a variable-length instruction format. The most commonly used instructions have been allocated shorter instruction lengths, making it possible to develop efficient programs that occupy less memory. The ISA of RX63N/RX631 Group has 90 instructions, out of which 73 are basic instructions, eight are floating-point operation instructions, and nine are digital signal processing (DSP) instructions. It achieves high-speed operation by executing instructions in a single cycle. It includes an internal multiplier and divider for high-speed multiplication and division. These operations take less time and hence add to the efficiency of the processor. The RX CPU has a five-stage pipeline for processing instructions.

1. Instruction fetching stage
2. Instruction decoding stage
3. Execution stage
4. Memory access stage
5. Write-back stage

In cases where pipeline processing is drawn-out by memory access, subsequent operations may in fact be executed earlier. By adopting out-of-order completion of this kind, the execution of instructions is completed in fewer clock cycles.

Register Set

The RX CPU has sixteen general-purpose registers, nine control registers, and one accumulator used for DSP instructions.

TABLE 3.1 Features of CPU.

FEATURES	DESCRIPTION
High instruction execution rate	One instruction per clock cycle.
Address space	4-Gbyte linear address space.
Register set of the CPU	There are sixteen 32-bit general purpose registers and nine 32-bit control registers. It has a 64-bit register accumulator.
Basic instructions	It has 73 basic instructions such as arithmetic/logic instructions, data-transfer instructions, branch instructions, bit-manipulation instructions, string-manipulation instructions, and system-manipulation instructions.
Floating-point operation instructions	It is an optional function that can be used. There are eight such operations.
DSP instructions	It is an optional function that can be used. There are nine such instructions. It supports 16-bit \times 16-bit multiplication and multiply-and-accumulate operations. It rounds the data in the accumulator.
Addressing modes	There are ten addressing modes.
Five-stage pipeline	It has a five-stage pipeline and allows out-of-order completion.
Processor modes	A supervisor mode and a user mode are supported.
Floating-point operation unit	It supports single-precision (32-bit) floating point operations and supports data types and exceptions in conformance with the IEEE 754 standard.
Data arrangement	The data can be selected either as little endian or big endian.

General-Purpose Registers (R0 to R15): The RX CPU has sixteen general-purpose registers (R0 to R15). R0 can function as a stack pointer (SP) and R1 to R15 can be used as data or address registers. The stack pointer can be made to operate either as an interrupt stack pointer (ISP) or user stack pointer (USP). The required stack pointer can be selected by the value of the stack pointer select bit (U) in the processor status word (PSW).

Control Registers: This CPU has the following nine control registers:

1. Interrupt stack pointer (ISP)
2. User stack pointer (USP)

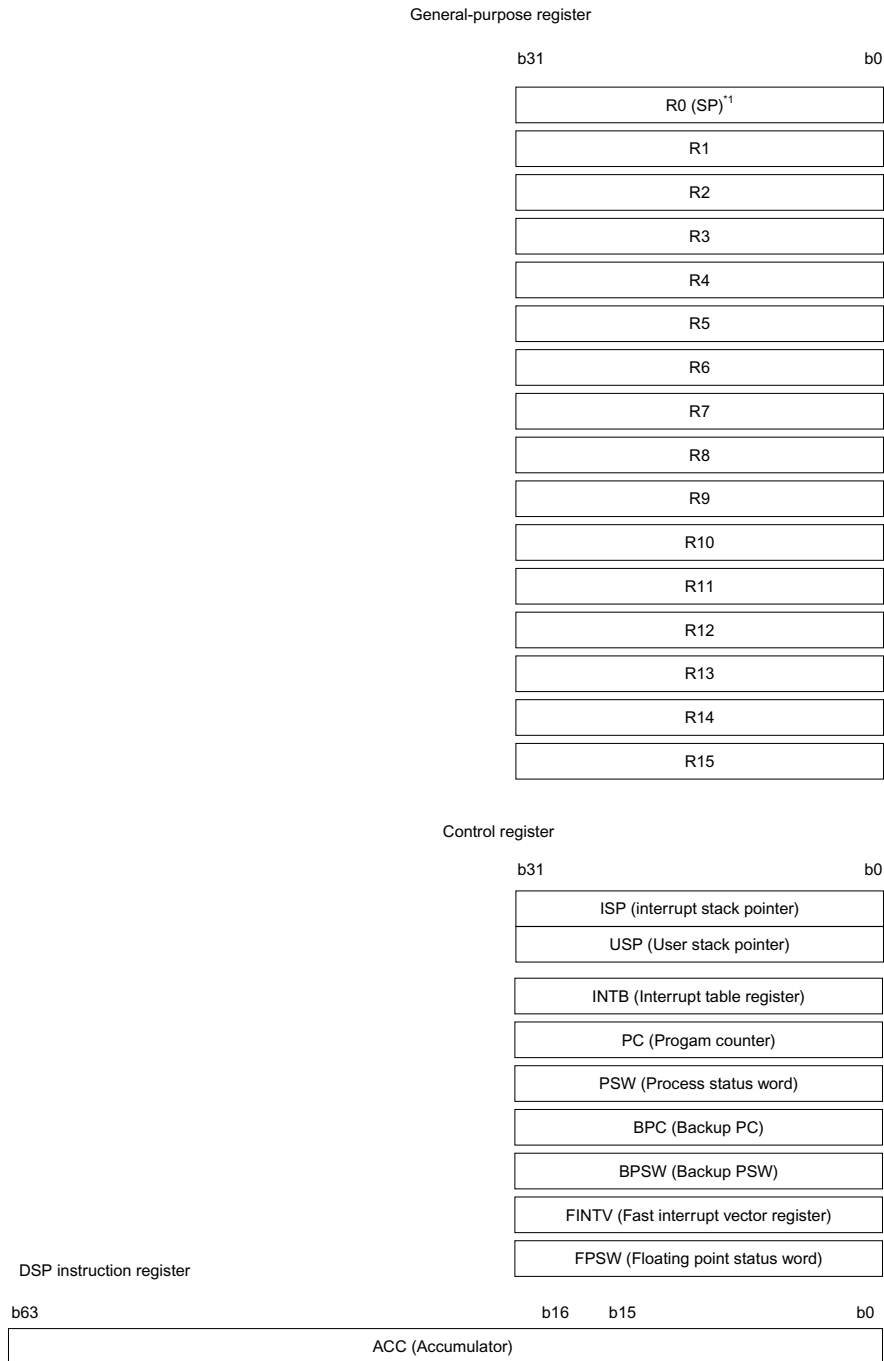


Figure 3.6 Register set of CPU [1], Figure 2.1, page 117.

3. Interrupt table register (INTB)
4. Program counter (PC)
5. Processor status word (PSW)
6. Backup PC (BPC)
7. Backup PSW (BPSW)
8. Fast interrupt vector register (FINTV)
9. Floating-point status word (FPSW)

The section below explains each control register briefly. It mainly focuses on the bit configuration and the functionality of each register.

1. **Interrupt Stack Pointer (ISP)/User Stack Pointer (USP):** After a reset, all the bits of the register hold the value zero. The register is configured with 32 bits. The register can be made to operate either as interrupt stack pointer (ISP) or user stack pointer (USP). The decision is made by the value of the stack pointer select bit (U) in the processor status word (PSW). Depending on the value of the bit, the stack pointer operates either as ISP or USP. Setting the value of ISP or USP to a multiple of four reduces the numbers of cycles required to execute interrupt sequences and instructions.
2. **Interrupt Table Register:** The interrupt table register (INTB) points to an address where the relocatable vector table starts and is configured with 32 bits. After reset, value of the register is undefined.
3. **Program Counter:** Value after reset: Contents of addresses FFFF FFFCh to FFFF FFFFh. The program counter (PC) points to the address of the instruction that will be executed next. As soon as that instruction's execution starts, PC value is incremented and it points to the next instruction. The PC is configured with 32 bits.
4. **Processor Status Word (PSW):**

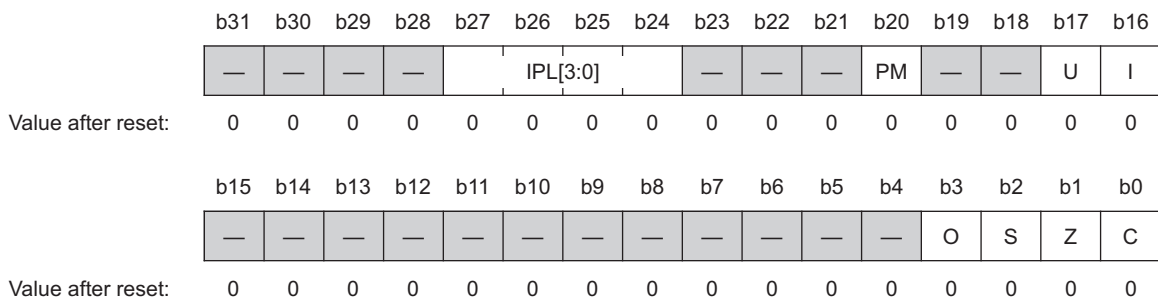


Figure 3.7 PSW [1], Section 2.2.2.4, Page 119.

After reset, all the bits of the register hold the value zero.

- **C Flag (Carry Flag):** Whenever an operation results in a carry, borrow, or shift-out, this flag is set. The bit position of the carry flag is b0 and when it is set as 1, it means a carry has occurred. When it is 0, it means no carry has occurred. The symbol of the flag is C and it can be read and written by the CPU.
- **Z Flag (Zero Flag):** Whenever an operation results in a zero, this flag is set. The bit position of the zero flag is b1 and when it is set as 1, it means the result of an operation is zero. When it is 0, it means the result is non-zero. The symbol of this flag is Z and it can be read and written by the CPU.
- **S Flag (Sign Flag):** This flag indicates that the result of an operation was negative. The bit position of the sign flag is b2 and when it is set as 1, it means the result of an operation is negative. When it is 0, it means the result is non-negative. The symbol of this flag is S and it can be read and written by the CPU.
- **O Flag (Overflow Flag):** This flag indicates that an overflow occurred during an operation. Whenever an operation results in an overflow, this flag is set. The bit position of the overflow flag is b3 and when it is set as 1, it means the result of an operation resulted in an overflow. When it is 0, it means there was no overflow. The symbol of this flag is O and it can be read and written by the CPU.
- **I Bit (Interrupt Enable):** Whenever this bit is set, an interrupt can occur. If this bit is disabled, then even if an interrupt occurs an exception will not be accepted. The bit position of interrupt enable is b16 and when it is set as 1, it means interrupt is enabled which means interrupt requests will be accepted. When it is 0, then interrupt requests will not be accepted. The symbol of this flag is I and it can be read and written by the CPU.
- **U Bit (Stack Pointer Select):** This bit specifies the stack pointer as either the ISP or USP. When an interrupt occurs and the interrupt enable bit is set to 1, an exception request is accepted. When this happens this bit is set to 0 and then this register acts as an interrupt stack pointer. When the processor mode is switched from supervisor mode to user mode, this bit is set to 1. Now the register acts as a user stack pointer. The bit position of the stack pointer select is b17. The symbol of this flag is U and it can be read and written by the CPU.
- **PM Bit (Processor Mode Select):** This bit specifies the processor mode. When an interrupt occurs and the interrupt enable bit is set to 1, an exception request is accepted. When an exception is accepted, supervisor mode is selected and the bit is set as 0. When user mode is selected then this bit is selected as 1. The bit position of the processor mode select is b20. The symbol of this flag is PM and it can be read and written by the CPU.
- **IPL[3:0] Bits (Processor Interrupt Priority Level):** The IPL[3:0] bits specify the processor interrupt priority level. There are in total sixteen levels from

zero to fifteen, wherein priority level fifteen is the highest. When the priority level of a requested interrupt is higher than the processor interrupt priority level, the interrupt is enabled; and when the priority level of a requested interrupt is lower than the processor interrupt priority level then the interrupt request is not accepted. So if the IPL[3:0] bits is set to a level fifteen (Fh) then it will disable all interrupt requests. The only case where IPL[3:0] bits are set to level fifteen (Fh) is when a non-maskable interrupt is generated. When interrupts in general are generated, the bits are set to the priority levels of accepted interrupts. The bit positions of the processor interrupt priority level are from b27 to b24. The symbol of this flag is IPL[3:0] and it can be read and written by the CPU.

The following list shows sixteen priority levels.

b27	b26	b25	b24	
0	0	0	0	0: Priority level 0 (lowest)
0	0	0	1	1: Priority level 1
0	0	1	0	0: Priority level 2
0	0	1	1	1: Priority level 3
0	1	0	0	0: Priority level 4
0	1	0	1	1: Priority level 5
0	1	1	0	0: Priority level 6
0	1	1	1	1: Priority level 7
1	0	0	0	0: Priority level 8
1	0	0	1	1: Priority level 9
1	0	1	0	0: Priority level 10
1	0	1	1	1: Priority level 11
1	1	0	0	0: Priority level 12
1	1	0	1	1: Priority level 13
1	1	1	0	0: Priority level 14
1	1	1	1	1: Priority level 15 (highest)

Reserved Bits:

The following bits are reserved in the PSW register. These bits are always read as 0. The write value should be 0.

b15 to b4; b19, b18; b23 to b21; b31 to b28

5. **Backup PC (BPC):** After reset, the value of the register is Undefined. The register is configured with 32 bits. The Backup PC (BPC) register assists in speeding up the response to interrupts. After a fast interrupt has been generated, the contents of the program counter (PC) are saved in the Backup PC register.
6. **Backup PSW (BPSW):** After reset, the value of the register is Undefined. The register is configured with 32 bits. After a fast interrupt has been generated, the contents of the processor status word (PSW) are saved in the Backup Processor status word (BPSW) register. The allocation of bits in the BPSW register corresponds to that in the PSW register.
7. **Fast Interrupt Vector Register (FINTV):** After reset, the value of the register is Undefined. The register is configured with 32 bits. As the name suggests, this register assists in speeding up the response to interrupts. As soon as a fast interrupt is generated, the FINTV register specifies a branch destination address.
8. **Floating-Point Status Word (FPSW):**

b31	b30	b29	b28	b27	b26	b25	b24	b23	b22	b21	b20	b19	b18	b17	b16
FS	FX	FU	FZ	FO	FV	—	—	—	—	—	—	—	—	—	—
b15	b14	b13	b12	b11	b10	b9	b8	b7	b6	b5	b4	b3	b2	b1	b0
—	EX	EU	EZ	EO	EV	—	DN	CE	CX	CU	CZ	CO	CV	RM[1:0]	

Figure 3.8 FPSW [1], Section 2.2.2.8, Page 121.

After reset, all the bits of the register hold the value zero.

The floating-point status word (FPSW) indicates the results of floating-point operations. The register can be broadly classified into three types of bit configuration. One type is enable bits, another type is flag bits, and the third type is cause bits. So for every exception that occurs, there exists an enable bit (E_j), a flag status bit (F_j), and an exception cause bit (C_j). When an exception handling enable bit (E_j) is enabled, which means when $E_j = 1$, corresponding C_j flag indicates the cause. If the exception handling is masked ($E_j = 0$), then the state of the F_j flag at the end of a series of instructions indicates whether an exception occurred. The F_j flag is the accumulation type flag where j represents X, U, Z, O, or V.

TABLE 3.2 Description of FPSW [1], Section 2.2.2.8, Page 121.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b1, b0	RM[1:0]	Floating-Point Rounding-Mode Setting	b1 b0	
			0 0 : Rounding towards the nearest value.	R/W
			0 1 : Rounding towards 0.	
			1 0 : Rounding towards $+\infty$.	
			1 1 : Rounding towards $-\infty$.	
b2	CV	Invalid Operation Cause Flag	0 : No invalid operation has been encountered.	R/W* ¹
			1: Invalid operation has been encountered.	
b3	CO	Overflow Cause Flag	0 : No overflow has occurred.	R/W* ¹
			1: Overflow has occurred.	
b4	CZ	Division-by-Zero Cause Flag	0 : No division-by-zero has occurred.	R/W* ¹
			1: Division-by-zero Overflow has occurred.	
b5	CU	Underflow Cause Flag	0 : No underflow has occurred.	R/W* ¹
			1: Underflow has occurred.	
b6	CX	Inexact Cause Flag	0 : No inexact exception has been generated.	R/W* ¹
			1: Inexact exception has been generated.	
b7	CE	Un-Implemented Processing Cause Flag	0 : No unimplemented processing has been encountered.	R/W* ¹
			1: Unimplemented processing has been encountered.	

Notes:

1. Writing 0 to the bit clears it. Writing 1 to the bit does not affect its value.
2. Positive denormalized numbers are treated as $+0$, negative denormalized numbers as -0 .
3. When the EV bit is set to 0, the FV flag is enabled.
4. When the EO bit is set to 0, the FO flag is enabled.
5. When the EZ bit is set to 0, the FZ flag is enabled.
6. When the EU bit is set to 0, the FU flag is enabled.
7. When the EX bit is set to 0, the FX flag is enabled.
8. Once the bit has been set to 1, this value is retained until it is cleared to 0 by software.

(Continued)

TABLE 3.2 Description of FPSW—Continued

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b8	DN	0 Flush Bit of Denormalized Number	0: A denormalized number is handled as a denormalized number.	R/W
			1: A denormalized number is handled as 0.* ²	
b9	—	Reserved	This bit is always read as 0. The write value should be 0.	R/W
b10	EV	Invalid Operation Exception Enable	0: Invalid operation exception is masked.	R/W
			1: Invalid operation exception is enabled.	
b11	EO	Overflow Exception Enable	0: Overflow exception is masked.	R/W
			1: Overflow exception is enabled.	
b12	EZ	Division-by-Zero Exception Enable	0: Division-by-zero exception is masked.	R/W
			1: Division-by-zero exception is enabled.	
b13	EU	Underflow Exception Enable	0: Underflow exception is masked.	R/W
			1: Underflow exception is enabled.	
b14	EX	Inexact Exception Enable	0: Inexact exception is masked.	R/W
			1: Inexact exception is enabled.	
b25 to b15	—	Reserved	These bits are always read as 0. The write value should be 0.	R/W
b26	FV* ³	Invalid Operation Flag	0: No invalid operation has been encountered.	R/W
			1: Invalid operation has been encountered.* ⁸	
b27	FO* ⁴	Overflow Flag	0: No overflow has occurred.	R/W
			1: Overflow has occurred.* ⁸	
b28	FZ* ⁵	Division-by-Zero Flag	0: No division-by-zero has occurred.	R/W
			1: Division-by-zero has occurred.* ⁸	
b29	FU* ⁶	Underflow Flag	0: No underflow has occurred.	R/W
			1: Underflow has occurred.* ⁸	

TABLE 3.2 Description of FPSW—*Continued*

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b30	FX* ⁷	Inexact Flag 0: No	0: No inexact exception has been generated. 1: Inexact exception has been generated.* ⁸	R/W
b31	FS	Floating-Point Flag Summary	This bit reflects the logical OR of the FU, FZ, FO, and FV flags.	R/W

- RM[1:0] bits:

These bits specify the floating-point rounding-mode.

Explanation of Floating-Point Rounding Modes

- Rounding to the nearest value (the default behavior):
An inaccurate result is rounded to the available value that is closest to the result which would be obtained with an infinite number of digits. If two available values are equally close, rounding is done to the even alternative.
- Rounding towards 0:
An inaccurate result is rounded to the smallest available absolute value.
- Rounding towards $+\infty$:
An inaccurate result is rounded to the nearest available value in the direction of positive infinity.
- Rounding towards $-\infty$:
An inaccurate result is rounded to the nearest available value in the direction of negative infinity.

The default mode is to round off to the nearest value in order to return the most accurate value. The other modes, such as rounding towards 0, rounding towards $+\infty$, and rounding towards $-\infty$, are used to ensure precision.

- Cj (Cause flag): The five floating-point exceptions based on IEEE 754 standard are overflow, underflow, inexact, division-by-zero, and invalid operation. The bit is set to 1 until and unless FPU instruction is executed. After that the bit is set to 0. When instructions like MVTC and POPC instructions write 0 to the bit, the bit is set to 0; and when they write 1, the bit retains the previous value. EV Bit (Invalid Operation Exception Enable), EO Bit (Overflow Exception Enable), EZ Bit (Division-by-Zero Exception Enable), EU Bit (Underflow Exception Enable), and EX Bit (Inexact Exception Enable)
- DN Flag: When this bit is set to 0, a denormalized number is handled as a denormalized number; and when this bit is set to 1, a denormalized number is handled as 0.
- Ej (Exception handle bit): When any of the five floating-point exceptions is generated by the FPU instruction, this bit then decides whether the CPU will handle the

exception or not. When the bit is set to 0, the exception handling is masked and the CPU will not handle the exception; when the bit is set to 1, the exception handling is enabled and CPU will handle the exception. The various exception handle bits are: EV Bit (Invalid Operation Exception Enable), EO Bit (Overflow Exception Enable), EZ Bit (Division-by-Zero Exception Enable), EU Bit (Underflow Exception Enable), and EX Bit (Inexact Exception Enable)

- Fj: While the exception handling enable bit (Ej) is 0 (exception handling is masked), if any of the five floating-point exceptions specified in the IEEE 754 standard is generated, the corresponding bit is set to 1. When Ej is 1 (exception handling is enabled), the flag retains its value. When the corresponding flag is set to 1, it remains 1 until it is cleared to 0 by software. (Accumulation flag) The various flag bits are: FV Flag (Invalid Operation Flag), FO Flag (Overflow Flag), FZ Flag (Division-by-Zero Flag), FU Flag (Underflow Flag), and FX Flag (Inexact Flag).
- FS bit (Floating-point flag summary bit): This bit reflects the logical OR of the FU, FZ, FO, and FV flags.

Accumulator (ACC):

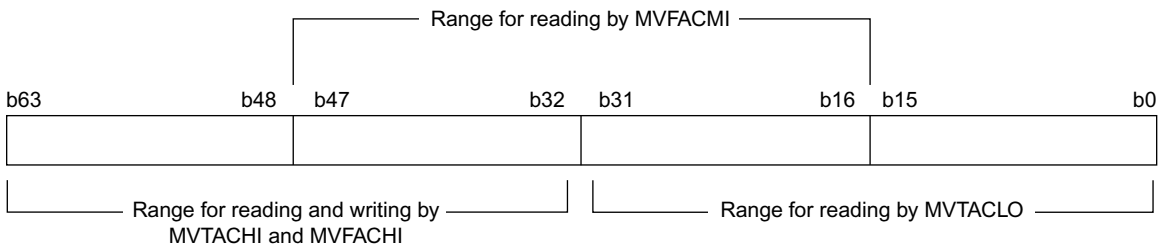


Figure 3.9 ACC [1], Section 2.2.3.1, Page 124.

This register is configured with 64 bits and is mainly used for DSP instructions. It is also used for the multiply and multiply-and-accumulate instructions, where the prior value in the accumulator is modified by the execution of instruction. The examples of such instructions are EMUL, EMULU, FMUL, MUL, and RMPA. To write to the accumulator, MVTACHI and MVTACLO instructions are used. These instructions write data to the higher-order 32 bits (bits 63 to 32) and the lower-order 32 bits (bits 31 to 0). To read from the accumulator, MVFACHI and MVFACMI instructions are used. The MVFACHI and MVFACMI instructions read data from the higher-order 32 bits (bits 63 to 32) and the middle-order 32 bits (bits 47 to 16), of the accumulator.

3.2.3 Data Types

The RX CPU supports four types of data: integer, floating-point, bit, and string.

1. Integer:

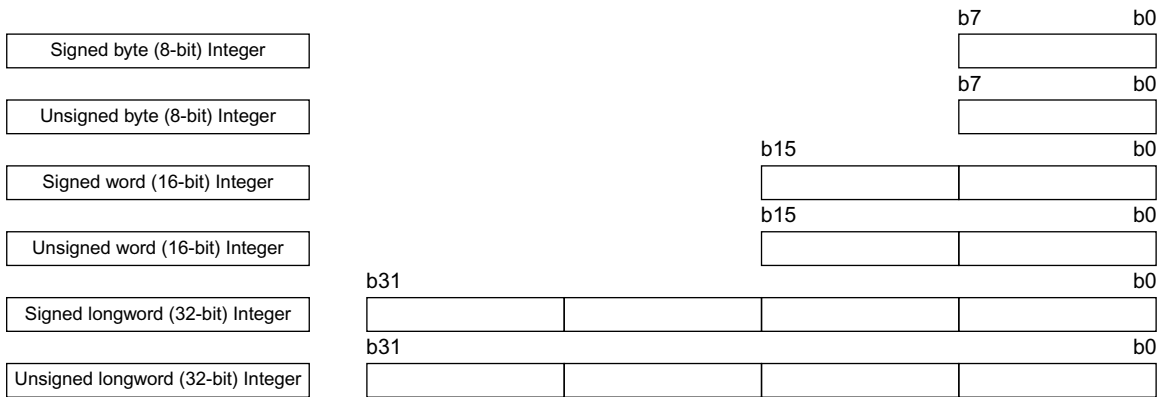


Figure 3.10 Integer [1], Figure 1.2, page 31.

2. Floating-Point:

The IEEE standard defines four different types of precision for floating point operations. They are single precision, double precision, single-extended precision, and double-extended precision. Most of the floating-point hardware follows IEEE 754 standard’s single and double precision for floating point computations. The RX Family supports single precision floating-point computation. There are in total eight operations that can be done with such floating-point operands: FADD, FCMP, FDIV, FMUL, FSUB, FTOI, ITOF, and ROUND.

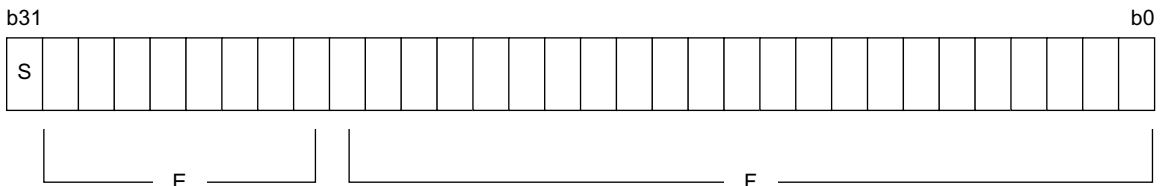


Figure 3.11 Floating point [1], Figure 1.3, page 31.

Single-precision floating-point

S: Sign (1 bit)

E: Exponent (8 bits)

F: Mantissa (23 bits)

$$\text{Value} = (-1)^S \times (1 + F \times 2^{-23}) \times 2^{(E-127)}$$

The floating-point format supports different values for exponent and mantissa. When the value of E is between 0 and 255 (i.e., $0 < E < 255$), then the number is considered as a normal number. For a signed zero number, the value of E and F should be 0. For denormalized numbers, the value of E is 0 and the value of F is greater than 0. When the value of E is 255 and the value of F is 0, then the number is considered as infinity. When the value of E is 255 and the value of F is greater than 0, then the number is not a number.

NOTE:

The number is treated as 0 when the DN bit in FPSW is 1. When the DN bit is 0, an unimplemented processing exception is generated.

3. Bitwise Operations:

There are five different types of bit-manipulation instructions for bitwise operations: BCLR, BMCnd, BNOT, BSET, and BTST. The register is a 32-bit register so the bits range from 0 to 31. In the Figure 3.12, notation looks like “#bit, R_n”; which means ‘corresponding bit in register n.’ Here the value of ‘n’ ranges from 0 to 15. So notation “#30, R1” suggests 30th bit in R1 register. For bitwise operation in memory, the notation is “#bit, mem.” For instance, #2, [R2] means address [R2] and bit 2. The bit value ranges from 0 to 7. The addressing modes available to specify addresses are register indirect and register relative.

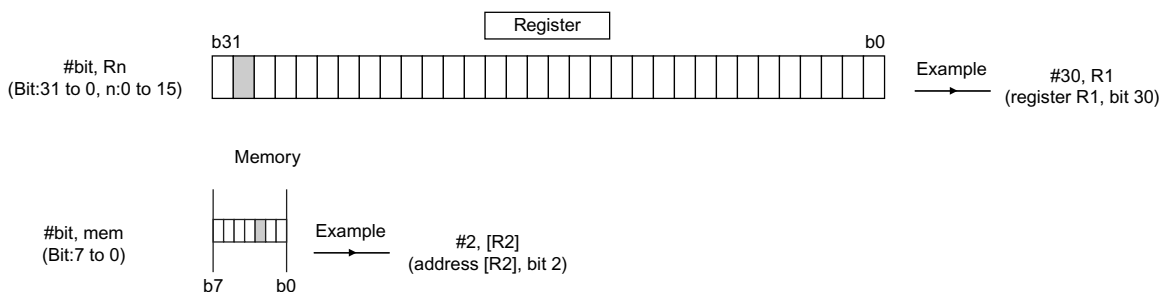


Figure 3.12 Bitwise Operation [1], Figure 1.4, page 32.

4. Strings:

The string data type consists of an arbitrary number of consecutive byte (8-bit), word (16-bit), or longword (32-bit) units. To work with strings there are seven string manipulation instructions: SCMPU, SMOVB, SMOVE, SMOVU, SSTR, SUNTIL, and SWHILE.

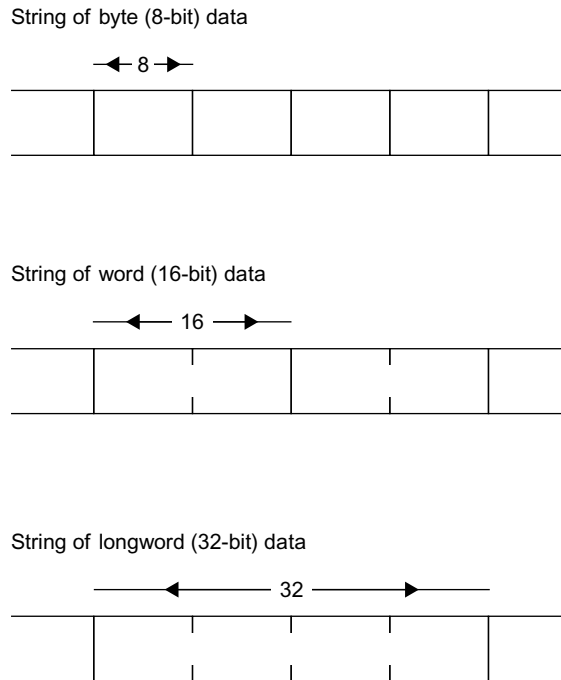


Figure 3.13 Strings [2], Figure 1.5, page 32.

3.2.4 Endianness

Endianness refers to the arrangement of sub-units such as bytes within a longer data word, while storing it in memory. Basically there are two types of endianness: big endianness and little endianness.

- Big endian: The most significant byte is stored at the lowest byte address of the memory.
- Little endian: The least significant byte is stored at the lowest address of the memory.

As arrangements of bytes, the RX63N/RX631 Group supports both big endian, where the most significant byte is stored at the lowest byte address of the memory; and little endian, where the least significant byte is stored at the lowest address of the memory. For the RX CPU, instructions are always little endian, but the way the user wants to handle data decides endianness. Therefore, if a programmer wants to change the endianness, it can be changed.

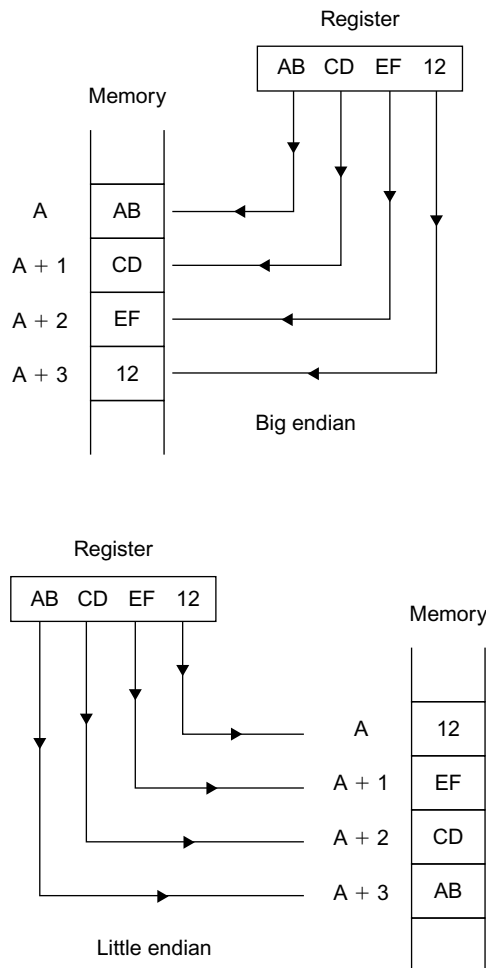


Figure 3.14 Endianness: Arrangement in memory.

3.2.5 Data Arrangement

1. Data Arrangement in Registers:

Figure 3.15 shows the relation between the sizes of registers and bit numbers.

2. Data Arrangement in Memory:

Data in memory have three sizes: byte (8-bit), word (16-bit), and longword (32-bit).

Figure 3.16 shows the arrangement of data in memory.

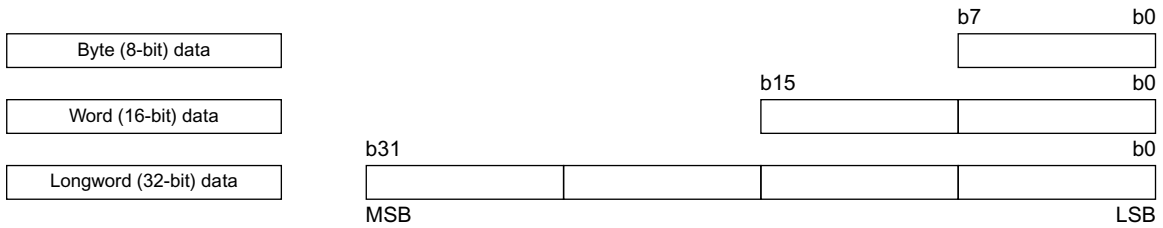


Figure 3.15 Data arrangement in registers [1], Figure 2.2, page 130.

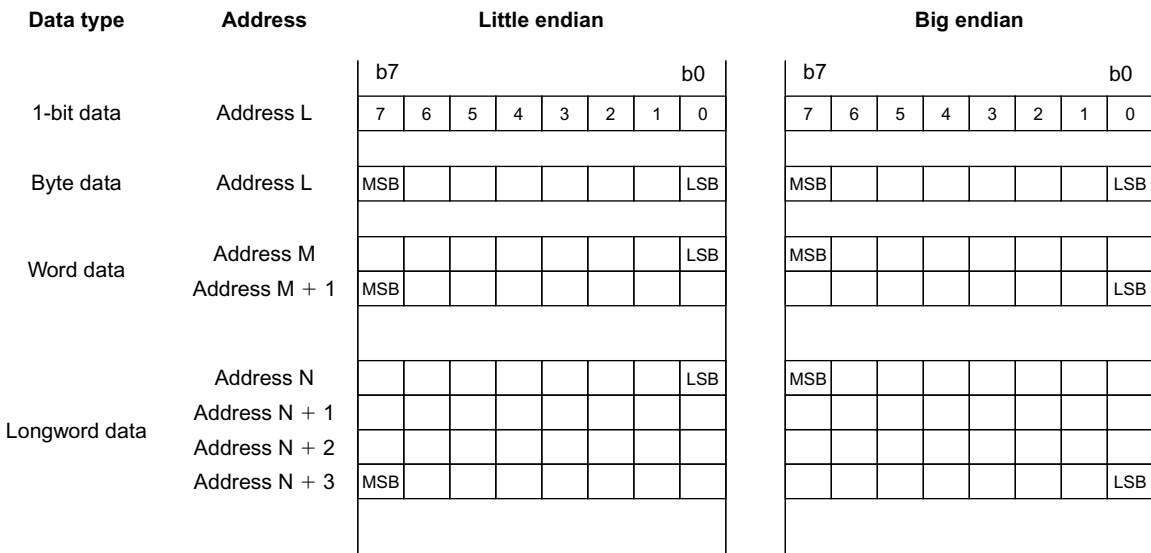


Figure 3.16 Data arrangement in memory [1], Figure 2.3, page 130.

3.2.6 Bus Specification

In total, there are five different types of buses in RX63N microcontroller board. The following section lists various bus specifications. It describes whether the bus operates in synchronization with a clock or not.

1. CPU bus:

- Instruction bus:

It is connected to the CPU and to the on-chip memory such as RAM and ROM. It operates in synchronization with the system clock (ICLK).

- Operand bus:
It is connected to the CPU and to the on-chip memory such as RAM and ROM.
It operates in synchronization with the system clock (ICLK).
- 2. Memory bus:**
 - Memory bus 1: It is connected to on-chip RAM.
 - Memory bus 2: It is connected to on-chip RAM.
- 3. Internal main bus:**
 - Internal main bus 1: It is connected to the CPU and operates in synchronization with the system clock (ICLK).
 - Internal main bus 2: It is connected to the DMACA, DTC, and EDMAC. Also, it is connected to on-chip memory, namely on-chip RAM and on-chip ROM. It operates in synchronization with the system clock (ICLK).
- 4. Internal peripheral bus:**
 - Internal peripheral bus 1: It is connected to peripheral modules (DTC, DMAC, EXDMAC, interrupt controller, and bus error monitoring section) and operates in synchronization with the system clock (ICLK) (EDMAC operates in synchronization with the BCLK).
 - Internal peripheral bus 2: It is connected to peripheral modules (modules other than those connected to internal peripheral buses 1, 3, 4, and 5) and operates in synchronization with the peripheral module clock (PCLKB).
 - Internal peripheral bus 3: It is connected to peripheral modules (USB) and it operates in synchronization with the peripheral module clock (PCLK).
 - Internal peripheral bus 4: It is connected to peripheral modules (EDMAC and ETHERC) and operates in synchronization with the peripheral module clock (PCLKA).
 - Internal peripheral bus 5: It is a reserved area.
 - Internal peripheral bus 6: It is connected to ROM (P/E) and E2 DataFlash memory and operates in synchronization with the flash interface clock (FCLK).
- 5. External bus:**
 - CS area: It is connected to the external devices and it operates in synchronization with the external bus clock (BCLK).
 - External bus SDRAM area: It is connected to the SDRAM and it operates in synchronization with the SDRAM clock (SDCLK).

Description of Buses

1. CPU Buses:

The CPU buses consists of instruction and operand buses, which are connected to internal main bus 1 as shown in Figure 3.17. The instruction bus is used to fetch instructions for the CPU, while the operand bus is used for operand access. These buses are connected to on-chip RAM and on-chip ROM and therefore the CPU can directly access these areas. Direct access refers to that access which is not by way

of internal main bus 1. In contrast to access through internal main bus 1, direct access allows only reading the on-chip ROM by the CPU. Programming and erasure are handled by way of an internal peripheral bus. Internal main bus 1 handles bus requests for instruction fetching and operand access. The operand access has a higher priority than instruction fetching. The bus-access operations can proceed simultaneously, irrespective of whether the instruction fetching and operand access need different buses or not. For example, parallel access to an on-chip ROM and on-chip RAM or to an on-chip ROM and external space is possible.


2. Memory bus:

There are two memory buses; namely memory bus 1 and memory bus 2. On-chip RAM is connected to memory bus 1 and on-chip ROM is connected to memory bus 2. Bus requests from the CPU buses and internal main bus 2 are handled through memory buses 1 and 2. Internal memory bus 2 has a higher priority than the CPU bus.

3. Internal main bus:

The internal main bus consists of two buses; one is internal main bus 1, which is used by the CPU; and internal main bus 2, which is used by the other bus-master modules such as the DTC, DMACA, and EDMAC. Bus requests for instruction fetching and operand access are handled through internal main bus 1. Operand access has higher priority than instruction fetching. Bus requests from the DTC, DMACA, and EDMAC are handled by internal main bus 2. The order of priority is EDMAC, DMACA, and then DTC, as shown in Table 3.3. The bus access operations can proceed simultaneously. For instance, if the CPU and another bus master are requesting access to different buses; in this case, the respective bus-access operations will take place simultaneously. Internal main bus 2 has a higher priority than internal main bus 1. However, when the CPU executes the XCHG instruction, the only request that can access bus is the request from CPU, until and unless data transfer for the XCHG instruction is completed. If data transfer for the XCHG is completed, requests for bus access from other masters will be accepted. Furthermore, during reading and writing back of control information, the only bus master which has access is DTC. Bus requests from other masters are not accepted.

TABLE 3.3 Priority of Bus Masters [12], Table 16.3, page 388.

PRIORITY	BUS MASTER
High  Low	EDMAC DMACA DTC CPU

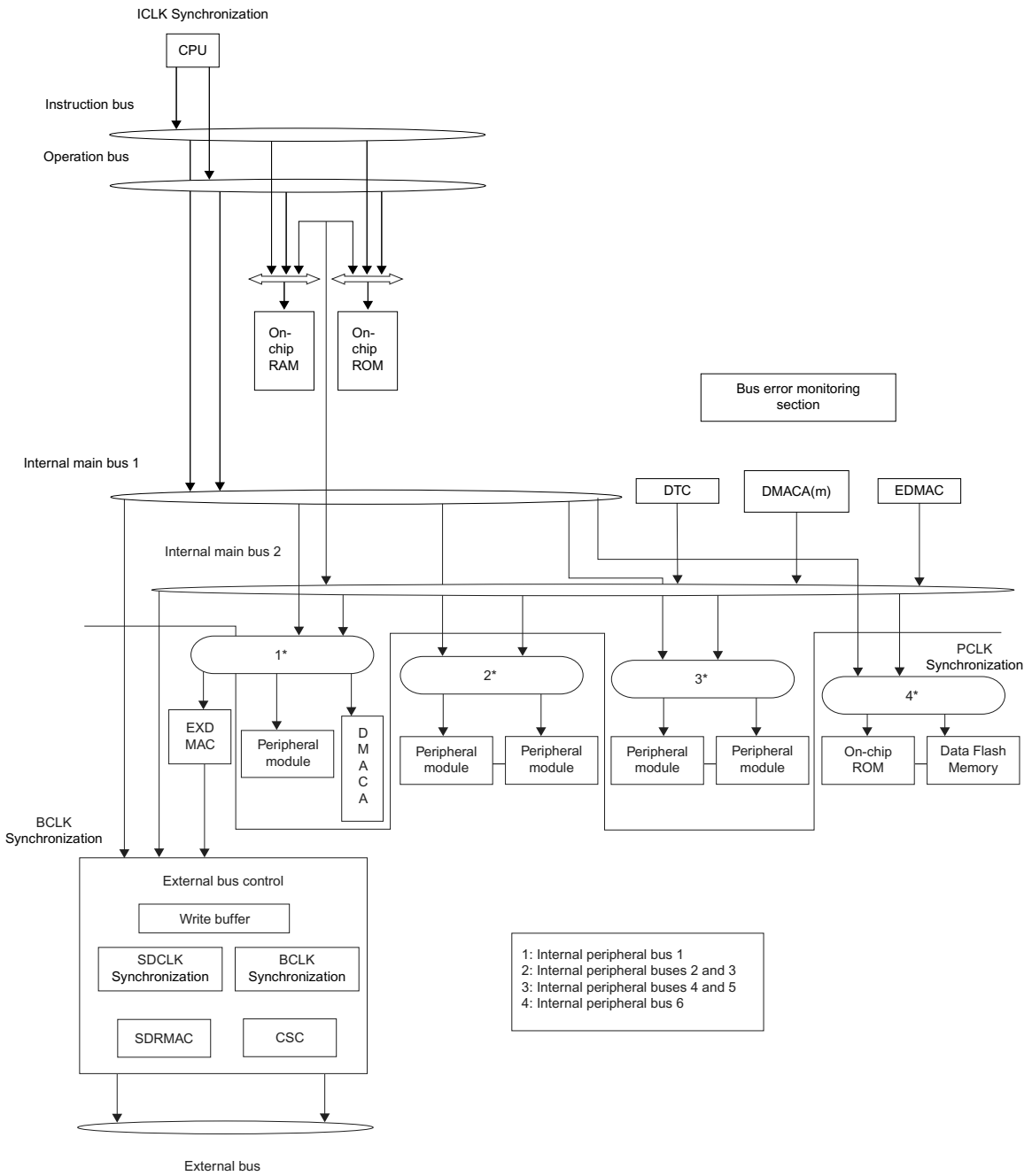


Figure 3.17 Bus Configuration [1], Figure 16.1, page 386.

4. Internal peripheral buses:

The following table lists various peripheral buses and the peripheral modules to which they are connected:

TABLE 3.4 Connection of Peripheral Modules [1], Table 16.4, page 388.

TYPES OF BUS	PERIPHERAL MODULES
Internal peripheral bus 1	DTC, DMAC
	EXDMAC
	Interrupt controller
	Bus error monitoring section
Internal peripheral bus 2	Peripheral modules other than those connected to internal peripheral buses 1, 3, 4, and 5
Internal peripheral bus 3	USB
Internal peripheral bus 4	EDMAC and ETHERC
Internal peripheral bus 5	Reserved area
Internal peripheral bus 6	ROM (P/E)/E2 DataFlash memory, and FCU RAM

Bus mastership requests from the CPU (internal main bus 1) and other bus masters (internal main bus 2) are handled through internal peripheral buses 1 to 6. The priority order of two internal main buses can be set using the bus priority control register (BUSPRI). Internal main bus 2 has higher priority than internal main bus 1.

- **Write Buffer Function (Internal Peripheral Bus)** The internal peripheral bus has the write buffer function, which allows the next round of bus access to start, before the current write access is completed, in write access. However, if the following round of bus access is from the same bus master but to the different internal peripheral bus, it is suspended until the bus operations already in progress are completed.

5. External Bus:

This section lists various specifications of the external bus. Bus masters such as internal main bus 1, internal main bus 2, and EXDMAC keep requesting bus mastership. In such a scenario, the external bus controller arbitrates various requests and decides the master. The order of priority determines which bus master will handle

mastership first, if all of them request at the same time. The order of priority is EXDMAC, internal main bus 2, and then internal main bus 1. The various areas of external bus and their specifications are as follows:

- External address space:
An external address space is divided into two specific areas. One area is further divided into eight areas (CS0 to CS7) and the other area is the SDRAM area (SDCS). This is how external address space is organized for better management. For each area the chip select signals can be output, an 8/16/32-bit bus space can be selected, and an endian mode can be specified.
- CS area controller:
The CS area controller deals with the read and write controls associated with CS areas (CS0 to CS7). In the controller, recovery cycles can be inserted. In read recovery up to fifteen cycles, and in the write recovery up to fifteen cycles can be inserted. The cycle wait function can wait up to thirty-one cycles. In the page access, wait function takes up to seven cycles. The controller uses wait control to set up timing of assertion and negation for chip-select signals (CS0# to CS7#) and for read signal (RD#) and write signals (WR0# to WR3#). It also sets up the timing with which data output starts and ends. It has two write access modes; one is single write strobe mode and other is byte strobe mode.
- SDRAM area controller:
The SDRAM Controller is a part of external bus. Several features are available in the SDRAM area controller. The SDRAM controller is capable of self-refresh and auto-refresh. It supports multiplexing output of row address/column address (8, 9, 10, or 11 bits). The CAS latency can be specified from one to three cycles.
- Write buffer function:
Write buffer function is used when there is data to be written to a buffer. When write data from the bus master has been written to the write buffer, the write access by the bus master is completed.
- Frequency:
As mentioned earlier, the CS area controller (CSC) operates in synchronization with the external bus clock (BCLK), while the SDRAM area controller (SDRAMC) operates in synchronization with the SDRAM clock (SDCLK).

NOTE:

When different bus-master modules request access to different slave modules, then all of the different masters can be given access to different peripheral modules. This is known as parallel operation as all of the accesses are taking place at the same time. Consider the case where the CPU is fetching an instruction from on-chip ROM and at the same time an operand is needed from on-chip RAM. What will happen in such a scenario? Here the master module

CPU wants to gain access to on-chip ROM as well as on-chip RAM. The DMACA simultaneously handles transfer between a peripheral bus and the external bus. In this example, the CPU uses instruction and operand buses for simultaneous access to on-chip ROM and RAM, respectively. So, with the help of instruction bus and operand bus, the CPU is able to fetch instructions and access an operand, both at the same time. Moreover, the DMACA simultaneously uses internal main bus 2 or the external bus to achieve parallel operation.

Bus Error Monitoring Section

Whenever an error occurs in a bus, the bus-error monitoring system comes into play. It monitors each individual area and whenever it detects an error, it generates an interrupt. Usually, two types of error occur in a bus, illegal address access error and timeout error. Whenever the bus-error monitoring system detects illegal access to an area, an illegal address access error is said to have occurred. Similarly, when the bus-error monitoring system detects any bus-access operation that is not being completed within 768 cycles, then a time out error is said to have occurred.

Types of Bus Error

As said earlier, there are mainly two types of error that can occur in a bus. The following section explains them briefly.

1. Illegal Address Access:

To detect illegal access to an area, first of all a bit in a register has to be set up. The bit is called an illegal address access detection enable bit (IGAEN) and is usually set to 1 in the bus error monitoring enable register (BEREN). If that happens, accesses of the following types lead to illegal address access errors:

- Access to those external areas for which operation has been disabled. The space area is disabled by setting up the value of registers CSnCNT.EXENB and SDCCR.EXENB as '0.'
- With respect to areas other than those described above, access to illegal address ranges.

2. Time out:

To detect time out error, first of all a bit in a register has to be set up. The bit is called a timeout detection enable bit (TOEN) and is usually set to 1 in the bus error monitoring enable register (BEREN). After setting up that bit, if any bus access is not completed within 768 cycles, then it leads to a timeout error. In the RX63N/RX631, a timeout error occurs for access to CS areas, internal peripheral buses (2 to 6). During these accesses, it might lead to timeout error if bus access is not completed (the WAIT# signal is not negated) within 768 external bus clock

(BCLK) cycles from the start of the access. When timeout error occurs, accesses to bus are prohibited. In fact, accesses from the bus master are rejected for 256 BCLK cycles. If a single bus request from bus master also contains generated multiple external bus accesses, then the bus access cannot be stopped by the timeout. At this time, timeout errors may occur repeatedly. The CPU is aware of the errors that are occurring in the bus section and whenever an error occurs the CPU is informed. The CPU does not poll for errors on the bus. Whenever there is an error, an interrupt is generated. The interrupt generated gives an indication to CPU that there is an error in the bus section. The IEN register in the ICU decides whether to generate an interrupt in the case of a bus error or not.

3.3 BASIC EXAMPLES

EXAMPLE 1

What is the difference between computer organization and architecture?

A computer's architecture is its abstract model and is the programmer's view in terms of instructions, addressing modes, and registers. A computer's organization expresses the realization of the architecture. Architecture describes what the computer does and organization describes how it does it. The architecture is like a blue print which mentions all the components and how they are connected, while the organization is an implementation of that blue print. Each vendor will have their own version of organization, and their own way of implementing the blue print.

Computer architecture = computer organization (what the machine looks like) + instruction set architecture (how you talk to the machine).

EXAMPLE 2

What is the difference between a microcontroller and a microprocessor?

The main difference is that a microcontroller incorporates features of a microprocessor (CPU, ALU, registers) along with the presence of added features like RAM, ROM, I/O ports, counter, etc. In addition, microcontrollers are usually designed to perform a small set of specific functions; for example, the case of a Digital Signal Processor which performs a small set of signal processing functions, whereas microprocessors tend to be designed to perform a wider set of general purpose functions.

EXAMPLE 3

1. Can you, the user, store a value at memory location 0008 C067h? Why or why not?
No, because address 0008 C067h corresponds to the memory area that stores special function registers. In the RAM, the memory addresses from 0000 0000h to 0001 8000h are reserved for special function registers and cannot be used by the user to save his data.
2. What area of Flash is available for the user program on the RX63N board? List the range of addresses and the exact size in bytes (not Kbytes).
In RX63N, the memory addresses of the on-chip ROM or data flash ranges from 0010 0000h to 0010 8000h. The total number of bytes available for user program is 32768 bytes.

3.4 ADVANCED CONCEPTS

3.4.1 Pipelining

Pipelining is an important technique used to make fast CPUs. It is implemented to increase the instruction throughput (i.e., the number of instructions that can be executed in a unit of time) but it does not reduce the time taken to execute an individual instruction. The execution time of an individual instruction actually increases due to overhead caused by implementing the pipeline. The overhead in the pipeline is from register delay (setup time) and clock skew. Improvement in instruction throughput means programs run faster and have lower execution time, though no single instruction runs faster. The performance will be reduced if there is an imbalance between the stages. For instance, if execution stage takes more time than memory access stage or, in other words, an instruction stays in execution stage longer than memory access stage, then the performance degrades because the clock cannot be faster than the slowest stage. Pipelining would provide optimal CPU performance CPU if every instruction was independent of every other instruction but, unfortunately, most of the instructions are dependent on each other.

The RX CPU is based on the classical five-stage pipeline. During the execution of an instruction, it is converted into various micro-operations. The five stages of the pipeline are described below. Only the Instruction Fetch (IF) stage is executed in the terms of instructions while others are executed in terms of micro-operations.

The operation of pipeline and respective stages is described as follows:

1. Instruction Fetch Stage (IF Stage):

In the IF stage, the CPU fetches 32/64 bit instructions from the memory. The Program counter (PC) fetches the instruction and then the PC is incremented by

4 or 8 since the instructions are 4 or 8 bytes long. The RX CPU has four 8-byte instruction queues. The RX CPU keep fetching instructions until the queues are filled.

2. Instruction Decode Stage (ID Stage):

The main function of this stage is decoding. Instructions are decoded in the ID stage and are converted into micro-operations. In addition to the decoding of the instructions, the values of registers (operands) are also read from the register file. If the value of a register needed is the result of the preceding instruction, then the CPU executes a bypass process (BYP). This process is also called forwarding.

3. Execution Stage (E Stage):

Two main types of calculation take place in this stage. One is normal ALU operations and the other is memory address calculations for memory access stage. Normal ALU operations are register to register operations which includes add, subtract, compare, and logical operations. The other calculations are memory reference operations which includes all load operations from the memory. During the execution stage, the ALU adds the two arguments; i.e., a register and a constant offset given in the instruction to produce an address by the end of this stage.

4. Memory Access (M Stage):

Memory is accessed either for fetching an operand from the memory or storing an operand in the memory. The address of an operand is calculated in the previous execution stage. This stage (M Stage) is divided into two sub-stages, M1 and M2. The RX CPU enables respective memory accesses for M1 and M2.

■ M1 stage (memory-access stage 1):

In this sub-stage, operand memory accesses OA1 and OA2 are processed. A store operation is processed when a write request is received via the bus. During the Load operation, the operation proceeds to the M2 stage only when a read request is received via the bus. In addition to the request, if the load data is received at the same timing (i.e., no-wait memory access), then the operation proceeds to the WB stage.

■ M2 stage (memory-access stage 2):

In this sub-stage operand memory access OA2 is processed. In this sub-stage the CPU waits for the load data, and once received the operation proceeds to the WB stage.

5. Write-back stage (WB stage):

The last stage of the pipeline writes data into the register file. In this stage, the operation result calculated in the execution stage and the data read from memory in the memory access stage are written to the register (RW). The data read from memory and the other type of data, such as the operation result, can be written to the register in the same clock cycles.

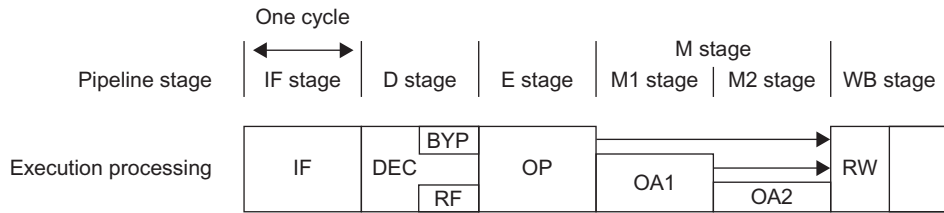


Figure 3.18 Pipeline Configuration and its Operation [1], Figure 2.6, page 133.

Pipeline Basic Operation

Ideally, each pipeline stage should take the same amount of time to process the instruction. Unfortunately, ideal conditions are hard to achieve and hence stalls are created in the pipeline and performance is degraded. The slowest stage which takes the maximum amount of time becomes the bottleneck. Once the pipeline is filled, each instruction will come out of the pipeline after one clock cycle. In a non-pipelined processor, if there are n tasks to handle and each task takes m clock period, then total time taken to process n tasks is $n*m$ clock periods. In a pipelined processor, when it has m stages, ideally n tasks will take $(m + (n - 1))$ clock periods. So, if we calculate the speed-up gained in this scenario, it will be $n * m / \{m + (n - 1)\}$.

Hazards prevent the next instruction from executing at the next cycle. They reduce the performance and speed-up gained by pipelining. There are three types of hazards:

1. Structural hazard:

It arises from resource conflicts when the hardware is not capable of supporting multiple instructions simultaneously in an overlapped manner.

2. Data hazard:

It arises when an instruction depends on the result of previous instruction. For instance, in the pipeline, an instruction $I + 1$ depending on the result of instruction I will cause a data hazard because one of the operands of the instruction $I + 1$ is the result of instruction I . In such a case, instruction $I + 1$ cannot execute, as the data is not available.

3. Control hazard:

It arises from pipelining of branches and other instructions that change the program counter; i.e., when a set of instructions are control dependent on the branch condition, and what value the PC will take is not known until the execution stage or decode stage.

Hazards in the pipeline cause stalls in the pipeline which simply means stalling the pipeline. Allowing some instructions to proceed and delaying other instructions helps in avoiding the

stall. When an instruction is stalled, the instructions issued (from the instruction stream) later than the stalled one are also stalled. And the ones which were issued earlier than the stalled instruction are allowed to proceed, so that the hazard goes away with time.

The following figures show typical cases that can occur in the pipeline. (In the following section, the abbreviation “mop” stands for micro-operations.)

1. Pipeline flow with stalls:

In Figure 3.19 the first instruction is a division operation and its execution stage takes more than one cycle to complete. The other instructions, such as the ‘ADD’ instruction, if allowed to execute will complete execution before the division operation. Since out-of-order completion might create a problem, the pipeline has to be stalled.

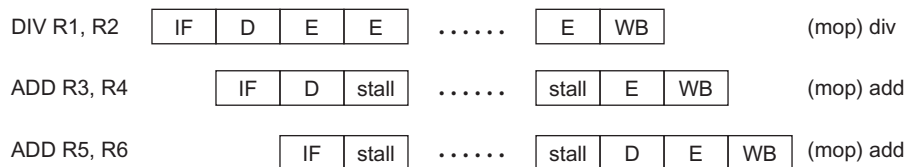


Figure 3.19 Stalls created due to an Instruction that requires multiple cycles to execute in the Execution Stage [1], Figure 2.17, page 139.

In Figure 3.20, the first instruction is a load instruction which takes more than one cycle to complete its operand access from memory. Again since in-order completion is important, the later instructions have to be stalled and no more fetching of instructions takes place. As soon as the memory access completes, the pipeline is no longer stalled and instructions are passed to their next stage.

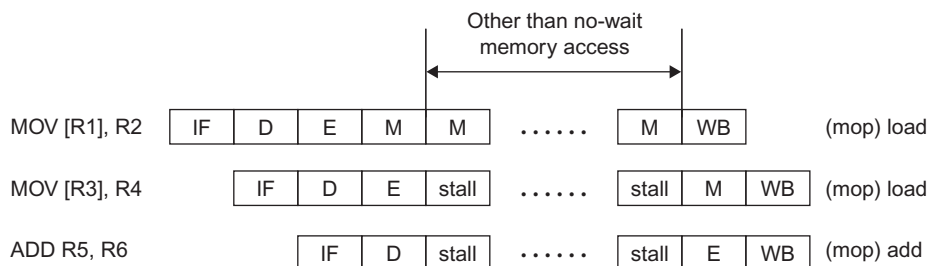


Figure 3.20 Stalls created due to an Instruction that requires more than one cycle for its operand access to execute in the Execution stage [1], Figure 2.17, page 139.

Figure 3.21 shows how control dependencies in the code cause stalls in the pipeline. For instance, consider a simple “if statement.”

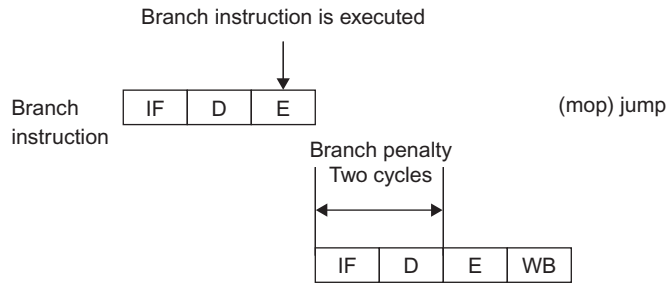


Figure 3.21 Stalls created due to control dependency on a Branch Instruction [1], Figure 2.18, page 139.

```

Code0
.....
.....
if (Cond1) {
    Code1
}
Code2
.....
.....

```

Code1 is control dependent on cond1. Code1 will only execute if Cond1 becomes true or is satisfied. Code2 is also control dependent on Cond1. When this code is converted into assembly code, a branch instruction such as jump executes. As the branch instruction goes into the instruction decode stage, it's time to fetch the next instruction. But which instruction should be fetched, Code1 or Code2? Since the decision is dependent on cond1 (branch instruction), and the result of the branch instruction will be available after execute stage (E stage), therefore the pipeline has to be stalled for two cycles. By the end of two cycles the address of next instruction is available in the program counter (PC), and then the next instruction will be fetched.

2. Pipeline flow with no stall:

■ Forwarding/Bypass Process:

Forwarding is a simple hardware technique used to minimize data hazard stalls. It is also called a bypass process. The result of an 'ADD' instruction is not needed until decode stage, or in extreme cases until execution stage. When the D stage of 'SUB' instruction needs the operand, it is not available since the result of 'ADD'

instruction is not yet written into register, so a stall is created. If the result can be moved from the execution stage of 'ADD' instruction to the start of the execution stage of the 'SUB' instruction, then the need for a stall can be avoided. To achieve this, 'ALU result' from both the E stage and M stage is fed back to the ALU inputs. If the forwarding hardware detects that the previous ALU operation generated a result which is going to be one of the inputs of a current ALU operation, then the control logic selects the forwarded result as the ALU input instead of reading from the register file.

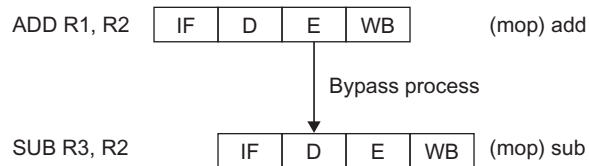


Figure 3.22 Forwarding done to reduce the number of stalls [1], Figure 2.20, page 140.

- When WB stages of two instructions are overlapped:

In this example, the first instruction is a 'MOV' instruction and the other instruction is an 'ADD' instruction. In Figure 3.23, the ADD instruction is more likely to create a structural hazard in the WB stage. But this does not happen; instead, both cause a write operation in the same cycle. In the first half of the cycle 'MOV' instruction writes and in the second half of the cycle 'ADD' instruction writes into the register.

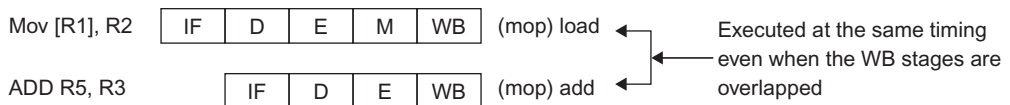


Figure 3.23 When WB Stages of two instructions are overlapped [1], Figure 2.21, page 140.

- When subsequent instructions write to the same register before the end of memory load:

In the following example, even when the subsequent instruction writes to the same register before the end of memory load the operation processing is pipelined, because the WB stage for the memory load is canceled.

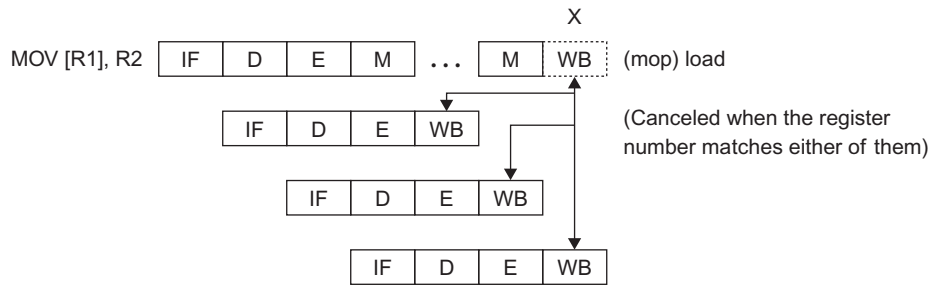


Figure 3.24 When subsequent Instruction writes to the same register before the end of Memory Load [1], Figure 2.22, page 141.

- When the load data is not used by the subsequent instruction: Out of order completion is allowed in pipelining if the correctness of the program is maintained. As in the following situation, when the load data is not used by the subsequent instruction, the subsequent operations are not stalled and in fact are allowed to execute. So, subsequent instructions are executed earlier and instructions are processed out-of-order.

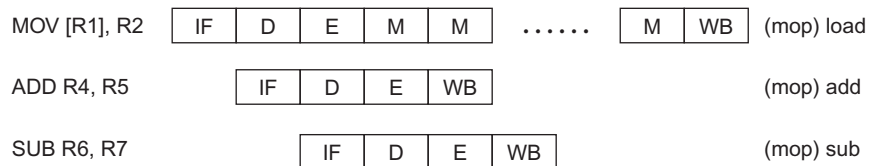


Figure 3.25 When Load Instruction data is not used by the subsequent Instruction [1], Figure 2.23, page 141.

3.4.2 Operating Modes

There are six operating modes with two types of operating-mode selection: one is selected by the level on pins at the time of release from the reset state, and the other is selected by software after release from the reset state. Table 3.5 shows mode pin settings for mode selection.

TABLE 3.5 Selection of Operating Modes by the Mode Pins [1], Table 3.1, page 142.

MD1	MD0	ROME	EXBE	OPERATING MODE	ON-CHIP ROM	EXTERNAL BUS
0	1	1	0	Boot mode	Enabled	Disabled
1	0	1	0	USB Boot mode	Enabled	Disabled
1	1	1	0	Single-chip mode	Enabled	Disabled

Table 3.6 gives a list of the operating mode settings that can be made with ROME and EXBE bits of system control register 0 (SYSCR0).

TABLE 3.6 Selection of Operating Modes by Register Setting [1], Table 3.2, page 142.

ROME	EXBE	OPERATING MODE	ON-CHIP ROM	EXTERNAL BUS
0	0	Single-chip mode	Disabled	Disabled
1	0	Single-chip mode	Enabled	Disabled
0	1	On-chip ROM enabled extended mode	Disabled	Enabled
1	1	On-chip ROM enabled extended mode	Enabled	Enabled

The endian is selectable in single-chip mode and user boot mode. Endian is set in the given operating mode by using the endian selection bits (MDE[2:0]) in the register indicated in Table 3.7

TABLE 3.7 Selection of Endianness [1], Table 3.4, page 142.

MDE	ENDIAN
0	Little endian
1	Big endian

The registers related to operating modes are given in Table 3.8.

TABLE 3.8 Registers Related to Operating Modes [1], Section 3.2, page 143.

REGISTER NAME	SYMBOL	ACCESS SIZE
Mode monitor register	MDMONR	16
Mode status register	MDSR	16
System control register 0	SYSCR0	16
System control register 1	SYSCR1	16

1. Description of operating modes:

- **Single-Chip Mode:** In this mode, on-chip ROM can be either disabled or enabled, but external bus is always disabled and all I/O ports are accessible. The on-chip ROM is enabled when the microcontroller is started. When ROME bit

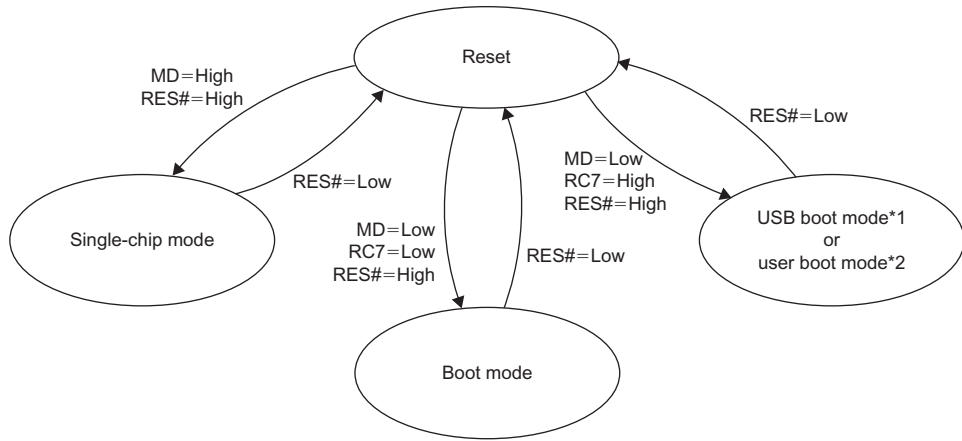
is set to 1 in SYSCR0, then on-chip ROM is enabled and it is again disabled when ROME bit is set to 0. The same is not true in reverse operation. While the on-chip ROM is disabled (i.e., ROME bit is set to 0 in SYSCR0), it cannot be enabled by setting the ROME bit in SYSCR0 to 1.

- **On-chip ROM Enabled Extended Mode:** In this mode, on-chip ROM is enabled and the external bus is always enabled. The on-chip ROM is enabled when the ROME bit is set to 1 in SYSCR0. The external bus is available as external extended mode when EXBE bit is set to 1 in SYSCR0. This mode allows some I/O ports to be used as data bus input/output, address bus output, or bus control signal input/output. The transition from this mode to single-chip mode (on-chip ROM enabled) is possible if 0 is written to EXBE, and a transition to on-chip ROM disabled extended mode is possible if 0 is written to ROME bit.
- **On-chip ROM Disabled Extended Mode:** In this mode, on-chip ROM is disabled and external bus is always enabled. The on-chip ROM is disabled when ROME bit is set to 0 in SYSCR0. The external bus is available as external extended mode when EXBE bit is set to 1 in SYSCR0. This mode allows some I/O ports to be used as data bus input/output, address bus output, or bus control signal input/output. It allows transition from this mode to single-chip mode (on-chip ROM enabled) which is possible if 0 is written to EXBE. The transition to on-chip ROM enabled extended mode is not possible.
- **Boot Mode:** Boot mode is provided for the flash memory. This mode functions in the same manner as single-chip mode except for data write/erase function to the flash memory.
- **USB Boot Mode:** USB boot mode is provided for the flash memory. This mode functions in the same manner as single-chip mode except for data write/erase function to the flash memory.
- **User Boot Mode:** In user boot mode, an on-chip flash memory modifying program (user boot program) created by the user operates. The chip starts up in user boot mode if the low level is on the MD pin and the high level is on the PC7 pin on release from the reset state.

Note: In user mode, do not make a transition to software standby mode or deep software standby mode. The setting in the OFS0/OFS1 registers is ineffective in user boot mode, and the value becomes FFFF FFFFh.

2. Transitions of Operating Modes:

- **Operating Mode transitions according to Mode Pin Setting:** Figure 3.26 shows operating mode transitions according to the setting of pins MD and PC7. Operating modes can shift in the direction of arrows.
- **Operating Mode Transitions according to Register Setting:** Figure 3.27 shows operating mode transitions according to the setting of the ROME and EXBE bits in SYSCR0. Operating modes can shift in the direction of arrows.



- Note 1. At the time of shipping, the user boot area holds a USB boot program. The product starts up in USB boot mode unless the USB boot program has been erased. It cannot start up in USB boot mode once the USB boot program has been erased.
- Note 2. To start the chip in user boot mode, settings for the UB code A and UB code B in the option setting memory are required along with the levels set on the mode-setting pins.

Figure 3.26 Operating mode transitions according to Mode Pin Setting [1], Figure 3.1, page 148.

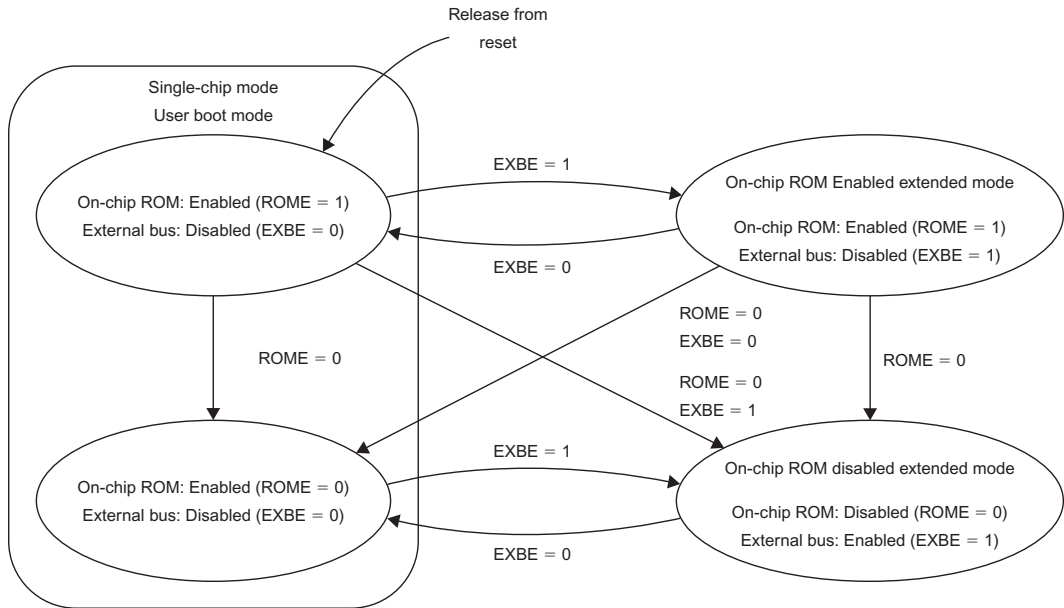


Figure 3.27 Operating mode transitions according to Mode Pin Setting [1], Figure 3.2, page 149.

3.4.3 Memory Organization

This section discusses some of the basic concepts of memory organization. The basic memory unit is organized into an array of addressable units. In a byte-addressable memory, each memory location contains 1 byte (8-bits) of data. Another way of addressing the memory is by grouping the bytes into a larger block called words or longwords and addressing that block. Consider a memory unit having k locations (bytes). If, for addressing every location (byte) a unique n -bit identifier is used, then the number of locations that can be addressed would be 2^n . So, k is equal to 2^n which is equal to the size of the memory. If each location stores m -bit value then the memory is said to be organized into an array of $k \times m$ stored bits. The address of each memory location will be a unique n -bit identifier and the content at each location will be an m -bit value. Figure 3.28 shows the basic arrangement of memory unit. In this figure the memory unit is a byte-addressable memory and, as can be seen, each location is addressed by 4-bits; therefore the size of memory is 2^4 or 16 bytes.

Byte Addressing vs. Word Addressing

By using N address lines we can address 2^N distinct addresses, numbered 0 through $2^N - 1$. Most of the modern computers use byte addressing but there are other cases possible, such as word addressing. Consider the computer having 16-bit address space; if the addressing scheme is byte-addressing, then the addressable entities would be 2^{16} bytes with byte addresses from 0, 1, 2 . . . $2^{16} - 1$. If the addressing scheme is word-addressing then the addressable entities would be 2^{15} words with byte addresses from 0, 2, 4 . . . $2^{16} - 2$.

2^{16} bytes with byte addresses from 0, 1, 2, to $2^{16} - 1$
 2^{15} words with byte addresses 0, 2, 4, to $2^{16} - 2$

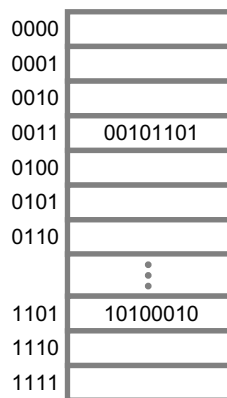


Figure 3.28 Logical layout of a block of memory.

0	8 bits of data
1	8 bits of data
2	8 bits of data
3	8 bits of data
4	8 bits of data
5	8 bits of data
6	8 bits of data

Figure 3.29 Byte addressing.

0	16 bits of data
2	16 bits of data
4	16 bits of data
6	16 bits of data

Figure 3.30 Word addressing.

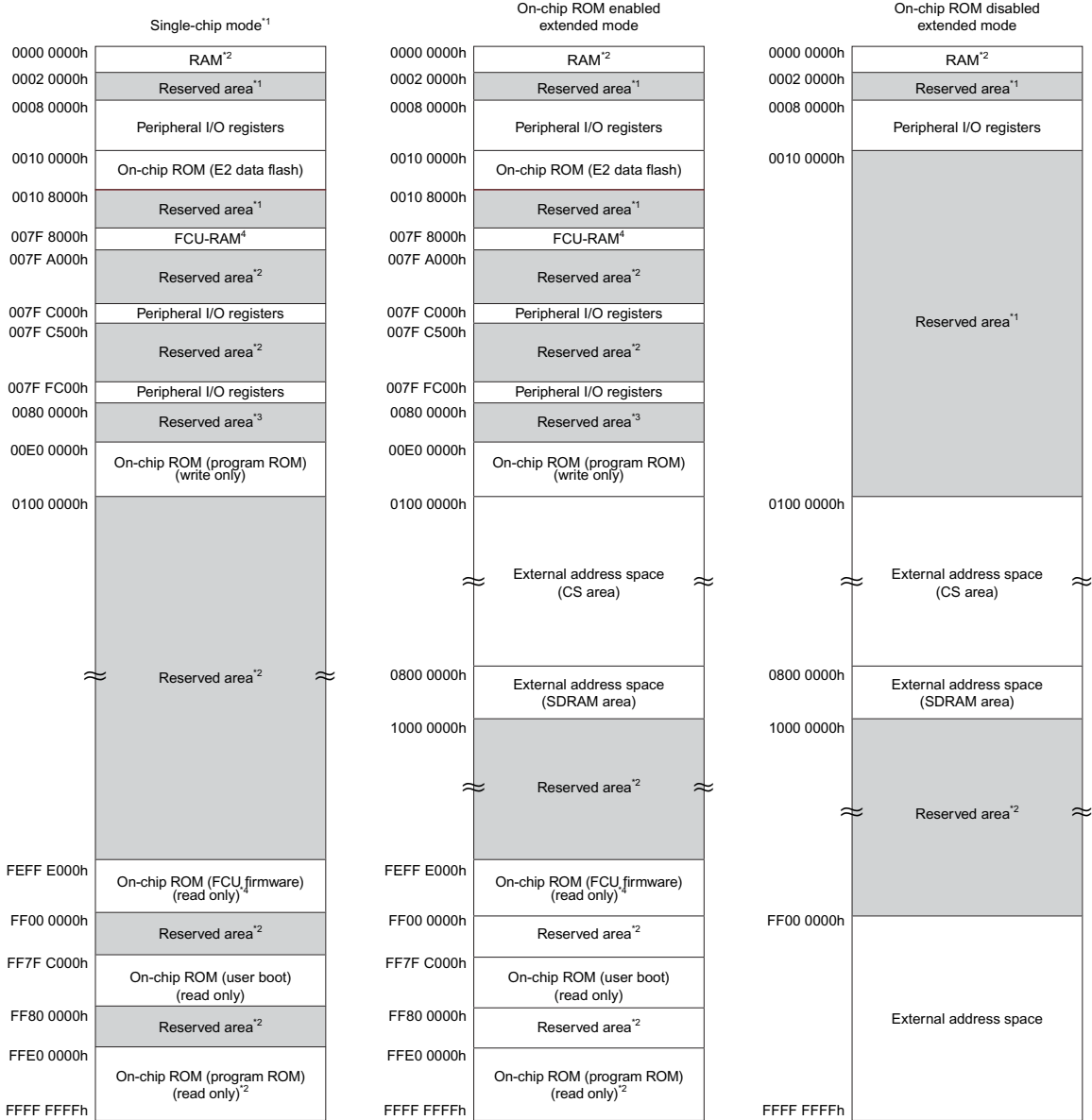
3.4.4 Memory Map

The following figure shows a memory map in various operating modes. The accessible areas will differ according to the operating mode and the states of control bits. This microcontroller has a 4-Gbyte address space, which ranges from 0000 0000h to FFFF FFFFh. The reserved areas shown in all three operating modes are not accessible by users/programmers.

In Figure 3.32, External Address Space is shown. It consists of CS areas (CS0 to CS7) and SDRAM area (SDCS). The CS area is further divided into eight areas (CS0 to CS7), each corresponding to the CS_{*i*} signal output from a CS_{*i*} ($i = 0$ to 7) pin.

3.4.5 I/O Registers

This section focuses on preventive measures that should be taken while using I/O registers. In some cases, after writing into I/O registers, you must check whether the write operation is completed. In some cases, a CPU behaves differently and could lead to unpredictable results. In such cases, the CPU starts executing subsequent instructions before the write operation is over. If the next instruction deals with the same I/O register, and it tries to read from the same register, then the subsequent instruction reads the value of an I/O register that is not yet updated. So, in such scenarios where the updated value of an I/O register is required in the future, or where a subsequent instruction must execute after the value in the I/O register is changed, special care must be taken. Examples of such situations could be where the subsequent instruction must be executed while an interrupt request is disabled, or where a WAIT instruction is executed immediately after the preprocessing for causing a



Note 1. The address space in boot mode and user boot mode/USB boot mode is the same as the address space in single-chip mode.
 Note 2. The capacity of ROM/RAM differs depending on the products.

Figure 3.31 Memory map in each operating mode [1], Figure 4.1, page 151.

Continued.

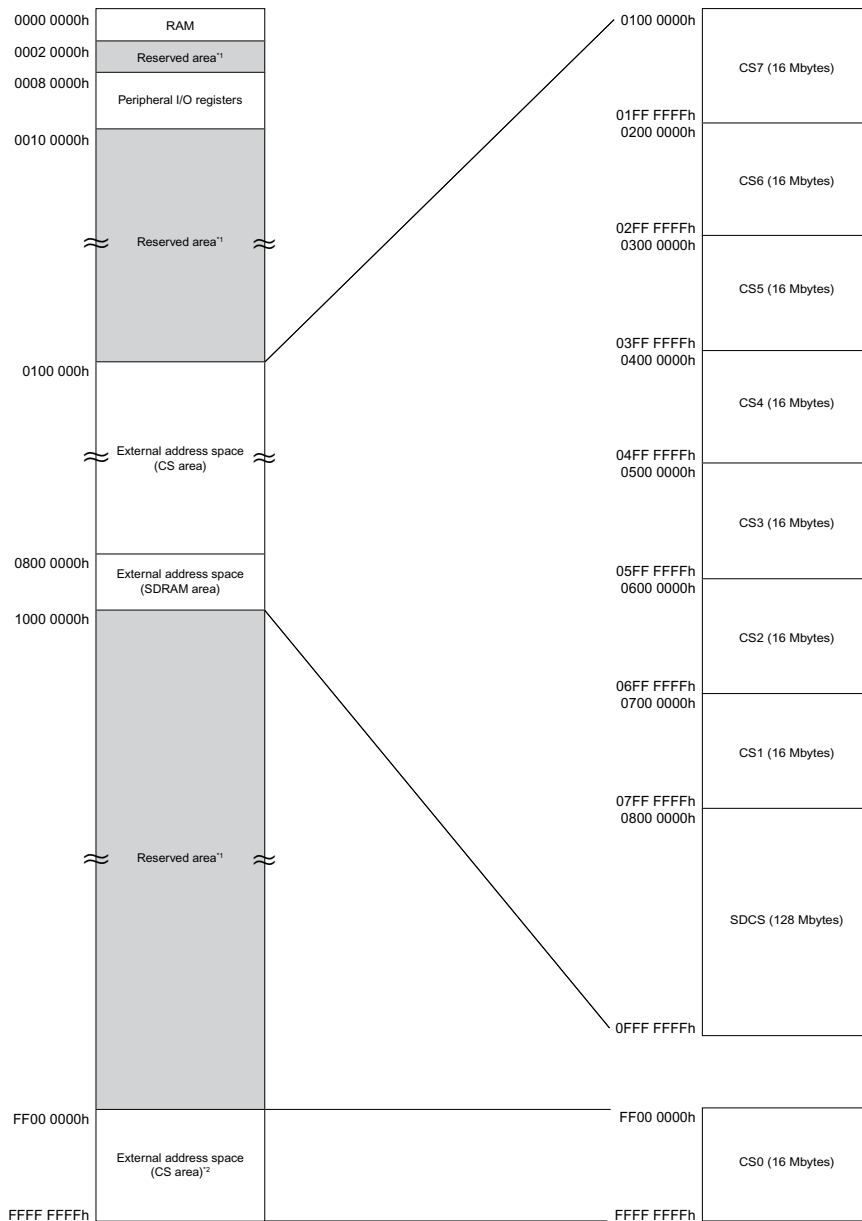
ROM (byt)			RAM (byt)	
CAPACITY	ADDRESS (FOR READING ONLY)	ADDRESS (FOR PROGRAMMING ONLY)	CAPACITY	ADDRESS
2 M	FFE0 0000h to FFFF FFFFh	00E0 0000h to 00FF FFFFh	256 K	0000 0000h to 0003 FFFFh
			192 K	0000 0000h to 0002 FFFFh
			128 K	0000 0000h to 0001 FFFFh
1.5 M	FFE8 0000h to FFFF FFFFh	00E8 0000h to 00FF FFFFh	256 K	0000 0000h to 0003 FFFFh
			192 K	0000 0000h to 0002 FFFFh
			128 K	0000 0000h to 0001 FFFFh
1 M	FFF0 0000h to FFFF FFFFh	00F0 0000h to FFFF FFFFh	256 K	0000 0000h to 0003 FFFFh
			192 K	0000 0000h to 0002 FFFFh
			128 K	0000 0000h to 0001 FFFFh
768 K	FFF4 0000h to FFFF FFFFh	00F4 0000h to 00FF FFFFh	64 K	0000 0000h to 0000 FFFFh
512 K	FFF8 0000h to FFFF FFFFh	00F8 0000h to 00FF FFFFh		
384 K	FFFA 0000h to FFFF FFFFh	00FA 0000h to 00FF FFFFh		
256 K	FFFC 0000h to FFFF FFFFh	00FC 0000h to 00FF FFFFh		
512 K	FFF8 0000h to FFFF FFFFh	00F8 0000h to 00FF FFFFh		
384 K	FFFA 0000h to FFFF FFFFh	00FA 0000h to 00FF FFFFh		
256 K	FFFC 0000h to FFFF FFFFh	00FC 0000h to 00FF FFFFh		
Note: * See table 1.3, List of Products, for the product type name.				
Note 3. Reserved areas should not be accessed.				
Note 4. For details on the FCU, see section 46. Flash Memory.				

Figure 3.31 Continued.

transition to the low power consumption state. The correct way to handle such situations is by waiting until the write operation is completed and following a debugging procedure. Follow these steps:

1. Write to an I/O register.
2. Read the value from the I/O register to a general register.
3. Execute the operation using the value read.
4. Execute the subsequent instruction.

Consider a situation where multiple registers need to be written first before subsequent instruction can execute. In other words, subsequent instructions should be executed after the write operations are completed. In such a case only read the I/O register that was last written to, and execute the operation using that value. Do not read or execute operation for all the registers that were written to.



Note:

1. Reserved areas should not be accessed
2. The CS0 are is disabled in on-chip ROM enabled extended mode.
In this mode, the address space for addresses above 1000 0000h is as shown in figure on this section, Memory Map in Each Operating Mode.

Figure 3.32 Correspondence between External Address Spaces, CS Areas (CS0 to CS7), and SDRAM area (SDCS) (In On-chip ROM Disabled Extended Mode) [1], Figure 4.2, page 152.

3.5 ADVANCED EXAMPLES

EXAMPLE 1

Show how the C arrays are laid out in memory for the Renesas board and compiler. Remember to pay attention to endianness, indicating which byte is located where. Assume the space for “*a*” starts in the first available space of user RAM (lowest address), and “*b*” starts 100 bytes (decimal) after where *a* starts.

a) int *a* [5]

ADDRESS	ARRAY ELEMENT	WHICH BYTE?
400	a[0]	Lower
401	a[0]	Upper
402	a[1]	Lower
403	a[1]	Upper
404	a[2]	Lower
405	a[2]	Upper
406	a[3]	Lower
407	a[3]	Upper
408	a[4]	Lower
409	a[4]	Upper

b) unsigned char *b* [4] [2]

ADDRESS	ARRAY ELEMENT	WHICH BYTE?
464	b[0][0]	
465	b[0][1]	
466	b[1][0]	
467	b[1][1]	
468	b[2][0]	
469	b[2][1]	
46A	b[3][0]	
46B	b[3][1]	

EXAMPLE 2

What is the speedup gained by implementing pipeline stages on a normal process?

Consider a normal process with n number of tasks, taking k number of clock periods to execute one task.

Then, the time taken by the process to complete n tasks = $n * k$ clock periods.

If k pipeline stages are implemented for the above scenario, then the time taken = $(k + (n - 1))$ clock periods.

Therefore,

$$\text{speedup} = d \frac{nk}{(k + (n - 1))}$$

EXAMPLE 3

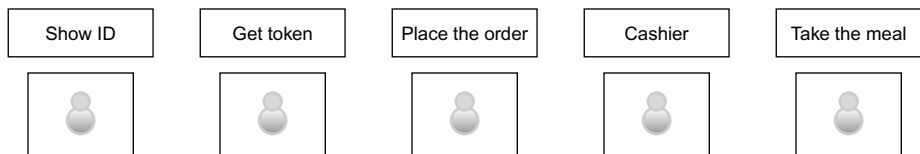
What are the various technologies used to implement embedded systems? Compare them on the basis of various parameters such as design cost, unit cost, upgrades and bug fixes, size, weight, power consumption, and system speed.

IMPLEMENTATION	DESIGN COST	UNIT COST	UPGRADES AND BUG FIXES	SIZE	WEIGHT	POWER	SYSTEM SPEED
Discrete logic	Low	Mid	Hard	Large	High	?	Very fast
ASIC	High (\$500K/mask set)	Very low	Hard	Tiny	Very low	Low	Obscenely fast
Programmable logic-FPGA,PLD	Low	Mid	Easy	Small	Low	Medium to high	Very fast
Microprocessor + memory + peripherals	Low to mid	Mid	Easy	Small to medium	Low to moderate	Medium	Moderate
Microcontrollers (including memory and peripherals)	Low	Mid to low	Easy	Small	Low	Medium	Slow to moderate
Embedded PC	Low	High	Easy	Medium	Moderate to high	Medium to high	Moderate

3.6 REFERENCES

- [1] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013.
- [2] Renesas Electronics, Inc., *RX Family User's Manual: Software, Rev.1.20*, April 2013.

3.7 EXERCISES



1. What are the benefits of a microprocessor/microcontroller-based embedded system over an ASIC-based embedded system?
2. Consider a college food court which involves five steps before you select and eat your food. Look at the following figure for solving the problem.
3. Suppose that in the food court pipeline the latency varies at each window. It varies from one to two minutes. When a student is done at each window he or she waits until the next window is available. Assume that there is no overhead involved while a student passes from one window to another window.
 - a. How should this pipeline be used to maximize its throughput?
 - b. Is the method of part 'a' applicable to a processor's data path?
 - c. What would be the throughput of the scheme in part 'a' if the latency of each window were uniformly distributed?
 - d. Discuss a method other than 'c' for improving throughput?
4. Consider 4 Kbyte SRAM chips having a data width of 4 bits. How many chips will be required to build a 32 MB memory unit with the word width of 8-bits?
5. The double word 0x AC35 FA34 is stored in memory addresses N through $N + 3$. Represent the storage using little endianness?
6. How many bits wide is the program counter register?
7. What will happen if you try to write to an array element larger than your array?
8. What is the total address space for our RX63N microcontroller?

9. What are the benefits of a microprocessor/microcontroller-based embedded system over an FPGA-based embedded system?
10. What is the number of address bits required to address any byte in a memory that contains 4096 address spaces?
11. MCU can run in three modes: single-chip, memory expansion, microprocessor modes. If used in single-chip mode, what areas in memory could be addressed?
12. What is the number of address bits required to address any byte in a memory that contains 65536 address spaces?
13. What is the difference between Big Endian and Little Endian? Suppose we have the value 0x02143657. How would the value be represented using Big and Little Endian?
14. List the stages in the pipeline used by RX63N CPU.
15. Differentiate between Byte Addressing and Word Addressing.
16. What is the need for using Floating Point Unit?
17. Assume the memory from part A is actually a microcontroller's memory space. 4K is allocated at the top (starting at address 0) for the special function registers, followed by 8K of RAM, followed by 4K of EEPROM; 64K of flash is located all the way at the end of the memory space.

Software Development Tools

4.1 LEARNING OBJECTIVES

In this chapter the reader will learn about:

- The process of compilation
- Features of the RX Family compiler
- Debugging tools
- Features of the High-performance Embedded Workshop
- Various header files associated with C/C++ Compiler and the RX Family

4.2 BASIC CONCEPTS

4.2.1 Compilation Mechanism

There are several steps involved from the stage of writing a C program to the stage of execution. Figure 4.1 shows these different steps.

In this process, a program written in C language gets translated into an assembly level program which the computer can understand. It can be seen from Figure 4.1 that the program passes through several tools before it is ready to be executed. The functions of each of these processors are:

- The **preprocessor** performs text replacement according to preprocessor directives. There are two main preprocessor directives—macro expansion (e.g. #define SIZE 30) and file inclusion (e.g. #include “config.h”).
- The **compiler** transforms source code, written in a programming language such as C, or C++ (*source language*) into another target language (*object code*) which is of binary form.
- The **linker** is a program that takes one or more objects generated by a compiler and combines them into a single executable program.

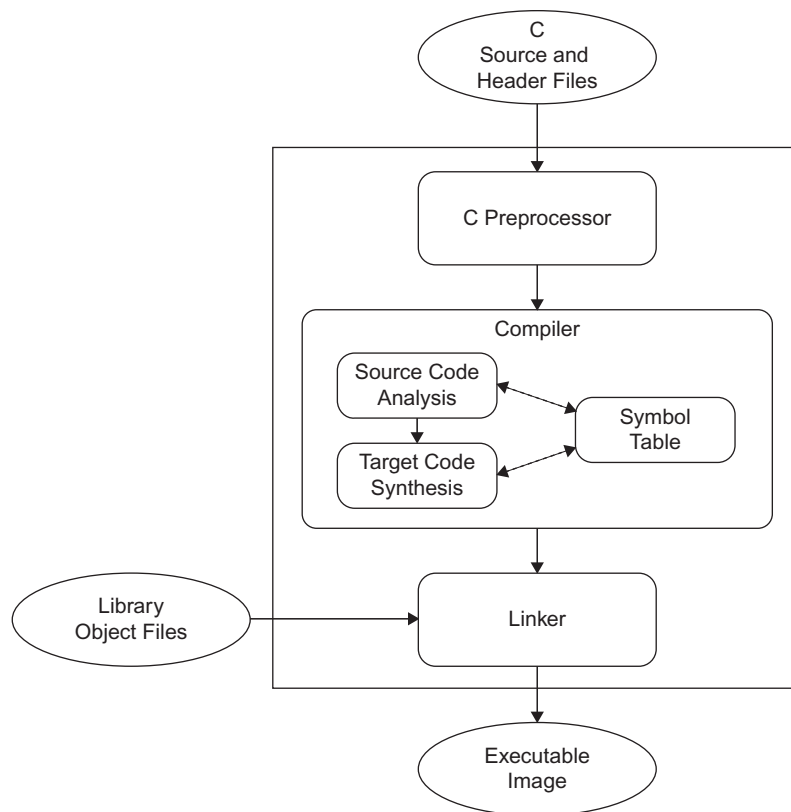


Figure 4.1 Compilation process for a C program.

The input and output to each of these processing stages is shown in Table 4.1.

TABLE 4.1 Input and Output to each Processor.

PROCESSOR	INPUT	OUTPUT
Preprocessor	C source code file	Source code file with processed preprocessor commands
Compiler	Source code file with processed preprocessor commands	Re-locatable object code
Linker	Re-locatable object code and the standard C library functions	Executable code in machine language

4.2.2 Compilers for Embedded Systems

Compilers for embedded systems differ from compilers for general-purpose processors (GPPs). Minimizing code and data size is often critical for embedded systems since memory sizes are limited due by price pressures. This makes compiler code and data size optimizations extremely important. The tongue-in-cheek “Software Gas Law” states that a program will eventually grow to fill all available resources. Embedded system software evolves as features are added and defects are fixed, while the hardware changes much more slowly. It is much easier to reprogram an MCU than redesign the hardware. As a result there is great value in compiler optimizations which can squeeze more code and data into the available resources.

Speed optimization is also often critical. However, it is done differently for embedded systems and GPPs. First, GPP instruction sets have evolved over time to enable extremely high clock rates (> 2 GHz) and deep instruction processing pipelines. Embedded processors with their lower clock rates do not need such deep pipelines, which leads to different code optimization trade-offs. Second, a lower clock rate means that embedded systems have a smaller performance penalty than GPPs for accessing memory instead of registers. This has two interesting effects. First, the compiler makes different optimization trade-offs with data allocation. Second, instruction sets for embedded systems can support memory-memory and bit-level operations rather than being forced into a load/store model.

4.2.3 RX Compiler Package

The RX compiler package includes the following embedded system development tools.

- **C/C++ Compiler**
The compiler translates source code into assembly code, and typically also invokes the assembler and linker to create an executable file. The Compiler is ANSI-compliant and supports exception processing and template functions. It supports C or C++ and generates compact and high-speed object code. It offers general optimization techniques such as deletion of common expression and register allocation. There are additional non-ANSI features which are helpful or necessary for embedded systems.
- **Assembler**
The Assembler translates assembly code into object (machine) code. It also provides pre-processor functions such as the file inclusion, conditional assembly, and macros, in order to simplify programming.
- **Optimizing Linkage Editor**
The Linkage Editor processes object files generated by the compiler and assembler to create load modules and library files.
- **Standard Library Generator**
The Standard Library Generator creates customized versions of the standard library files based on the user-specified options.

- **Simulator/Debugger**

This Simulator/Debugger provides the capability for debugging in targetless system. It is also a highly accurate simulator, supporting program performance evaluation.

- **Utilities**

The RX package contains various utility tools. Call Walker shows stack use corresponding to the C/C++ function call tree. Moreover, function allocation editing by drag & drop is available. Map Viewer provides a GUI display of the various sections in a map file (output by the Optimizing Linkage Editor).

- **IDE (Integrated Development Environment): HEW (High-performance Embedded Workshop)**

High-Performance Embedded Workshop provides a GUI-based integrated development environment on Windows operating systems for the development and debugging of embedded applications for the Renesas microcontrollers. It supports seamless integration and easy access to all tools for coding, compiling, linking, and debugging. All the tools in the package together offer a variety of functions and increase productivity greatly.

Features of RX Family C/C++ Compiler

1. **Easy optimization setting and the optimization features**

- Compiler Optimization: It provides an easy selection of optimization as in the selection of size, speed, priority, and also in the selection of the optimization level (optimize level: 0, 1, 2, or max).
- Supports wide-ranging optimization when compiling; function's inline-expansion between files and symbol access optimization which uses external symbol allocation information from the optimization linker.
- Has a detailed setting of optimization that is useful in loop expansions, instructions order, optimization range specification, register allocation, etc.

2. **Linker optimization**

- Handles inter-module optimization such as the removal of an unreferenced symbol, optimization for branch order, and provides a detailed setting of partially disabled optimization.

3. **Optimization of standard library**

- Application of compiler optimization: A standard library is targeted on optimization and a compact code is generated with the entire program.

4. **Easy translation environment from the existing product**

- Supports the option of controlling different language specifications.
- Language specification of another compiler is checked by the RX compiler.
- RX supports Bi-endian operation. The compiler can select between big endian and little endian.

4.2.4 Debugging Tools

There are two primary tools for debugging embedded real-time systems:

- a. **Debugger:** The debugger allows a developer to observe and control a program's execution and data. The execution can be started, paused and stopped, or advanced by a single instruction or program statement. Breakpoints can typically be inserted. Data stored in variables as well as raw memory and register values can be examined and modified.
- b. **Monitor:** The monitor allows a developer to examine the program's temporal behavior. The most common monitors are oscilloscopes and logic analyzers connected to the embedded system. For instance, while implementing interrupts in serial communication, one can measure useful information such as the duration of the transmit ISR and the receive ISR, or the delay between sending a character and receiving a reply. This information can be used to find maximum latency, and maximum frequency. Hence the monitor tool is helpful in giving you insights about the timing of various operations happening inside the system.

4.2.5 Introduction to HEW

This section deals with the concepts and functionalities associated with the High-performance Embedded Workshop V.4.09 (HEW).

Overview: HEW organizes your work with the concepts of workspaces and projects.

- **Workspace:** This is the largest unit which contains programs written in the HEW workshop. It can have several projects. A project is automatically created when we create the workspace.
- **Project:** The project is where you write your program. In fact, creating a new project is making a new program. You can also make hierarchical levels between several modules. It, along with other projects, will be included in the workspace.

A simple diagram below shows the relationship between a project and the workspace.

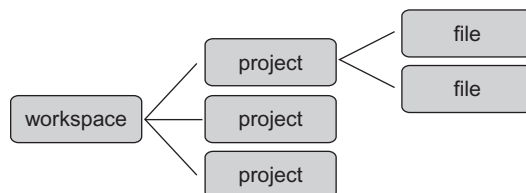


Figure 4.2 Relationship between a project and the workspace.

Creating or Opening a Project in HEW-IDE

To launch HEW, open the start menu, select **All Programs**, select **Renesas**, select **HEW**, and then select the shortcut of the **High-performance Embedded Workshop**.

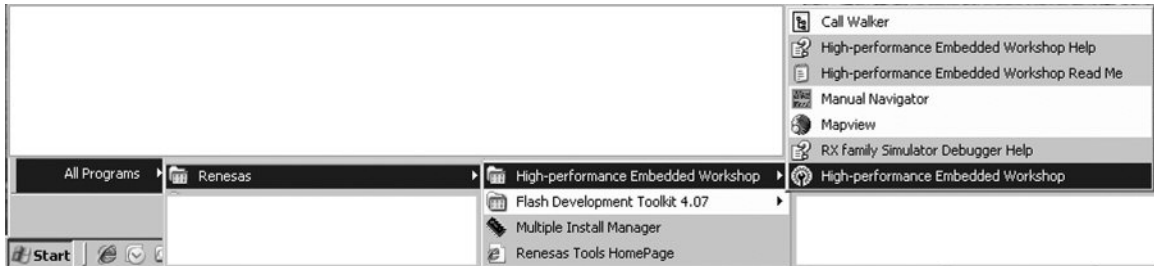


Figure 4.3 Launching of HEW [1], page 1.

The following dialog box is displayed:

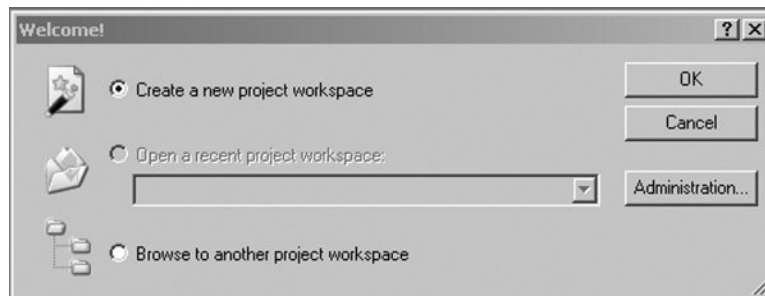


Figure 4.4 Welcome dialog box in HEW [2], page 15.

To create a new workspace:

- Select the **Create a new project workspace** option from the **Welcome!** dialog box, and click the **OK** button or select [**File** → **New Workspace**]. The New Project Workspace dialog box will be displayed.
- Enter the name of the new workspace into the **Workspace Name** field. To select the directory in which you would like to create the workspace, use the Browse button or type the directory into the **Directory** field manually.
- Select the CPU family and tool chain upon which you would like to base the workspace.

- When a new workspace is created, the HEW will also automatically create a project and place it inside the new workspace. From the project types list, select the type of project that you want to create from this list. The project types are of mainly three types: tool chain-only, debug-only, and a full project generator that contains both the debugger and tool chain aspect of the HEW.
- Click the **OK** button to create. This then launches the HEW window.

To open a new workspace:

- Select **Browse to another project workspace** option from the dialog box shown in Figure 4.4 and then click the **OK** button or select [**File** → **Open Workspace**]. The Open Workspace dialog box will be displayed. Select the workspace file (“.HWS” file) that you want to open.
- Click the **Select** button to open the Properties dialog box to open the workspace. Click the **Cancel** button to stop opening the workspace.

To open a recently used workspace:

- Select **Open a recent project workspace** in the dialog box: select the name of the workspace from the dropdown list, and then click the **OK** button.

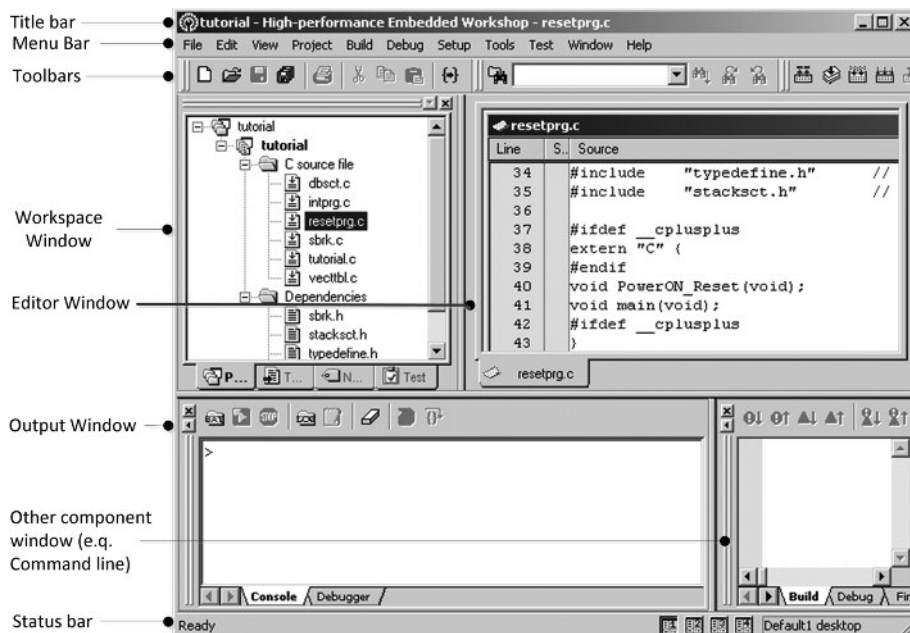


Figure 4.5 HEW workspace showing various windows [2], page 2.

Windows in HEW

There are three main windows in HEW:

Workspace Window: Shows the projects and files that are currently in the workspace. It has four tabs: Projects, Templates, Navigation, and Test.

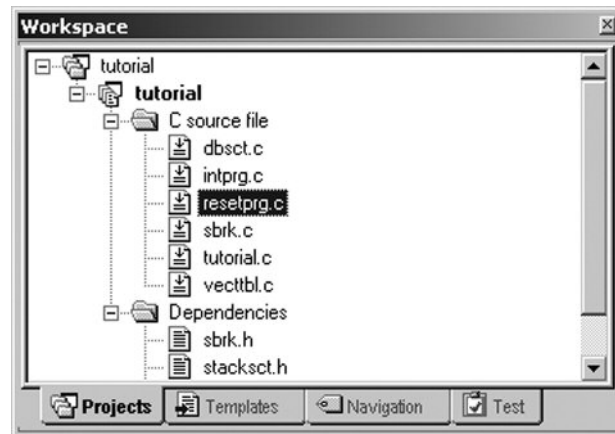


Figure 4.6 Workspace window in HEW [2], page 6.

Output Window: Shows the results of a various processes (e.g., build). By default, it has seven tabs (Build, Debug, Find in Files 1, Find in Files 2, Macro, Test, and Version Control) on display.

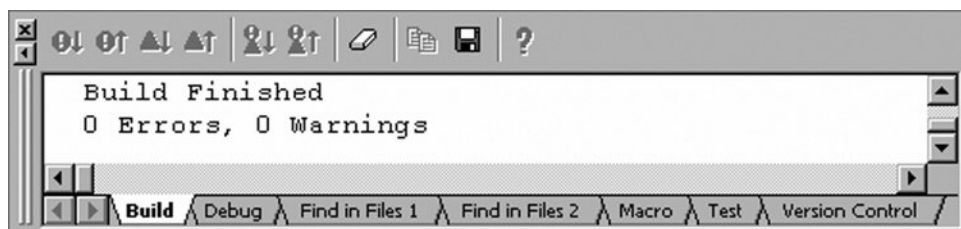


Figure 4.7 Output window in HEW [2], page 9.

Editor Window: Provides file viewing and editing facilities. It is in this window where you will edit files of your project. It allows you to have many files open at one time, so you can switch between them. You can edit them in whichever order you want. Each file has a separate tab associated with it, and you can navigate easily to any tab you want.

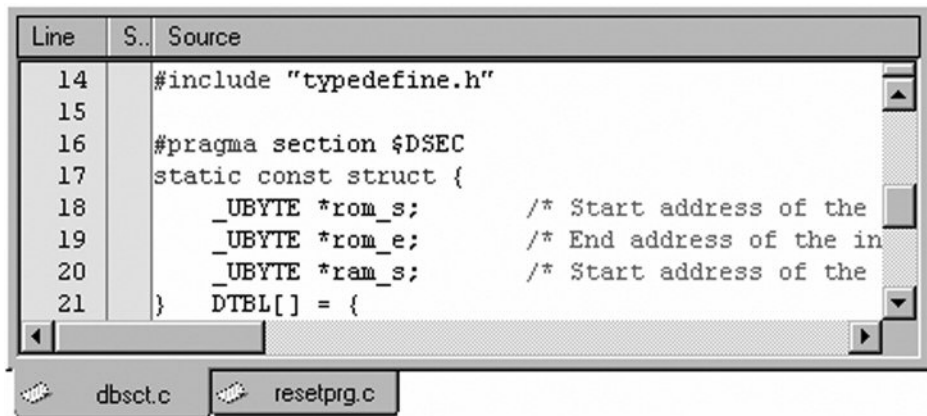


Figure 4.8 Editor window in HEW [2], page 9.

Concept of Configuration and Session

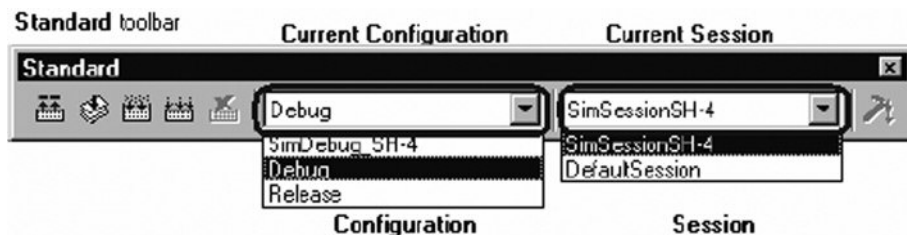


Figure 4.9 Configuration and session selection in HEW [2], page 20.

By looking at the Standard toolbar you will know your current configuration and session. You can also select your session and configuration by looking into the drop-down list box. For instance, Figure 4.9 shows that the selected debugger is “SH-4 Simulator” which works along with Renesas SuperH Standard toolchain.

Before going any further, let me clarify the concept of configuration and session.

Configuration

After selecting a toolchain, you will create a project. Once the project is created, the HEW will automatically create configurations “**Debug**” and “**Release**.” As shown in Figure 4.9, configurations “**SimDebug_SH-4**,” “**Debug**,” and “**Release**” are available. At the time of the creation of the project, if you have selected a target debugger HEW will automatically create a configuration best suited for that debugger. For instance, if you have selected “**SH-4 Simulator**” in the **Target** tab while creating a project, configuration “**SimDebug_SH-4**” is created. Configurations are the settings that have to be set before the building process starts. It can also be referred to as “build configuration.”

Session

Sessions are the units basically used to manage various settings. For instance, they may refer to the settings associated with debugging options of a specific debugger and data values on the memory and register windows. The term “session” is also referred as “debugger session.” If you look at the figure of the Standard toolbar (Figure 4.9), sessions “**SimSessionSH-4**” and “**Default Session**” are available. Information on each session is saved in an individual file in the HEW project. Just like a configuration is created as you create a project after selection of the toolchain, a session called “**Default Session**” is also created. Also, if you select a target debugger at the creation of project, a session is created for connecting the debugger. For example, if you have selected “**SH-4 Simulator**” in “**Target**” at the creation of a project, session “**SimSessionSH-4**” is automatically created.

4.2.6 Concepts of Header Files

Most of the programming languages (for instance C and C++) use header files. These files hold certain elements (program’s source code) which are reusable. Header files contain common repeatable elements such as forward declarations of classes, sub-routines, structure, unions, variables, and other identifiers. Declaring the same standardized identifiers in more than one source file can be a cumbersome task for a programmer.

The solution to this is declaring that identifier in a single header file and when there is a need for that identifier in some other source file, a programmer can just include that header file in order to include all declarations. The C standard library and C++ standard library traditionally declare their standard functions in header files that implement standard processing operations such as input/output and string handling. They can be used by including the standard include files which contain declarations for the corresponding libraries and definitions of the macro names necessary to use them.

Header Files Used in RX Family C/C++ Compiler

C and C++ are the most famous programming languages that implement the concept of header files.

Table 4.2 lists the various library types, and their corresponding standard include files.

Some include files consist only of macros, as seen in Table 4.3, to improve the program efficiency.

Header Files Associated with RX63N

Some of the header files used in the demo program can be seen in Table 4.4.

TABLE 4.2 Library Types and Their Corresponding Header Files [3], table 9.26, page 401.

LIBRARY TYPES	DESCRIPTION	STANDARD INCLUDE FILES
Program diagnostics	Outputs program diagnostic information.	<assert.h>
Character handling	Handles and checks characters.	<ctype.h>
Mathematics	Performs numerical calculations such as trigonometric functions.	<math.h> <mathf.h>
Non-local jumps	Supports transfer of control between functions.	<setjmp.h>
Variable arguments	Supports access to variable arguments for functions with such arguments.	<stdarg.h>
Input/output	Performs input/output handling.	<stdio.h>
General utilities	Performs C program standard processing such as storage area management.	<stdlib.h>
String handling	Performs string comparison, copying, etc.	<string.h>
Complex arithmetic	Performs complex numeric operations.	<complex.h>
Floating-point environment	Supports access to floating-point environment.	<fenv.h>
Integer type format conversion	Manipulates greatest-width integers and converts integer format.	<inttypes.h>
Multibyte and wide characters	Manipulates multibyte characters.	<wchar.h> <wctype.h>

TABLE 4.3 Standard Include Files Comprising Macro Name Definitions [3], table 9.27, page 402.

STANDARD INCLUDE FILE	DESCRIPTION
<stddef.h>	Defines macro names used in common by the standard include files.
<limits.h>	Defines various limit values relating to the compiler internal processing.
<errno.h>	Defines the value to be set in errno when an error is generated in a library function.
<float.h>	Defines various limit values relating to the limits of floating-point numbers.
<iso646.h>	Defines alternative spellings of macro names.
<stdbool.h>	Defines macros relating to logical types and values.
<stdint.h>	Declares integer types with specified width and defines macros.
<tgmath.h>	Defines type-generic macros.

TABLE 4.4 Header Files Used in Demo Program of RX63N Microcontroller Board.

STANDARD INCLUDE FILE	DESCRIPTION
<config.h>	Defines macros relating to the font size.
<glyph.h>	Defines external constants, typedef enumerations and structures, prototype for minimum, and full access for glyph API library.
<preamble.h>	Defines basic definitions of all simple constants and types.
<st7579_lcd.h>	Defines prototypes that are required by the LCD driver in the glyph API.
<r_glyph.h>	Defines prototypes for the glyph communication API.
<typedefine.h>	Defines aliases of Integer Type.
<sbrk.h>	Defines macro relating to size of area managed by sbrk.
<vect.h>	Defines vector table.
<stacksct.h>	Defines macros that refer to setting of stack area.
<iodefine.h>	Define various input and output registers.

4.3 BASIC EXAMPLES

(Source: *High-performance Embedded Workshop V.4.09, User's Manual*. Renesas Electronics America, Inc., 2011.)

EXAMPLE 1

This is an example demonstrating how to Build, Debug, and Run a Project on the HEW-IDE.

If you are testing your board for the first time, you will test it with the demo code that comes with the package. After launching the main window, you probably want to download and run it on the board. Follow these steps to acquaint yourself with the whole process:

Step 1: Ensure that **'JLink'** session in the right-hand drop-down list on the tool bar is selected.



Step 2: Click the **<Connect>** button on the 'debug' toolbar.



When you click on the **connect** button, an initial settings window will appear. Ensure that you select the right MCU group and device. Select the debugging mode as shown in Figure 4.10.

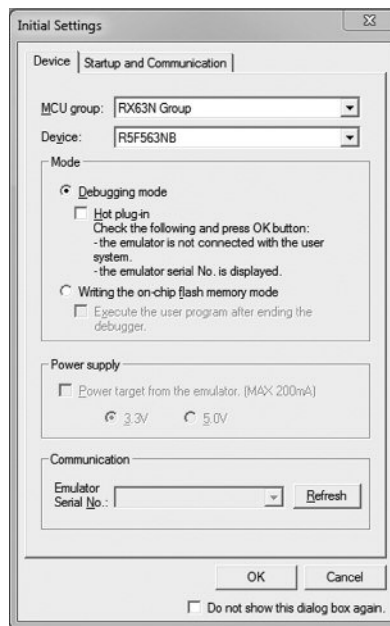


Figure 4.10 Initial setting window while connecting the board.

After clicking **OK**, a window will pop up which will show the status as **connecting**. This window indicates whether an initial configuration has been done or not. See Figure 4.11 to get an idea.



Figure 4.11 Window showing the status as connecting.

This window will show up for just a few seconds, and then automatically close.

Once connected, you can see the status in the output window (Figure 4.12) as **'connected.'** Also, you can see the status of the platform tab of other component windows. Here is the snapshot:

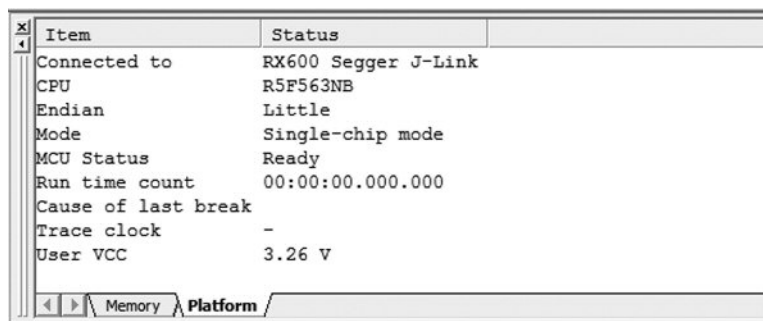


Figure 4.12 Window showing the status after the board has connected.

Step 3: The next step is building the program to check for any compiling error. Typically, in build process, each phase of the build takes a set of project files and builds them. If every file builds successfully, then the next phase is executed. Let me shed some light on the build process. The building process takes place in three phases: the Compiler is the first phase, the Assembler is the second phase, and the Linker is the third and final phase. During the

Compiler phase, the C/C++ source files from the various projects are compiled in turns. During the Assembler phase, the assembler source files are assembled. During the Linker phase, all library files and output files from the Compiler and Assembler phases are linked together to produce the load module. Depending on your requirement, you can choose from the various build options available to you. If you want to build an individual file, first select it from project tab of the workspace window, and then you can select any one of these options:

- Click the **Build File** toolbar button (Figure 4.13)
- Select **Build <file>** from the pop-up menu
- Select the [**Build** → **Build File**] menu option
- Press CTRL + F7

If you want to build a project, you can select any one of these:

- Click the **Build** toolbar button (Figure 4.13)
- Press F7
- Select [**Build** → **Build**]
- Right-click on a project in the **Project** tab of the **Workspace** window and select [**Build** → **Build**] from the pop-up menu

Typically, the build operation compiles or assembles those files that are changed since the last build command. The **Build all** operation builds all files irrespective of whether the file has been modified or not.

For performing a **build all** operation, you may select any of these options:

- Click the **Build All** toolbar button (Figure 4.13)
- Select [**Build** → **Build All**]
- Right-click on a project in the **Projects** tab of the **Workspace** window and select [**Build** → **Build All**] from the pop-up menu

In each of the cases discussed, you can see the status of the build process in the **build** tab of the output window. An example that shows the status in the output window after the build process is next.

EXAMPLE

Build Finished
'x' Errors, 'x' Warnings

Here 'x' could be 0 or a larger number depending on your coding skills.

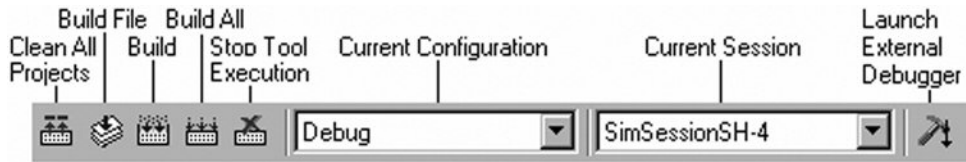


Figure 4.13 Explanation of icons on the toolbar [2], page 4.

Step 4: After the build process, you should download the code onto your board. For that, first go to the **debug** tab on the menu bar. Click on it and select **‘download modules’** in the drop-down menu list. Click on **‘all modules’** and wait for the HEW to download all modules onto the board. When downloaded, a status will appear on the memory tab of the other component window, indicating the memory area where the program has been downloaded. A snapshot of the same is shown in Figure 4.14.

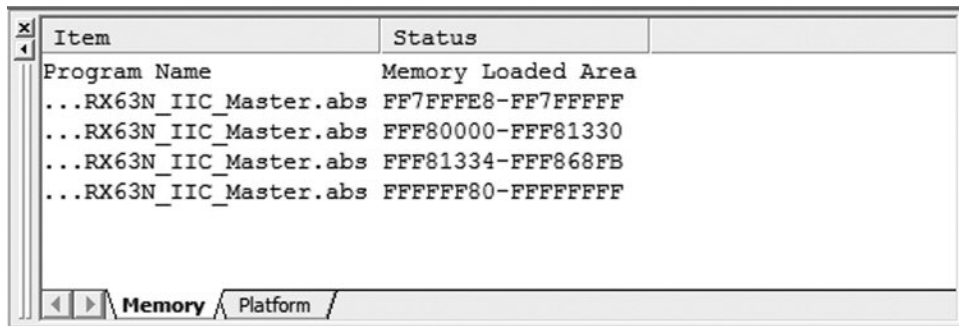


Figure 4.14 Memory tab of other component window showing status of download.

Step 5: After downloading the program onto the board, you need to make it run to see the response. Click on **‘reset go’** from various other go options as shown in Figure 4.15.

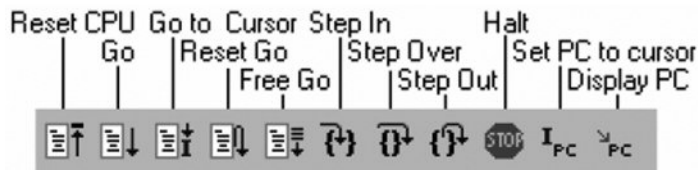


Figure 4.15 Explanation of icons on the toolbar [2], page 4.

You can easily see the response on the output window as well as on the MCU board. The status on the output window will look like: Reset CPU.

Step 6: If you need to halt the program for debugging or editing the code, you can just click on the red **stop** button, as seen in Figure 4.16.



Figure 4.16 Snapshot of toolbar before halting the program.


EXAMPLE 2

This is an example demonstrating how to create and save a header file in the workspace. This example also demonstrates how to add that header file to the current project, and how to edit it.

A programmer can create a ‘Header file’ when there is a need for some subroutines, structure, variables, unions, enumerations, and other definitions to be commonly repeated. Declaring the same identifiers again and again can be a tedious task, so the solution is creating a header file that contains all the elements that are being repeated in more than one source file. In a header file, a programmer just declares common declarations, and when there is need for any identifier the programmer can just include that header file in the main source file, and the purpose will be fulfilled in an easier way. Follow these steps to add a header file to your current project.

Step 1: Creating a header file

To create a new header file, you need to create a new editing window first. For this, you can apply one of the following:

- Click the **file** tab on the menu bar, and then click the **new file** option in the drop-down menu
- Press CTRL + N
- Click the new file toolbar icon 

By default, a new file will be given an arbitrary name which you can change when you save the file. To make a header file you just need to save that file as “.h” extension file. It is always good to name the file according to its functionality because other programmers who might want to edit the project later must also know the types of declarations the header file contains. This is the reason the header file that defines input and output registers is named **<iodefine.h>**. After you have created a file, the next step is to edit the file.




Step 2: Editing a header file

In the editor window, you can identify the basic declarations that are being repeated in more than one source file. Before writing the definitions and declarations, do yourself a

favor by writing the description of the current header file, to give other programmers an idea as to what this header file contains in general. Then, you can proceed with writing your content as your application demands. After you have written those basic definitions, you can edit it by using the basic tools available to you such as the menu, toolbar, and keyboard shortcuts. In addition, HEW provides you the functionality of editing through a pop-up menu that is local to the editor window. That menu will appear when you right click in an editor window.

Table 4.5 outlines the basic operations.


TABLE 4.5 Basic Operations for Editing a Header File [2], page 104.


OPERATION	EFFECT	ACTION
Undo	Reverses the last editing operation.	Select [Edit → Undo]
		Press CTRL + Z
Redo	Repeats the last undone editing operation.	Select [Edit → Undo]
		Press CTRL + Z
Cut	Removes highlighted text and places it on the Windows clipboard.	Click the Cut toolbar button ()
		Press CTRL + X
		Select [Edit → Cut]
		Select Cut from the pop-up menu
Copy	Places a copy of the highlighted text into the Windows clipboard.	Click the Copy toolbar button ()
		Press CTRL + C
		Select [Edit → Copy]
		Select Copy from the pop-up menu
Paste	Copies the contents of the Windows® clipboard into the active window at the position of the insertion cursor.	Click the Paste toolbar button ()
		Press CTRL + V
		Select [Edit → Paste]
		Select Paste from the pop-up menu
Clear	Removes highlighted text (it is not copied to the Windows clipboard).	Select [Edit → Clear]
		Press Delete
Select All	Selects (i.e. highlights) the entire contents of the active window.	Select [Edit → Select All]
		Press CTRL + A

While you are editing your file, the title bar will show an asterisk (*). For instance global.h*

Step 3: Saving a header file

This step discusses how to save a file as a header file and how to save the contents of the editor window in general. To save the contents of a newly created file as a header file, make sure that it is an active window; i.e., open in an editor window, and then select one of the following:

- Click the **file** button on menu bar, then click the **new save** button in the drop-down menu
- Press CTRL + S
- Click the Save File toolbar icon ()


Since the file has not been saved before, the save operation will provide a file save dialog box. Enter a filename, and ensure that you put “.h” as the extension of the file. After making it a (.h) header file, specify a directory and then click the **OK** button to create the file with the name given in the directory specified. If you edit and make changes to an already saved file, then you just need to click on the save icon. No dialog box will appear in this case. If you want to save the contents of the file under a new name, you must click the **file** button on the menu bar, then click the **save as** instead of the **new save** button in the drop-down menu. Again a file save dialog box will be displayed. Enter a filename, specify a directory, and then click the **OK** button to create the file with the name given in the directory specified. In order to save the contents of every open window, either click on the **save all** toolbar button () or Click the **file** button on the menu bar and then click the **save all** button in the drop-down menu.

NOTE:

Saving the file as a “.h” extension file is the key in making a newly created file a header file.

Step 4: Opening a header file

To open a file you can do one of the following operations:

- Click the **file open** toolbar button ()
- Press CTRL + O
- Click the **file** button on menu bar, and then click the **open** button in the drop-down menu

This operation will lead to the directory browser. You can then navigate to the desired directory to open the file. Once located, you can open that file.

NOTE:

You can use the **Files of Type** combo box to select the type of file you want to open. For instance, if you select ‘.h’ extension in the combo box then you will be able to see only files that are of the ‘.h’ extension. Surely this will narrow down your search.

Step 5: Adding a header file to the current project

For adding a header file to the current project click on the **projects** tab in the menu bar, and in the drop-down menu click on the “**add files**” button. This operation will lead to the directory browser. You can then navigate to the desired directory to find the header file. Once located, you can add that file by clicking the “**add**” button on the directory browser window. If you want to add that file to one of the folders in the workspace window, such as the C header file or C source file, then just go to that folder and right click. Select **add files** from the pop-up menu. Again the directory browser will pop-up and you can navigate to your desired file. Once added, you do not need to open that file in a conventional way as discussed in Step 4. Follow these steps to open that header file:

- Spot your file in workspace window and double-click the file to open it
- Select the file and click the right-hand mouse button; select **Open <file name>** from the pop-up menu
- If it is already selected, press enter

NOTE:

To remove a header file:

For removing a header file from the current project, click on the project tab in the menu bar and in a drop-down menu, click on the “**remove files**” button. A window, as seen in Figure 4.17, will appear.

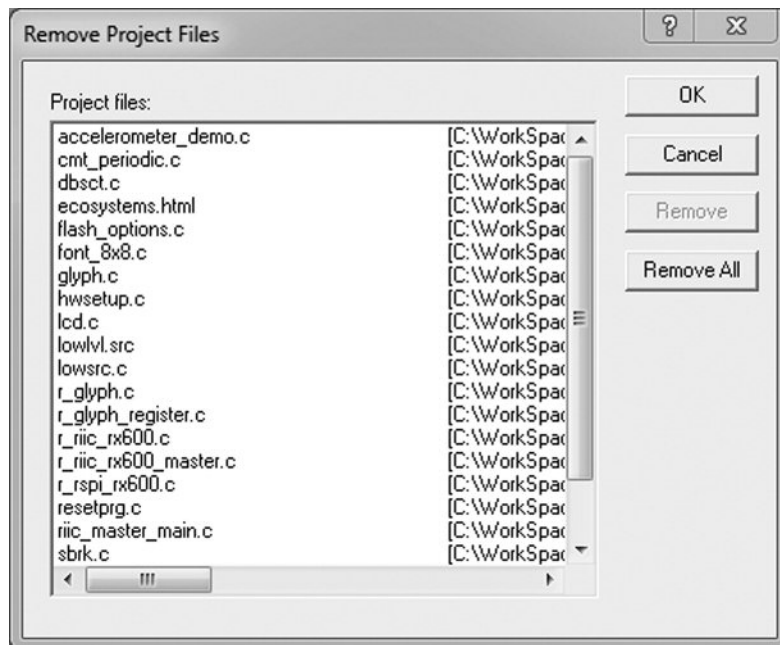


Figure 4.17 Removing a header file.

Select the header file you want to remove from your project. If you want to remove a header file from one of the folders in the workspace window, such as the C header file or C source file, then just go to that folder and right click. Select **remove files** from the pop-up menu. Again, the window shown in Figure 4.17 will appear and you can select the file you want to remove.

4.4 ADVANCED CONCEPTS

4.4.1 Advanced Debugging Concepts

(Source: *HEW User Manual V.4.09.*)

This section describes in detail the various debugging tools and operations present in high performance embedded workshop. As discussed in Section 4.2.4 there are two primary tools for debugging embedded real-time systems: the debugger and the monitor. This section discusses the first tool, the debugger, in detail. Details regarding the functionality and operations of the debugger and its related windows and dialog boxes are discussed. The debugger used in the RX Family is the J-Link Debugger.

- **Debugger options in HEW**

The debugger can debug at assembly language level, as well as at the C/C++ source level. It depends on which setting the user chooses. If users make the **debug** option enabled, the debugger debugs the code at C/C++ source language level; and if that setting is not enabled then the debugger by default debugs the code at assembly language level. More precisely, your C/C++ program must be compiled and linked with the **debug** option enabled for debugging at C/C++ source level. When the **debug** option is enabled, the compiler puts all the information necessary for debugging the C/C++ code into the management information file, which is usually called the ‘debug object files.’ Thus, the debug object files are those absolute files that contain only the specific information essential for debugging, instead of the whole C/C++ code. While creating a new project, an initial debug session will be automatically configured. A user has to ensure that the **debug** option is enabled on the compiler and linker while generating an object file for debugging. When the **debug** option is not enabled, then debugging information will not be present in your debug object file. You can still load that file into the debugger, but it will only debug at the assembly language level.

- **Debugger sessions in HEW**

The High-performance Embedded Workshop offers you the functionality of storing all of your builder options into a configuration. This means you can put all of your building information into one place and refer to it with a name. Similarly, you

can store all the debugger options in a session. Later on, you can get back to the same session when required, and all of the debugger options will be restored. These sessions allow the user to specify target, download modules, and debug—which basically means you can have different sessions each targeted at different debugger options. For instance, you can easily have different sessions using the same target but with minor variations in session options. As an advantage, you can easily switch sessions as and when required. You can even modify certain things such as register values, or target settings such as clock speed. Look at Figure 4.18. The five sessions shown share the same target, but the sessions are slightly different with regard to the options defined.

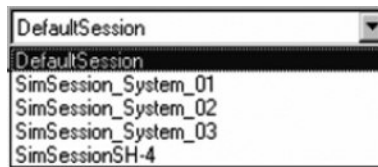


Figure 4.18 Sessions in HEW [2], page 354.

In this particular case, there is no need to rebuild because the sessions share the same download module and they are never directly related to the build configuration data. In addition, each session's information is stored in a separate file in the High-performance Embedded Workshop project so that you can later manipulate the data according to your application.

- **Selecting a session:**

Click on the **debug** tab on the menu bar. In the drop-down menu, click on the **debug sessions** and the debug sessions dialog box will open. After that, select the session that you want to use from the **current session** drop-down list box, and then click the ok button.

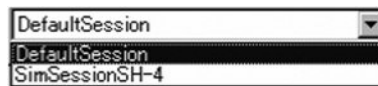


Figure 4.19 Selecting a session [2], page 355.

- **Adding a session:**

HEW provides you the functionality of creating and naming a new session with an attached target and setup. You can create a new session by clicking on the **file** tab on the menu bar. In the drop-down menu, click on **new session** and the new session dialog box will open.

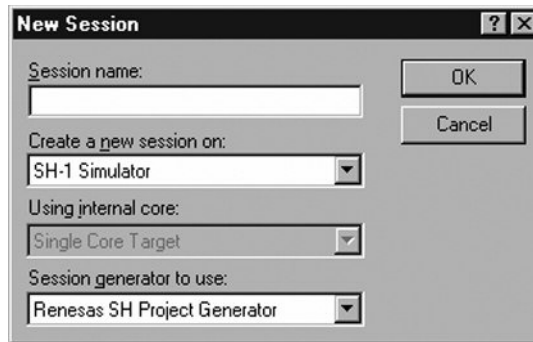


Figure 4.20 Creating and naming a new session [2], page 355.

You need to fill out the required fields one by one. You can start with the name of the new session, and then select the target you wish to use, followed by selecting the core from the internal core list. This item is only available when you use the synchronized debugging facility. Select the generator in the **session generator** to use the list. It is possible that there may be multiple generators that support the same target. The last step is to click the **OK** button to launch the generation process. At this point, an additional dialog box may be displayed for target setup options. When finished, a new session is added to the current project. It should be available in the session's drop-down list box on the main toolbar.

- **Removing a session:**

Click on the **debug** tab on the menu bar. In the drop-down menu, click on the **debug sessions** option, and the debug sessions dialog box will open. After that, select the session that you want to remove and then click the **remove** button. Click the **OK** button to close the debug sessions dialog box.

NOTE:

It is not possible to remove the current session.

- **Saving session information:**


You can save the new session by clicking on the **file** tab on the menu bar, and then in the drop down menu click on the **save session** button. If you have checked the **“prompt before saving session”** checkbox, a dialog box is displayed which asks you whether you wish to save the information. To see whether it is checked or not, click on the **settings** tab on the menu bar, then click on the **options** in the drop-down menu (a dialog box will appear), and then click on the **workspace** tab to look for the checked boxes.

- **Operating memory**

This section describes one of the ways to debug your code. A user must know how to look at the memory in the CPU's address space. It would be very useful if a user

knows how to look at the memory area in different formats. This section also discusses ways to fill and move a memory block.

- **Opening the memory window:**

A memory window is a window that shows the contents of contiguous memory areas. To open the window, click on the **view** tab on the menu bar. In the drop-down menu, click on the **CPU**, then on the **memory**; or click the Memory toolbar icon (). A box, as shown in Figure 4.21, will pop up. It is known as the Display address box. In that box, you can specify the **display address**, **scroll start address**, and **scroll end address**.

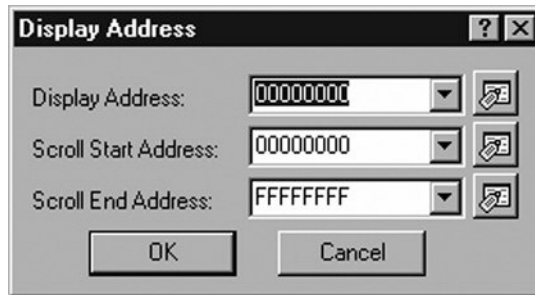


Figure 4.21 Display address box [2], page 378.

Click the **OK** button to launch the memory window. The display can be scrolled up and down. The range can be selected by entering the values of the scroll start and scroll end address fields in the display address box.

- **Window configuration:**

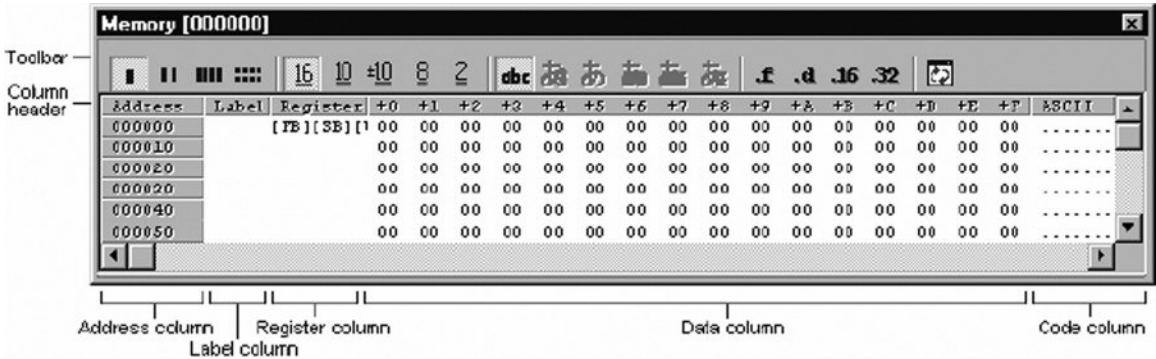


Figure 4.22 Memory window [2], page 378.

The **label** and **register** columns are hidden by default. You can make it visible by customizing the toolbar. The **label column** shows the name of the label allocated to the data on the first memory address displayed on the row. Similarly, the **register column** shows the name of the register allocated to data on the first memory address, displayed on the row. The ‘+*n*’ in the column header of the **data column** defines the offset value from the first address of the row. The header of the **code column** shows the code name. In order to change the first address being displayed, double-click the **address** or **label** column. In order to change the memory data at the selected address, double-click the **data** or **code** column. Changing the values can be recorded in a macro (Macro Recording) to help you remember previous settings. In case the new setting does not go your way, you can then always get back to your initial settings since you have the previous data saved somewhere. Moreover, values in the address, data, and code columns can be changed by in-place editing. You can always customize your toolbar by right-clicking, and when it displays a pop up window you can select from the various options available. For instance, one of the options would be ‘**move**’ which moves a specified memory block. In this feature, macro recording is also available to retain your previous memory block.

- **Setting data at a desired memory address:**

To set data at a memory address, you can do an in-place editing of the code as well as the data column.

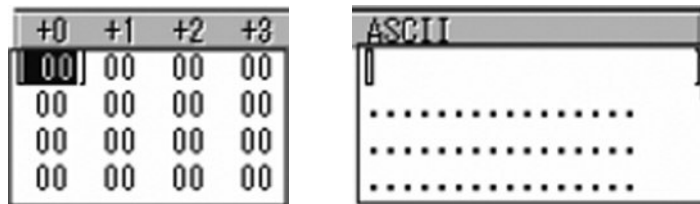


Figure 4.23 Data and Code column [2], page 381.

The first figure in Figure 4.23 shows the **data column** and second figure shows the **code column**. To change the contents of the memory, open a **set** dialog box. This is done as follows:

- a. Double-click the Data column
- b. Double-click the Code column
- c. Select the data you want to change and choose **set** from the pop-up menu



Figure 4.24 Set dialog box [2], page 381.

Fill in the required fields, such as **address** and **data type**. **Value** can be either a numeric value or a character. If you are setting a numeric value, then set **value** as the **data type**. If you are setting a character value, then select **string** as the **data type**. Make sure to select the **verify** check box.

- **Filling an area of memory with constant data:**

HEW provides you with the feature of setting the range of memory addresses with the constant value. For this, you need to select an address range to fill in the memory window. Select **fill** from the pop-up menu of the **memory** window, and then edit the **fill** dialog box.

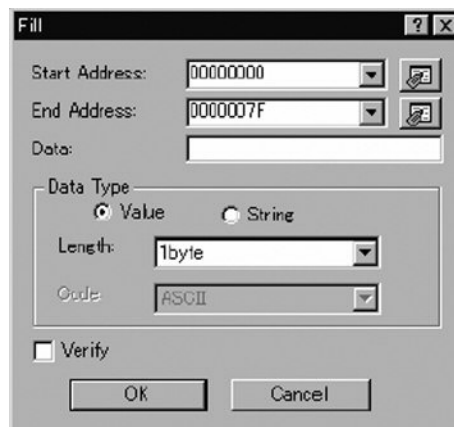


Figure 4.25 Fill dialog box [2], page 382.

You must enter the **start address** and **end address**. The **end address** can also be prefixed by a plus (+): the **end address** will become (**start address**) + (the entered value).

- **Copying an area of memory:**

To copy an area of memory into another area, you can use the memory copy feature provided by HEW. First, select a copy-source address range in the memory window using the mouse. Right click on the memory window and choose ‘**move**’ from the pop-up menu. The **move** dialog box opens as shown in Figure 4.26. Click on the **move address** field pop-up menu and choose the **copy destination address**. Check the **verify** check box. If you choose not to drag the copy-source address range, you have to enter the start and end address. The **end address** can also be prefixed by a plus (+): the **end address** will become the (**start address**) + (the entered value).



Figure 4.26 Move dialog box [2], page 383.

- **Comparing the memory contents:**

To compare the contents of two memory blocks, you can use the memory compare feature provided by HEW. First, select a source address range in the memory window using the mouse. Right click on the memory window and choose ‘**compare**’ from the pop-up menu. The **compare memory** dialog box opens as shown in Figure 4.27. Enter the **start address** of the destination memory area in the **compare address** field and the data length in the **data length** field. Check the **verify** check box. If you miss dragging the copy-source address range by any chance, you can enter the start and end address now. The **end address** can also be prefixed by a plus (+): the **end address** will become the (**start address**) + (the entered value).

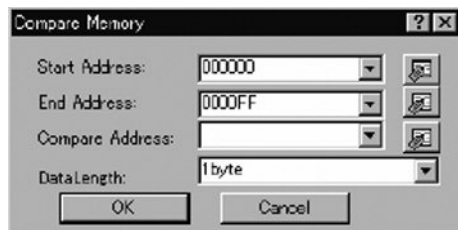


Figure 4.27 Compare memory dialog box [2], page 384.

There exists only two cases, either mismatch or match. In the former case, the address where the mismatch was found is displayed in a message box. In the latter case, the message “**comparison successful**” appears.

- **Saving memory contents in a text file:**

What if you want to edit the contents of some of the memory addresses, and before doing that you want to save those readings? HEW provides you the functionality of saving the memory contents in a text file using the **save memory contents** feature. First, select a source address range in the memory window by dragging the mouse. Right click on the memory window and choose ‘**save memory contents**’ from the pop-up menu. The **save memory contents** dialog box opens as shown in Figure 4.28. Select the output range in the **memory save area field**, length of the data in the **data length field**, number of digits in the **column field** and the radix in the **radix field**. You can also select displaying/hiding the **Label column** and **Register column** by checking the **output the label column** and the **output the register column** fields, respectively. If you did not drag the address range to be saved, you must enter the output range.

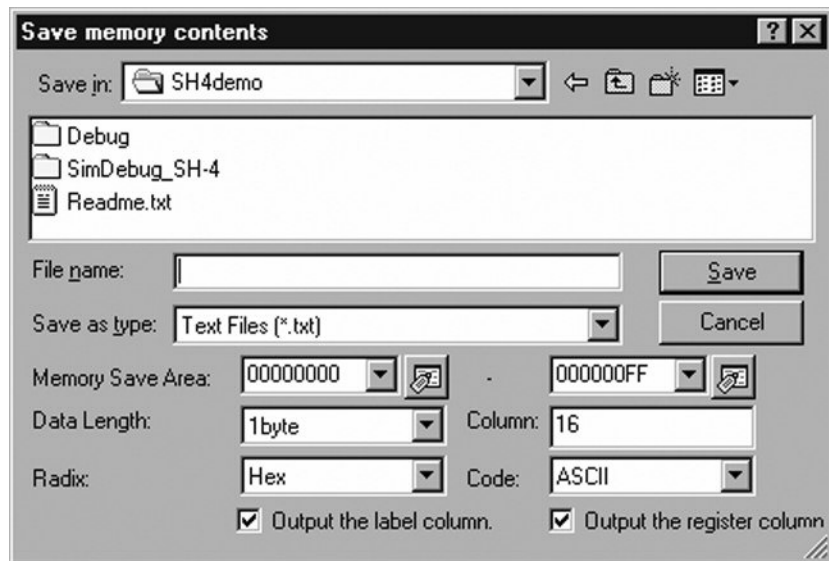


Figure 4.28 Save memory contents dialog box [2], page 385.

- **Looking at I/O memory:**

A microcontroller contains various on-chip peripheral modules. The modules vary according to devices, but some of the common modules are DMA controllers,

serial communications interfaces, A/D converters, integrated timer units, a bus state controller, and a watchdog timer. Accessing registers play a very important role in programming on-chip peripherals. Since the setting up of such on-chip peripheral registers is usually very important in an embedded microcontroller application, it would be very useful if we can look into the values of the registers. As discussed in the previous section, the memory view allows you to look at the data in the memory only as a byte, word, longword, single-precision floating-point, double-precision floating-point, or ASCII values. So the High-performance Embedded Workshop also provides an I/O window to analyze the values inside the registers.

- **Opening the I/O window:**

To open the I/O window, click on the **view** tab on the menu bar. Select **CPU** from the drop down menu. Choose **I/O** to open the window or click the view I/O toolbar button (🔍). Modules that match the on-chip peripheral modules organize the I/O register information. The I/O window has two tabs: **All Register** and **Selected Register**. When the I/O window is first opened, only a list of module names are shown on the **All Register** tabbed pane.

- **Window configuration:**

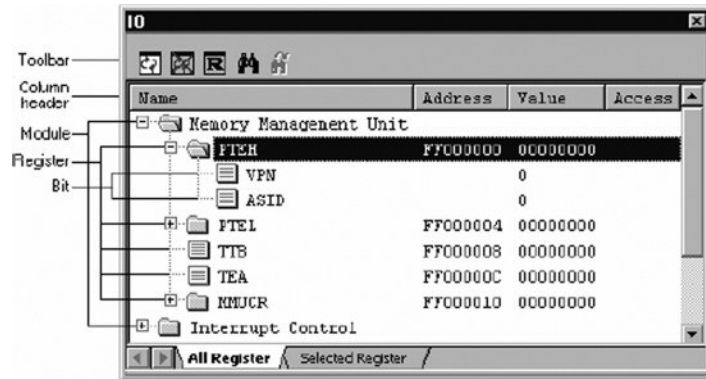


Figure 4.29 Input-output window [2], page 408.

The **All register tab** displays all I/O registers and the selected register tab displays selected I/O registers. By default, this page is blank. I/O registers can be used as and when required. While running the code, if the value of an I/O register is changed, the value is displayed in red. If you need to change the value of a register, then double click on the line of an I/O register. You can even record the value in a macro. In addition, the value can be changed in the **value** column by in-place

editing. HEW provides various options which can be expanded by right-clicking on the I/O window. It will display a pop-up menu containing options such as **refresh**, **load I/O file**, **print**, **toolbar display**, **customize toolbar**, etc. For displaying the names, addresses and values of the I/O registers you can either double-click on the module name or select the module name. To select the module name, click on it or use the cursor keys, and press the right cursor key. The module display will expand to show the individual registers names, addresses, and their values. To close the I/O register display, once again double-click on the module name (or press the left cursor key).

- **Modifying the values of I/O registers:**

To modify the value of an I/O register, select either of the following:
In-place edit in the value column.

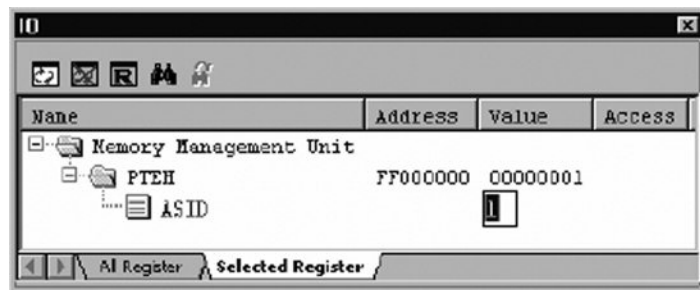


Figure 4.30 Selected register tab of Input-output window [2], page 410.

Double-click on the line of the I/O register or bit to open a dialog box.

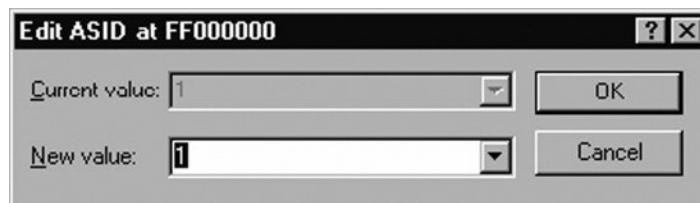


Figure 4.31 Edit dialog box [2], page 410.

- **Selecting the I/O register(s) for viewing:**

First, click on the **select register** tabbed pane of the I/O window. To view the value of the registers, open a pop-up menu by right-clicking within the window. Then select **I/O register**, and a dialog box will open as shown in Figure 4.32.

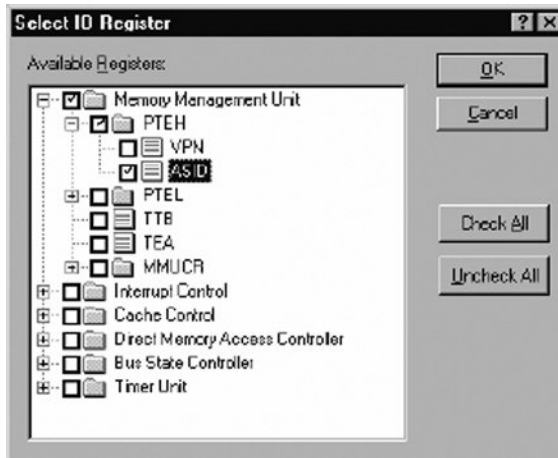


Figure 4.32 Selecting I/O register [2], page 411.

As you can see, there is a checkbox in front of every item; clicking on it selects the specific item. Clicking the ‘+’ sign expands the collapsed item while clicking on ‘-’ collapses the expanded item. If you select the checkbox for an item with ‘+’ or ‘-’ the checkboxes for all of its elements are also selected. Similarly, if you deselect the checkbox for an item, all of its elements are also deselected. You should select the checkboxes for the I/O register(s) you wish to view. After checking the item, click **OK** to close the dialog box. The selected I/O registers are shown on the **select I/O register** tabbed pane of the I/O window.

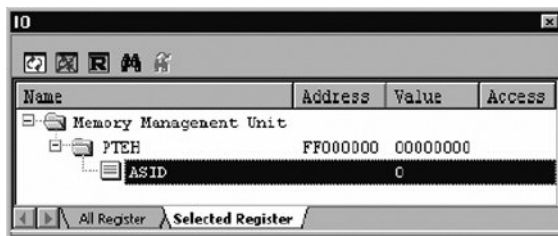


Figure 4.33 Selected register tab of Input-output window [2], page 412.

- **Finding an I/O register:**

Many times you might want to know the value stored in a particular register. In such a case, instead of selecting an I/O register to view, you can try a faster way of directly accessing your desired register. In order to achieve this, right click within the window to open up a pop-up menu. After that select **find** and a dialog box will open as shown in Figure 4.34.

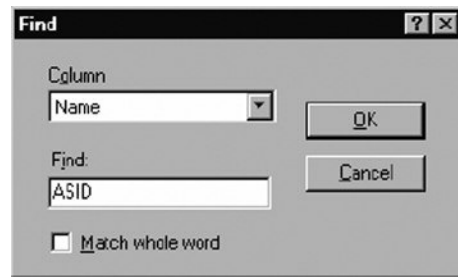


Figure 4.34 Find dialog box [2], page 414.

Fill in the fields one by one in any order you want. Select the **column** of an I/O register: you can select either the address or name of an I/O register. Then in the **find** field, select the string to be found in the selected column. The characters are case-insensitive. You can use the **'match whole word'** feature to completely match the string entered. If you type a more general word and want to see all registers that partially match with the entered string, then do not check the **'match whole word'** box. Finally, click **OK** to start the search from the first line.

4.4.2 The J-Link Debugger

(Source: <http://www.segger.com/cms/jlink.html>.J-Link Debugger)

The debugger used for the RX Family is the J-Link Debugger. J-Link RX supports all RX-CPU's with RX600 core and JTAG interface. The RX630, RX631, and RX63N Groups are compatible with this debugger. The J-Link RX is compatible to the Renesas E1 emulator and works with the Renesas HEW and the IAR Embedded Workbench for RX (EWRX).

Features

- Flash breakpoints are much faster on J-Link than on E1 or E20. J-Link uses different techniques like: Instruction set simulation, use of hardware breakpoints where possible, dynamic conversion of breakpoint types, flash caching, CRC, and others to minimize the amount of times a flash breakpoint is set or removed.
- It supports direct download into flash memory.
- It also supports software breakpoints in flash memory (Flash breakpoints).
- Seamless integration into the Renesas HEW & IAR Embedded Workbench IDE.
- Virtual UART support (C2E support) provided.
- All kinds of events are supported (execution break, data access, trace break, combination/sequence of events).
- USB 2.0 interface provided.
- JTAG speed up to 12 MHz or 25 MHz (depending on the J-Link model).
- No power supply required since it is powered through the USB.
- All JTAG signals can be monitored and the target voltage can be measured.
- Supports multiple devices.
- Wide target voltage range: 1.2 V—3.3 V, 5 V tolerant.
- Target power supply: J-Link can supply up to 300 mA to target with overload protection.

4.4.3 Description of the Header Files Used in the RX Family

1. <config.h>

This is a configuration file for the generic API for graphics LCD glyph; i.e., “**glyph.c**”. It defines macro names used in common in the “**glyph.h**” include file. The macros defined here can be used to select the font size. It includes a header file “**preamble.h**” which defines simple types and constants.

2. <glyph.h>

This is the main header file for glyph API library. The Generic API for Graphics LCD (nicknamed “Glyph”) is a reusable software design to support multiple projects where the LCD size and resolution may change, but the basic feature set will stay consistent. Glyph is a standard library interface for use with any graphic LCD. It uses macros already defined in the header file “**config.h**”. It defines external constants, typedef enumerations, typedef structures, prototype for minimum access, and prototype for full access.

a. Type: External constant

This declares constant values for various font sizes that will be available to all users of glyph API.

Example:

```
extern const uint8_t * FontHelvr10_table [256];
```

FontHelvr10_table is a macro defined in “**config.h**” that signifies the default font size.

b. Type: Typedef definition

The **typedef** keyword defines new types or provides an alternative name to the already existing types.

- 1) The **typedef** allows you to use **t_glyphhandle** as a type rather than using **void***. Now, **t_glyphhandle** can be used to declare a pointer to the type **void**.

Example:

```
typedef void *T_glyphHandle.
```

- 2) The **enum** keyword is used to create an enumerated type that consists of constants that represent error identifiers of the glyph API. Since each subsequent value is incremented by one over the previous constant, the value of **GLYPH_ERROR_ILLEGAL_OPERATION** is 1.

Example:

```
typedef enum {
    GLYPH_ERROR_NONE = 0,
    GLYPH_ERROR_ILLEGAL_OPERATION
} T_glyphError;
```

- 3) The **enum** keyword is used to create enumerated type that consists of constants that represent status values of the glyph API. By default, the first constant in an enumeration is assigned value zero, and each subsequent value is incremented by one over the previous constant. In this particular case, since each constant is given a specific value, each subsequent value is not incremented. Instead, it retains the value that is set in the declaration.

Example:

```
typedef enum {
    GLYPH_STATUS_READY = 0,
    GLYPH_STATUS_BUSY = 2,
    GLYPH_STATUS_FULL = 4
} T_glyphStatusBits;
```

- 4) The **enum** keyword is used to create enumerated type that consists of constants that represent font values of the glyph API. By default, the first

constant in an enumeration is assigned value zero, and each subsequent value is incremented by one over the previous constant.

Example:

```
typedef enum {
    GLYPH_FONT_8_BY_8,
    GLYPH_FONT_8_BY_16,
    GLYPH_FONT_5_BY_7,
    . . . . .
} T_glyphFont;
```

- 5) The **enum** keyword is used to create an enumerated type that consists of constants which define drawing modes of the glyph API. Since each subsequent value is incremented by one over the previous constant, the value of `GLYPH_CMD_ERASE_BLOCK` is 8.

Example:

```
typedef enum {
    GLYPH_CMD_NOP = 0,
    GLYPH_CMD_SCREEN_CLEAR,
    GLYPH_CMD_SCREEN_INVERT,
    GLYPH_CMD_SCREEN_REGULAR,
    . . . . .
} T_glyphDrawMode;
```

- 6) Description: The **enum** keyword is used to create enumerated type that consists of constants that represent the glyph API registers. These are used by **Glyph Read** and **Glyph Write** to specify a function of the glyph API to run.

Example:

```
typedef enum {
    GLYPH_STATUS = 0,
    GLYPH_CHAR_X,
    GLYPH_CHAR_Y,
    . . . . .
    . . . . .
    . . . . .
    GLYPH_CONTRAST,
    GLYPH_CONTRAST_BOOST
} T_glyphRegisters;
```

- 7) A **struct** in C programming language is a collection of elements, in which each element belongs to a different type. The total storage required for a struct object is the sum of the storage requirements of all the elements. This typedef allows you to use **T_glyphVersionInfo** as a type rather than using a struct. Now, **T_glyphVersionInfo** can be used instead of **struct T_glyphVersionInfo** whenever you want to declare a new instance of the structure `struct_glyph_version_info` named `T_glyphVersionInfo`. The structure below contains elements that depict various versions of glyph API structure.

Example:

```
typedef struct_glyph_version_info
{
    uint8_t strVersionAPI [50];
    uint8_t strVersionIMPL [50];
    int32_t nVersionAPIMajor;
    int32_t nVersionAPIMinor;
    int32_t nVersionIMPLMajor;
    int32_t nVersionIMPLMinor;
    int32_t nImplementationID;
} T_glyphVersionInfo;
```

- 8) In future statements, you can use the specifier **T_LCD_API** (instead of the expanded struct `T_LCD_API`) to refer to the structure and create an instance. The structure below contains elements that are used in applications where LCD is required. This is a glyph API LCD structure which is frequently used by the LCD drivers.

Example:

```
typedef struct {
    /* Adding Font-Decal Section */
    const uint8_t ** iFont;
    /* Define Global Variables */
    uint32_t iCharX_Position;
    uint32_t iCharY_Position;
    uint32_t iCharX2_Position;
    uint32_t iCharY2_Position;
    uint32_t iCharFont;
    . . . . .
    . . . . .
    . . . . .
```

```

    T_glyphError (*iWrite)(T_glyphHandle aHandle, uint32_t
    aRegister, uint32_t Value);
} T_LCD_API;

```

- 9) In future statements, you can use the specifier `T_Comm_API` (instead of the expanded struct `T_Comm_API`) to refer to the structure and create an instance. The following structure contains elements that are used in applications where communication needs to be set up. This is a glyph API communication structure which is frequently used by the Communication drivers.

Example:

```

typedef struct {
    T_glyphError (*iOpen)(T_glyphHandle aHandle);
    void (*iCommandSend)(int8_t cCommand);
    void (*iDataSend)(int8_t cData);
} T_Comm_API;

```

- 10) In future statements, you can use the specifier `T_glyphworkspace` (instead of the expanded struct `T_glyphworkspace`) to refer to the structure and create an instance. The following structure contains elements that are used in applications where LCD is required and communication needs to be set up. This is a glyph API workspace structure which is frequently used by Communication and LCD drivers.

Example:

```

typedef struct {
    T_LCD_API *iLCDAPI;
    T_Comm_API *iCommAPI;
} T_glyphWorkspace;

```

c. Type: Function

Glyph API provides you the capability to interact with the graphical LCD. The prototypes defined in the following example are used to access the glyph API library definitions. Its implementation totally depends on the type of application. These prototypes define the functions for minimum and full access of the members of the glyph library.

Examples:

Prototypes for minimum access:

```

T_glyphError GlyphOpen(T_glyphHandle *aHandle, int32_t
    aAddress);

```

```

T_glyphError GlyphClose(T_glyphHandle *aHandle);
T_glyphError GlyphWrite(T_glyphHandle aHandle,
    uint32_t aRegister, uint32_t * aValue);
T_glyphError GlyphRead(T_glyphHandle aHandle,
    uint32_t aRegister, uint32_t *aValue);
Prototypes for full access:
T_glyphError GlyphGetStatus(T_glyphHandle aHandle,
    T_glyphStatusBits *aStatus);
T_glyphError GlyphSetX(T_glyphHandle aHandle, uint32_t aX);
T_glyphError GlyphSetY(T_glyphHandle aHandle, uint32_t aY);
. . . . .
. . . . .
T_glyphError GlyphSetContrastBoost(T_glyphHandle aHandle,
    uint8_t cContrastBoost);

```

3. <preamble.h>

Description: This header file contains basic definitions of all simple constants and types. The purpose of this file is to maintain compatibility between the compilers and hardware. It defines macros which can be used in other header files or in source code of any application.

a. Type: Constant.

```

Example:
#define ON 1
#define OFF 0
#define ENABLE 1
#define DISABLE 0

```

b. Type: Typedef definitions.

In future statements, any variable can be used as a type instead of its pre-existing type. For instance, `Int8_t` can be used as a type instead of a signed `char`.

```

Example:
typedef signed char int8_t;
typedef unsigned char uint8_t;
typedef signed short int16_t;

```

c. Type: Bit definitions.

A bit from b0 to b7 signifies some hexadecimal value as defined in the following example.

```
Example:
#define b0 0x01
#define b4 0x10
#define b7 0x80
```

4. <st7579_lcd.h>

Description: It defines prototypes that are required by the LCD driver in the glyph API. It includes all the definitions of “glyph.h”.

Note: The name of the header file comes from st7579 which is a driver and controller LSI for the graphic dot-matrix liquid crystal display systems. This chip is connected directly to a microprocessor, accepts 3-line serial peripheral interface (SPI) with a four wire independent transmit only, displays data, and can store an on-chip display data RAM of 68×102 bits.

a. Type: Macros

These macros signify function sets, which are used to define the function set call for every command that is sent to the ST7579 Display controller. When setting the display controller to the four different function sets of commands to be sent to the controller, setting the function set also sets the following:

```
MX direction: normal or reverse i [0:1]
MY direction: normal or reverse [0:1]
PD controller active or power down [0:1]
```

If the preprocessor directive #if, is set to 1, then every Function Set call will produce MY set to the reverse direction. This is required for Glyph to work. Otherwise, MY will be set to the normal direction and Glyph will not work. These function sets do not take any arguments and do not return any value.

```
Example:
#if 1
//MY reverse direction
#define LCD_FUNCTION_ZERO 0X28
#define LCD_FUNCTION_ONE 0X29
#define LCD_FUNCTION_TWO 0X2A
#define LCD_FUNCTION_THREE 0X2B
//command sets
#define LCD_DISPLAY_REVERSE 0x280D
```

```

#define LCD_DISPLAY_NORMAL 0x280C
#else
//MY normal direction
#define LCD_FUNCTION_ZERO 0X20
#define LCD_FUNCTION_ONE 0X21
#define LCD_FUNCTION_TWO 0X22
#define LCD_FUNCTION_THREE 0X23
//command sets
#define LCD_DISPLAY_REVERSE 0x200D
#define LCD_DISPLAY_NORMAL 0x200C
#endif

```

b. Type: Functions

- 1) The prototypes defined in the following example are used to access “glyph LCD API” library definitions.

Example:

```

T_glyphError ST7579_Open(T_glyphHandle aHandle,
    uint32_t aAddress);
T_glyphError ST7579_Close(T_glyphHandle aHandle);
T_glyphError ST7579_Write(T_glyphHandle aHandle,
    uint32_t aRegister, uint32_t aValue);
T_glyphError ST7579_Read(T_glyphHandle aHandle,
    uint32_t aRegister, uint32_t *aValue);

```

- 2) The prototypes defined in following example are used to access “LCD API” library definitions.

Example:

```

void ST7579_Config(T_glyphHandle aHandle);
void ST7579_SetSystemBiasBooster(T_glyphHandle aHandle,
    int8_t c Value 0 To 17);
void ST7579_SetVO_Range(T_glyphHandle aHandle,
    int32_t n Value 0 to 254);

```

5. <r_glyph.h>

Description: This header file defines prototypes for the glyph communication API.

Example:

```
T_glyphError R_GLYPH_Open(T_glyphHandle aHandle);  
void R_GLYPH_CommandSend(int8_t c_command);  
void R_GLYPH_DataSend(int8_t c_data);
```

6. <typedefine.h>

Description: In further statements, any variable can be used as a type instead of its pre-existing type. For instance, `_SBYTE` can be used as a type instead of signed char. Here, an underscore before the variable name `SBYTE` signifies that it is a global variable.

Example:

```
typedef signed char _SBYTE;  
typedef unsigned char _UBYTE;  
typedef signed short _SWORD;
```

7. <sbrk.h>

Description: This is a header file for `sbrk.c`. It defines a macro that signifies the size of the area managed by `sbrk`.

Example:

```
#define HEAPSIZE 0x400
```

8. <vect.h>

Description: This header file defines various vectors. The vector list is basically a list which indicates where the ISRs (interrupt subroutines) are located in memory. Each entry in the list is called a vector. Vector signifies the 4-byte address of each ISR. Some of the vectors are reserved—like vector 16 is reserved by an interrupt `Excep_BUSERR`; i.e., the ISR to be called when exception happens during a bus error; and the rest of them are free to be occupied. Vector table starts with the vectors that refer to the fixed interrupts. These vectors cannot be changed since they point to ISRs at hardware-defined addresses such as undefined instruction, supervisor instruction, floating point, NMI, Dummy, or BRK. Then comes the variable vectors that point to ISRs at user-definable vectors.

Example:

```
Fixed interrupts:
//Exception(Supervisor Instruction)
#pragma interrupt (Excep_SuperVisorInst)
void Excep_SuperVisorInst(void);
//Exception(Undefined Instruction)
#pragma interrupt (Excep_UndefinedInst)
Variable Interrupts:
#pragma interrupt (Excep_BUSERR(vect = 16))
void Excep_BUSERR(void);
//vector 17 reserved
//vector 18 reserved
//vector 19 reserved
//vector 20 reserved
//FCU_FCUERR
#pragma interrupt (Excep_FCU_FCUERR(vect = 21))
void Excep_FCU_FCUERR(void);
//vector 22 reserved
```

9. <stackset.h>

Description: This header file defines macros that refer to the setting of the stack area.

Example:

```
#pragma stacksize su = 0x300
#pragma stacksize si = 0x100
```

10. <iodefne.h>

Description: This header file uses numerous macros, about 117 structures and seven enumerations to define the various input and output registers.

Example:

a. Macros:

```
#pragma bit_order left
#pragma unpack
#define SYSTEM (*(volatile struct st_system
    __evenaccess *)0x80000)
#define BSC (*(volatile struct st_bsc __evenaccess *)0x81300)
#define IEN_FCU_FIFERR IEN5
#define IEN_FCU_FRDYI IEN7
```

b. Structure:

The structure below defines various input and output registers that are used in analog to digital conversion. Within the structure, a union is being used to declare variables of different types. It is the same as structure, except that instead of struct you write union. Also, in union you can only store information in one field at any one time. Technically, it can be seen as a chunk of memory that is used to store variables of different types. Once a new value is assigned to a field, the existing data is wiped over and rewritten with the new data.

Example:

```
struct st_da {
    unsigned short DADR0;
    unsigned short DADR1;
    union {
        unsigned char BYTE;
        struct {
            unsigned char DAOE1:1;
            unsigned char DAOE0:1;
            unsigned char DAE:1;
        } BIT;
    } DACR;
    union {
        unsigned char BYTE;
        struct {
            unsigned char DPSEL:1;
        } BIT;
    } DADPR;
    union {
        unsigned char BYTE;
        struct {
            unsigned char DAADST:1;
        } BIT;
    } DAADSCR;
};
```

In this example, the structure **st_da** contains four members; namely DADR0, DADR1, union DACR, union DADPR, and a union DAADSCR. This is an example of nested unions. Union DACR has two members. BYTE and structure BIT. The BIT member is a structure with three bit-field members, DAOE1, DAOE0, and DAE, all of them are of type unsigned char. Member BYTE is of type unsigned char. Union DADPR has two members, BYTE and structure BIT.

The BIT member is a structure with one bit-field member, DPSEL of type unsigned char. Member BYTE is of type unsigned char. Union DAADSCR has two members, BYTE and structure BIT. The BIT member is a structure with one bit-field member DAADST of type unsigned char. Member BYTE is of type unsigned char. At any given time, each union element holds either the unsigned char represented by BYTE or the structure represented by BIT. The other two variables of st_da are of type unsigned char. Table 4.6 provides an explanation of the terms that were used in the previous example.

TABLE 4.6 Register Description.

ADDRESS	NUMBER OF BITS	MODULE-ABBREVIATION	REGISTER NAME	REGISTER ABBREVIATION
0008 80C0h	16	D/A	D/A data register 0	DADRO
0008 80C2h	16	D/A	D/A data register 1	DADR1
0008 80C4h	8	D/A	D/A control register	DACR
0008 80C5h	8	D/A	D/A data placement register	DADPR

c. Enumerations:

These are used to define various ICU registers.

- 1) Usage of some specific registers such as IR_n (interrupt request register n), DTCE_n (DTC activation enable register n), IER_m (interrupt request enable register m), and IPR_n (Interrupt source priority register n) follows. The bit access operation is “bit name (interrupt source, name)”. A part of the interrupt source can be omitted.

Example:

```
IR(TPU0, TGI0A) = 0;
DTCE(ICU, IRQ0) = 1;
IEN(CMT0, CMI0) = 1;
IPR(TPU0, TGI0A) = 2;
IPR(TPU0, TGI ) = 2; //TGI0A, TGI0B, TGI0C, TGI0D share IPR
level.
IPR(SCI0, RXI0) = 3;
IPR(SCI0, ) = 3; //SCI0 uses single IPR for all sources.
```

- 2) Usage of the interrupts listed in vector table:

#pragma interrupt Function_Identifier (vect = **).The number of vector is “(interrupt source, name)”.

Example:

```
#pragma interrupt INT_MTU0_TGIA0 (vect = VECT(MTU0, TGIA0))
#pragma interrupt INT_IRQ0 (vect = VECT(ICU, IRQ0))
#pragma interrupt INT_CMT0_CMI0 (vect = VECT(CMT0, CMI0))
```

- 3) Usage of some specific system registers such as MSTPCRA (Module stop control register A), MSTPCRB (Module stop control register B), MSTPCRC (Module stop control register C), and MSTPCRD (Module stop control register D) is given as follows: The bit access operation is “MSTP (name)”. The name that can be used is a macro name defined with “iodefine.h”.

Example:


```
MSTP (TMR2) = 0; //TMR2, TMR3, TMR23
MSTP (SCI0) = 0; //SCI0, SMCI0
MSTP (MTU4) = 0; //MTU, MTU0, MTU1, MTU2, MTU3, MTU4, MTU5
MSTP (TPU4) = 0; //TPU0, TPU1, TPU2, TPU3, TPU4, TPU5
MSTP (CMT3) = 0; //CMT2, CMT3
```

4.5 ADVANCED EXAMPLES

(Source: *HEW User Manual V.4.09.*)

EXAMPLE 1

This example demonstrates how to look at the contents of the CPU’s general registers.

To view the contents, first open the register window. For this, click on the **view** tab on the menu bar, and in the popup menu select **CPU** from the drop down menu. Choose **register** to open the window or click on the registers toolbar button (). The Register window gives the status of current register and flag data. You can even modify the register/flag value from the window.

Window Configuration

Double-clicking the register display line opens a dialog box, which allows you to change a register value. Everything can be recorded by macro recording. This is helpful in a case where you want to get back to older values. The easy way to change the register’s contents is by using in-place editing. Also, you can change a flag value by clicking the button corresponding to the flag. If you right click on the window, you can change the display radix point and the register bank.

Name	Value
R0	00001700
R1	FFFFFF03F
R2	00000000
R3	00000000
R4	00000000
R5	00000000
R6	00000000
R7	00000000
R8	00000000
R9	00000000
R10	00000000
R11	00000000
R12	00000000
R13	00000000
R14	00000000
R15	00000000
USP	00001700
ISP	00001804
PSW	0000000000100110000
PC	FFFFFF8567
INTB	FFFFFF8154
BFSW	80000000
BFC	00000000
FINTV	00000000
FESW	00000100
ACC	0000000000000000

Figure 4.35 Register window.

Changing the Register Display Radix

To change the display radix, right click the mouse on the register to be changed and select **display radix** from the pop-up menu. You can select one of the four radix options shown in Table 4.7.

Setting the Layout

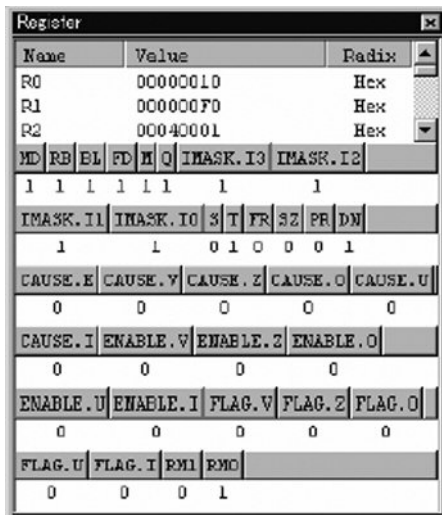
To change the layout of the register window, choose **layout** from the pop-up menu. The following settings are displayed:

Radix: It Switches display or non-display of the radix.

TABLE 4.7 Display Radix Point and the Register Bank Options [2], page 415.

MENU OPTION	FUNCTION
Radix: Hex	Displays in hexadecimal
Radix: Dec	Displays in Decimal
Radix: Oct	Displays in Octal
Radix: Bin	Displays in Binary
Layout: Radix	Switches display or non-display of radix
Layout: FLAGs	Switches display or non-display of flags display area
Layout: Settings	Chooses a register to be displayed
Edit	Changes a register's contents
Refresh	Refreshes the Register window
Lock Refresh	Disables refresh of the Register window
Split	Splits up the window display
Save To File	Saves register contents in a text file

Flags: It Switches display or non-display of the flags display area.

**Figure 4.36** Displays the radix and flags [2], page 417.

Choosing a Register to be Displayed

Figure 4.37 shows the dialog box which is displayed when you choose the **settings** tab from the **register** pop-up menu. In this way you can choose a register to be displayed in the Register window.

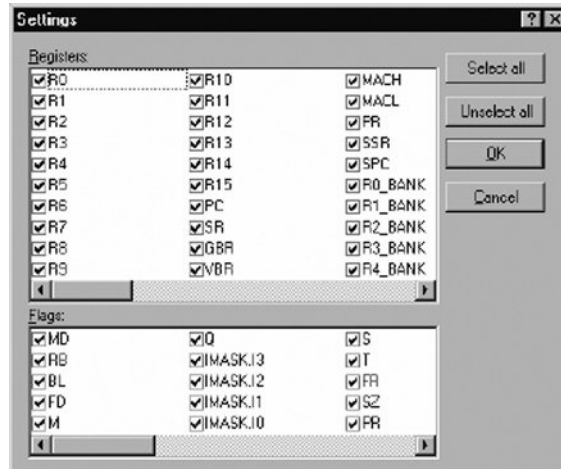


Figure 4.37 Settings dialog box to select register to be displayed [2], page 418.

Modifying the Register Contents

To change the register contents, enter a value in the **value** field of the register as shown in Figure 4.38.

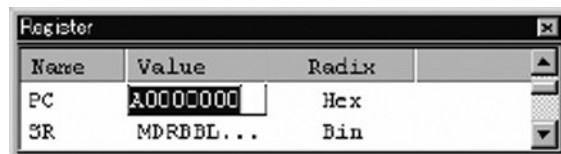


Figure 4.38 In place modification of register value [2], page 418.

To change a register's contents, open the **Set Value** dialog box as described in the following and select one of the operations:

1. Double-click the register to be changed.
2. Select the register and choose the Edit option from the pop-up menu.

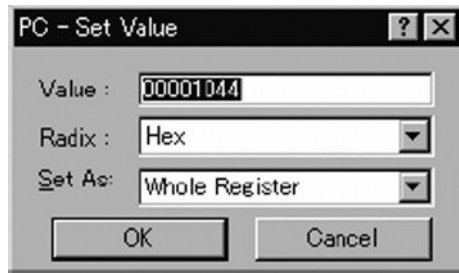


Figure 4.39 Set value dialog box [2], page 418.

Setting the Flag Value

When the flag itself is displayed, click the flag which you want to change. Every time a flag is clicked, the flag status switches from either 1 to 0 or 0 to 1. If a flag is composed of multiple bits, then a dialog box will open, where you can enter a value.

Screenshot:



Figure 4.40 Flag status [2], page 419.

When the flag is displayed in the register, double-click the FLG line. A dialog box will open and then you can enter the value to be changed.

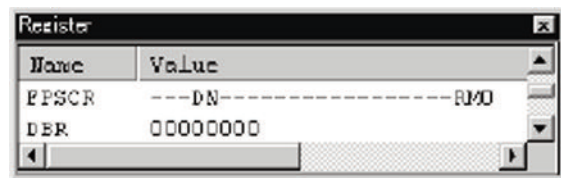


Figure 4.41 Debugger (FLG line (FPSCR)) [2], page 419.

Saving Register Contents

To save the register contents in a text file, choose **Save to file** from the register pop-up menu. The **Save As** dialog box will open, which allows you to specify the file name.

EXAMPLE 2

Displaying memory contents as waveforms.

NOTE:

Support for this function depends on the debugger.

To analyze the data that has just been saved into the memory, creating a waveform could be a very good option. It gives insight into how your code is responding to the application that you are making. For creating a waveform, first you need to open the **waveform properties** dialog box. Click on the **view** tab on the menu bar, select **graphics**, and then **waveform** to get the **waveform** window. The other way is to just click on the waveform toolbar button (📄).

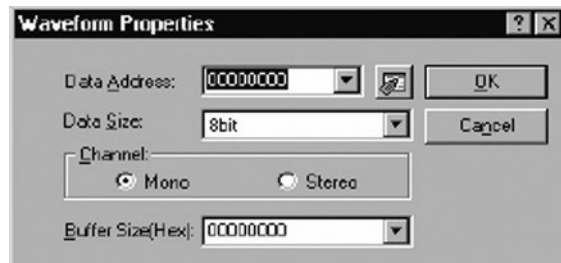


Figure 4.42 Waveform properties dialog box [2], page 404.

You need to fill in the properties before going any further. For **data address** property, you need to specify the start address of the data in memory. It should be displayed in hexadecimal. **Data size** property signifies the size of the data, which can be either 8 bit or 16 bit. Two types of channels are supported: **mono** and **stereo**. Select **buffer size** to specify the buffer size of the data in hexadecimals. Now click the **OK** button to open the **waveform** window. You can change the display contents later by right clicking the window and choosing **properties** from the pop-up menu. In the pop-up menu, some of the other fields are zoom in, zoom out, zoom magnification, scaling, refresh now, etc.

Figure 4.43 shows the display of the memory contents as a waveform. The X-coordinate refers to the number of sampling data and the Y-coordinate refers to the sampling value.

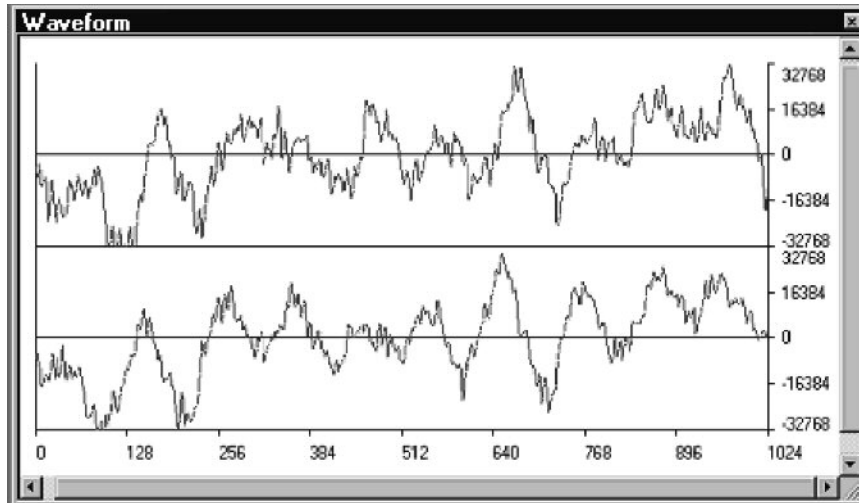


Figure 4.43 Memory contents as waveform [2], page 404.

If you double-click the coordinate where you wish to view the sampling information, the **sample information** dialog box appears. For refreshing the window, there is a function called **auto refresh**, available in the pop-up menu. Selecting **auto refresh** and then **non refresh** will not refresh the window. Selecting **auto refresh** and then **stop** from the pop-up menu will allow the window contents to be automatically refreshed. Selecting **auto refresh** and then **real time** from the pop-up menu will allow the window contents to be refreshed while the user program is running. To specify the refresh interval, select **update interval** from the pop-up menu. This item can be selected only when it is supported by the debugger.

4.6 REFERENCES

- [1] Renesas Electronics, Inc., *RX63N Group, Renesas Starter Kit+ for RX63N Quick Start Guide, Rev 1.00*, July 2012.
- [2] Renesas Electronics, Inc., *RX63N Group, High-performance Embedded Workshop V.4.09 User's Manual, Rev 1.00*, February 2011.
- [3] Renesas Electronics, Inc., *RX63N Group, RX63N Group, RX Family C/C++ Compiler Package V.1.01 User's Manual, Rev 1.00*, February 2012.

4.7 EXERCISES

1. What is the difference between compilers used for embedded systems and compilers used for desktops PCs?
2. How does the linker differ from the compiler?
3. Other than macro definition, for what purpose can the “#define” identifier can be used?
4. What are the various phases of the building process in HEW?
5. Where in HEW debugger options are saved and why?
6. Can all debuggers display the contents of the memory as a waveform?
7. For what purpose is synchronized debugging used?
8. We have an integer array called x . All the numbers from 1 to 100 appear exactly once in x but the numbers are not sorted (e.g., the order can be $x[100] = \{2; 10; 3; 8; 9; 4; 97; 94; \dots \dots \dots 37; 99\}$). Due to alpha particles destroying a particular entry in x , a number is missing and is read as 0 when accessed. Use less than ten lines of C code (one statement per line) to find the missing number (not the index) and put it in an integer variable called `missing`. Don't forget to include proper documentation suggested in coding guidelines (comments, header, etc.).

(Hint: consider the current $\sum_{i=0}^{99} x[i]$ and what the uncorrupted value of $\sum_{i=0}^{99} x[i]$ would be).

9. What is the one thing that all of our code should have?
10. Which header file defines prototypes for the glyph communication API?
11. Which header file is mandatory to include in source code if your code uses an Interrupt Subroutine?
12. What numbers will be printed from running the code below?

```
int i, sum;
sum = 0;
i = 0;
for(i = N; i < 100; i++)
{
    if((i % 2))
        sum += i;
}
```

13. Consider the code below. The first printf statement below prints “1C3F”. What is printed by the second printf?

```
union {
    int w;
    char b [2];
}x;
x.w = 0x1C3F;
printf("%X \n", x.w);
x.b [1] = 0xA6;
printf("%X \n", x.w);
```

14. In C, why is the term *volatile* applied to a variable?
15. For our processor and compiler, does the stack grow toward larger or smaller addresses?
16. For our processor and compiler,
- How many bytes are required to represent the data type: char?
 - How many bytes are required to represent the data type: int?
 - How many bytes are required to represent the data type: short?
 - How many bytes are required to represent the data type: long?
 - How many bytes are required to represent the data type: float?
17. A C source program is converted into an executable file with the help of what tool?
18. What is a header file?
19. State the difference between the following two #include directives:

```
#include <"Config.h">
#include <Config.h>
```


Software Engineering for Embedded Systems

5.1 LEARNING OBJECTIVES

We have tremendous flexibility when creating software; we make many decisions going from an idea to a final working system. There are **technical decisions**, such as which components we use to build a system, their internal structure, and how we interconnect them. Some of the technical decisions will lead to a product that works, but not all will. There are also **process decisions**, such as how we plan to build the system and how to select those components. Similarly, some process decisions can lead to an easier or more predictable development effort, while others will lead to project delays or cancellation, or can even bankrupt the company. A good software process will evolve over time, incorporating lessons learned from each project's successes and failures. Hence a good process will make it easier to do the technical work. The goal of this chapter is to show how both **process** and **technical** issues need to be considered to successfully create a product on time and on budget.

In this chapter we try to present just the most critical concepts to help the reader understand that “does the code work?” is **one question**, but **not the only question** to answer. There are many excellent books and articles which go into great depth on software engineering for embedded and general purpose software; a few are listed in the references section. For example, Jack Ganssle has a “top ten list” of why embedded systems projects get into trouble [1]. In this chapter we discuss how a good software engineering process addresses eight of them. Philip Koopman presents a detailed and practical book on embedded software development processes and issues [2]. We will refer the reader to specific chapters in the latter text periodically in order to keep this chapter short and readable.

5.2 INTRODUCTION

5.2.1 Risk Reduction

Reducing risks is a driving force behind software engineering and project management. A software development organization can benefit by constantly refining its processes as it learns both what it does well, and how to improve what it does poorly.

Developing embedded software is usually **unpredictable**. For example:

- What if there is a bug in our code? What if the compiler sometimes seems to generate buggy code?
- What if the code we need to write actually turns out to be a lot more complex than we thought?
- What if we don't have enough memory for our program or its data? What if the processor can't run our code fast enough?
- What if activating a motor resets the processor due to a weak power supply?
- What if that external A/D converter peripheral doesn't seem to work the way the datasheet said it would?
- What if the lead developer wins the lottery and quits a month before the product deadline?
- What if the new developer we hired turns out to be incompetent, lazy, or both?
- What if half of our development team gets sick, is laid off, or is reassigned?
- What if the customer adds new requirements every week, or wants the product done two months early?

If any of these risks actually occur they will increase the amount of development work needed. Whether it affects the product development deadlines depends on how much overtime the development team is willing to put in, whether other developers can help out, whether anything in the development process turns out to be faster than expected, and so forth. Missing deadlines will have negative financial impacts: project costs will increase and income from product sales will be delayed. Some of these risks also have other impacts: higher power consumption, fewer features, board redesign, and so forth.

Ganssle identifies “Unrealistic Schedules” as the number one reason for embedded system project problems [1]. Successful software organizations create a **development plan** for the project to show development tasks and output products, as well as risk management approaches [2], Chapters 2–4.

5.3 SOFTWARE DEVELOPMENT STAGES

5.3.1 Development Lifecycle Overview

The embedded product lifecycle has multiple steps, as shown in Figure 5.1.

The software process consists of multiple steps within the embedded product lifecycle. One example process model is the V model, shown in Figure 5.2. It consists of:

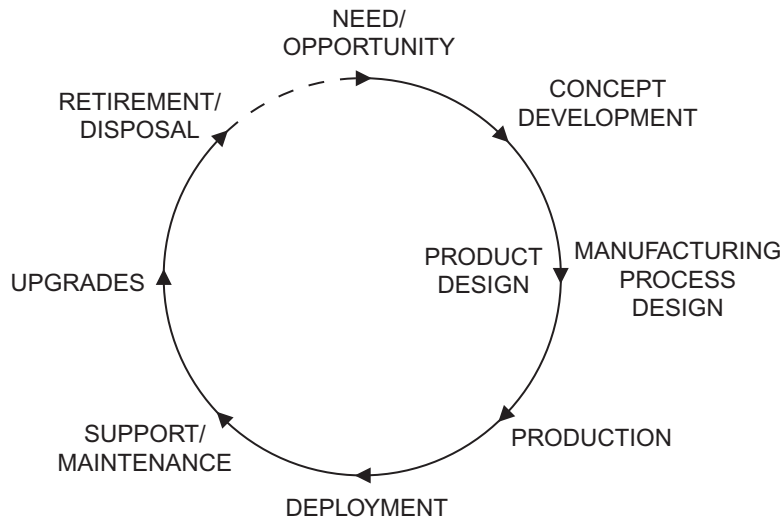


Figure 5.1 The embedded product lifecycle [2].

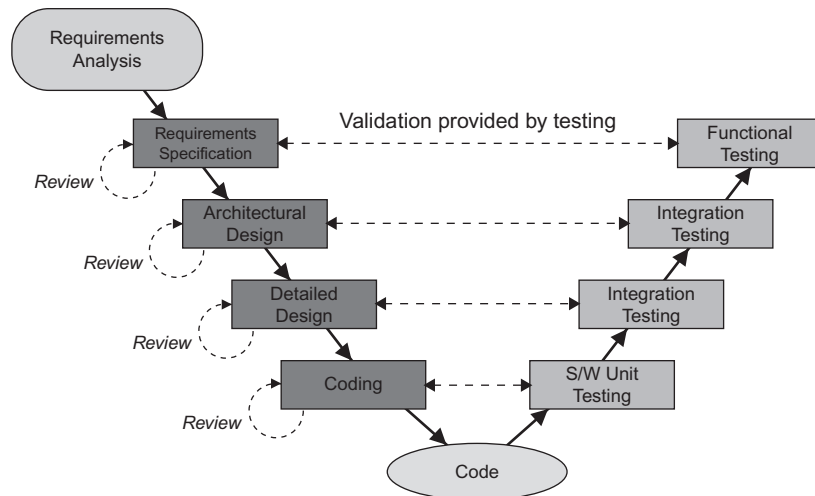


Figure 5.2 The “V” model of software development emphasizes testing at each level of design detail.

- Defining system requirements.
- Creating an architectural or high-level design, deciding on the general approach to build the system, and then creating appropriate hardware and software architectures.

- Creating detailed designs.
- Implementing code and performing unit testing.
- Integrating the code components and performing integration testing.
- Changing the code after “completion” to fit custom deployment requirements, fix bugs, add features, etc.

The process breaks a problem into smaller easier problems through the process of **top-down design** or **decomposition**. Each small problem is solved and the solutions are combined into a software solution. There are many approaches possible:

- Do we design everything up front, and then code it? This is called a **big up-front design**.
- Do we have a prototype or a previous version which we can build upon?
- Do we design and build a little at a time?
- What do we work on first, the easy or the hard parts?

Which model we should use depends on the types and severity of risks. Some industries may be required to follow a specific development process in order for the product to receive certification. Ganssle identifies “Poorly Defined Process” as reason number six for embedded system project troubles [1].

In this chapter we will use an example embedded system to illustrate the issues involved. Our target system is an electronic chartplotter for boats. The chartplotter can display a depth chart on a graphical LCD with an icon superimposed to show the boat’s current position and direction, as shown in Figure 5.3. This helps the user steer the boat to avoid shallow water. Alternatively, we may choose to have a numerical display and omit the chart, as shown

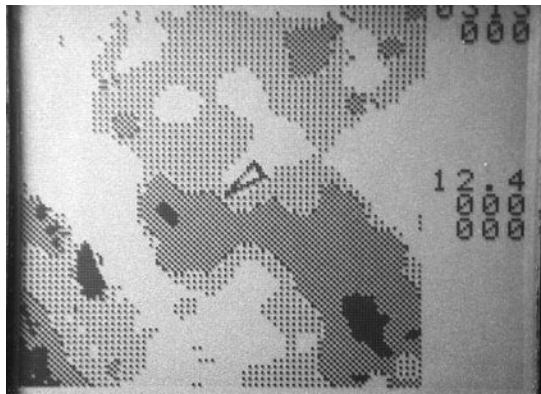


Figure 5.3 Chartplotter screen with boat icon overlaid on depth chart.

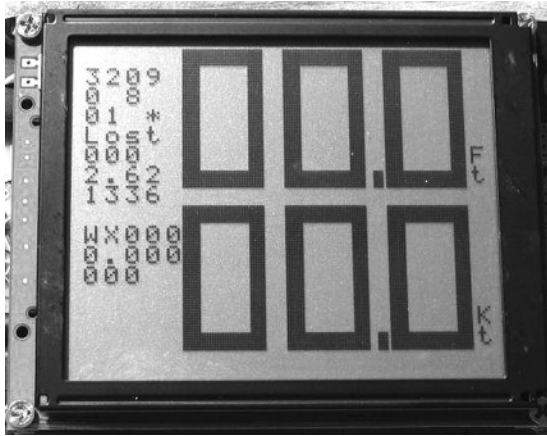


Figure 5.4 Chartplotter screen with numerical depth and speed information.

in Figure 5.4. The chartplotter receives position, direction, and speed information from a GPS receiver, and depth and battery voltage information from a depth sounder.

Later in this chapter we discuss various development models. At this point, it is sufficient to understand that there are different ways to “slice and dice” the work to be done, keeping in mind that we should develop each sub-system in the order: **architect-design-implement**. For example, don’t start writing code if you haven’t designed the algorithm yet. This sequencing is quite important, so we discuss it further.

5.3.2 Requirements

A system design begins with functional requirements. Ganssle identifies “Vague Requirements” as reason number five for projects getting into trouble [1]. Koopman presents an excellent discussion of software requirements so we will just present a high-level view here [2], Chapters 5–9.

- Requirements should be **written down**. This helps everyone have the same picture of what needs to be accomplished, and makes omissions easier to spot.
- There are three types of requirements. **Functional** requirements define what the system needs to do. **Nonfunctional** requirements describe emergent system behaviors such as response time, reliability, and energy efficiency. **Constraints** define the limits on the system design, such as cost and implementation choices.
- There are multiple ways to **express requirements**, both in text and graphically. The most appropriate and convenient method should be used. Graphical methods

such as state charts, flow charts, and message sequence charts should be used whenever possible because (1) they concisely convey the necessary information and (2) they often can be used as design documents.

- Requirements should be **traceable to tests**. How will the system be tested to ensure that a requirement is met? Requirements should be quantified and measurable.
- The requirements should be **stable**. Frequent changes to requirements (“churn”) often have side effects and disrupt the ideal prioritization of work tasks. It is easy for the latest changed requirement to be interpreted as the most important requirement, when in fact this is rarely the case.

5.3.3 Design Before Coding

One of the most effective ways to reduce risks in developing software is to **design before writing code**.¹ Ganssle identifies “Starting Coding Too Soon” as reason number nine for projects getting into trouble [1]. We refer to high-level design as the architecture, and the low-level design as the detailed design.

- **Writing code locks you in to specific implementations** of an algorithm, data structure, object, interface method, and so forth. If this happens before you understand the rest of the system, then you probably haven’t made the best possible choice, and may end up having to make major changes to the code you’ve written, or maybe even throw it away.
- Designing the system before coding also gives you an **early insight** into what parts are needed, and which ones are likely to be complex. This helps prevent the surprises which slow down development. One of the best ways of reducing schedule risk is to understand the system in depth before creating a schedule, and then add in extra time buffers for dealing with the risky parts. **Estimation** is the process of predicting how long it will take to create the system.
- Designs should include graphical documents such as flowcharts and state machines when possible. The goal is to have a **small and concise set of documents** which define how the system should do its work. Graphical representations are easier to understand than code because they abstract away many implementation details, leaving just the relevant items.² This makes it easy for others to understand your design and identify risks. It also helps bring new hires up to speed on the project and reduces the chances they’ll break something when they start maintaining or enhancing the code.

¹ There is related prior work in carpentry: Think thrice, measure twice, cut once.

² Different businesses may have differing levels of formality (e.g., UML), but do not underestimate the benefit of a simple diagram (whether hand-written or created in Visio).

5.3.4 Peer Reviews of Design Artifacts

It is very helpful to have other team members review artifacts before proceeding to the next phase of development. First, having another perspective on an issue brings in greater experience and helps detect oversights. Ganssle identifies “Bad Science” as reason number seven for projects getting into trouble [1]. Second, if you know that someone else will be reviewing what you are creating, you are likely to be more careful and professional. Peer reviews should be applied to all development artifacts: **requirements, test plans, architecture, detailed designs, and code.** We refer the reader elsewhere for more details on peer reviews [2].

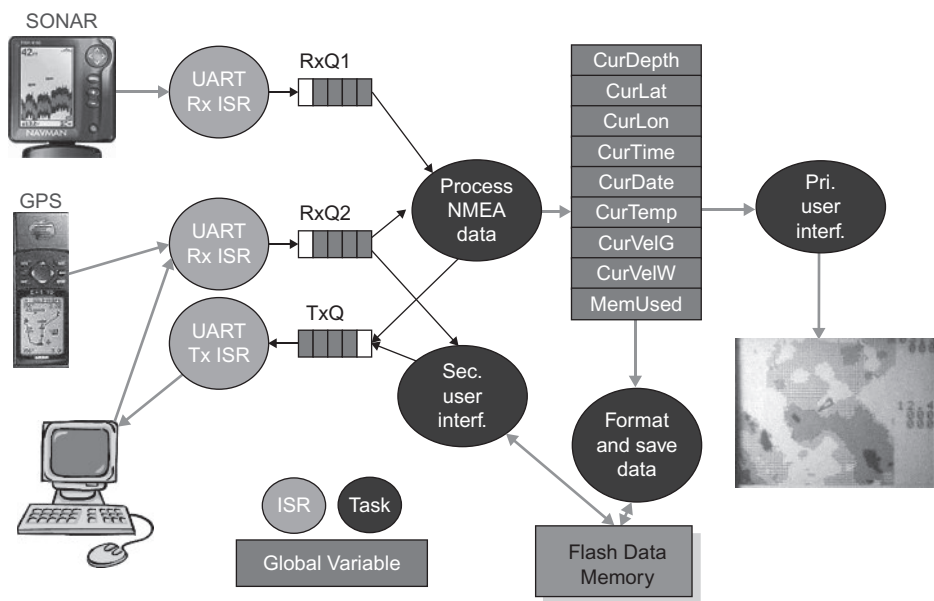


Figure 5.5 System architecture for chartplotter.

5.3.5 System Architecture and Design Approach

The system architecture defines your approach to building the system. What pieces are there, and how are they connected? What type of microcontroller and peripherals will be used? What major pieces of software will there be? How do they communicate? What will make them run at the right time? We present a summary of architectural concepts here, and encourage the reader to dig deeper in the referenced text [2], Chapter 10 and 11.

In Figure 5.5 we see the system architecture for the chartplotter. Sonar and GPS information is delivered through two serial ports to the system. We will use interrupt service

routines and queues to buffer the data between the serial ports and the main application task code. There are four separate tasks in the system:

- The Process NMEA Data task will receive the data from the sonar and GPS, decode it, and update the relevant variables which indicate current depth, position, and so forth.
- The Primary User Interface task will update the display.
- The Format and Save Data task will convert the depth and other variables into a human-readable text format and write them to flash memory.
- The Secondary User Interface task will provide a serial console interface so we can read the logged data from flash memory, erase it, and perform other system maintenance functions.

We also see how information is shared between tasks in the system:

- Queues buffer the incoming and outgoing serial data.
- A table of global variables is written by Process NMEA Data and read by two other tasks.

How does this architecture meet the most critical aspects of the requirements? These may be related to time, safety, robustness, or something else which is application-specific. In any case it is important to convey these concepts.

Time-Critical Processing

It is quite helpful to have a section in the architecture document which describes **which processing is time-critical**, and **how the system is architected** to ensure the timing requirements are met. For example, consider a light dimmer controller:

The system must switch power outputs within 50 microseconds of a zero-crossing of the AC power line. Failure to switching within this time will lead to electrical noise and interference with other devices. The system is designed so that a hardware analog window comparator detects zero crossings and triggers a non-maskable interrupt. All power output switching is performed by the ISR, which controls its outputs based on flags set by the main code which indicates which outputs to enable. Hence interrupts must not be disabled for longer than x microseconds.

The system must shut down within 10 ms of an overcurrent or overvoltage condition occurring. Failure to shut down within this time can lead to equipment damage and failure. We plan to use a periodic interrupt running at 1 kHz in order to sample dedicated analog hardware comparators which detect these conditions. Because of the 1 kHz interrupt rate, interrupts must not be disabled for longer than 8 ms, in order to allow a 1 ms safety margin.

Further information on real-time system design is available in the referenced text [2], Chapter 14.

Safety-Critical Processing

It is quite helpful to have a section in the architecture document which describes **which processing is safety-critical** and **how the system is architected**, to ensure the safety requirements are met. For example:

The software tasks X, Y, and Z are safety-critical. They cannot be modified without triggering recertification. In order to ensure real-time performance, we use a preemptive scheduler and assign X, Y, and Z priorities higher than all other tasks. In order to minimize the chances of data corruption, all critical variables used by X, Y and Z are protected by storing them with complements or with a block CRC.

Again, there is further detailed information in the referenced text [2], Chapters 26–30.

5.3.6 Detailed Design

After we have decided upon an architecture for the system, we can work on designing the subsystems within it. Again, graphical representations can be quite useful; especially if the corresponding requirements are graphical, as in this and similar cases they can be reused.

For example, state-based system behavior is best presented graphically. Figure 5.6 shows a finite state machine design for a UART Receive data ISR (the two circles labeled “UART Rx ISR” in Figure 5.5) which recognizes certain valid NMEA-0183 messages and enqueues them for later decoding. Corrupted or unneeded messages are discarded, saving buffer space in RAM and processor time. These messages have a specific format which includes the talker type (GPS, depth sounder, etc.), the message type, multiple data fields (often with each followed by engineering units), and a checksum for error detection.

We use an FSM-plus-ISR combination for two reasons. First, we want to minimize the amount of time spent in the ISR. Structuring the problem as an FSM allows us to write code which doesn’t waste any time waiting for things to happen. The ISR is only executed when the UART has received a byte of data. Second, parsing data such as text is a good match for FSMs as it allows us to define rules to step through the different fields in a message and validate them.

Figure 5.7 shows a flowchart design for the task “Process NMEA Data” which decodes these enqueued messages and acts on the data. This code is much less time-critical, so it is implemented in a task which the scheduler runs after being notified that the RxQ holds at least one valid message. The flowchart emphasizes the consecutive and conditional processing nature of the activity: decode the message, check to see if it is valid or not, update variables, and so on.

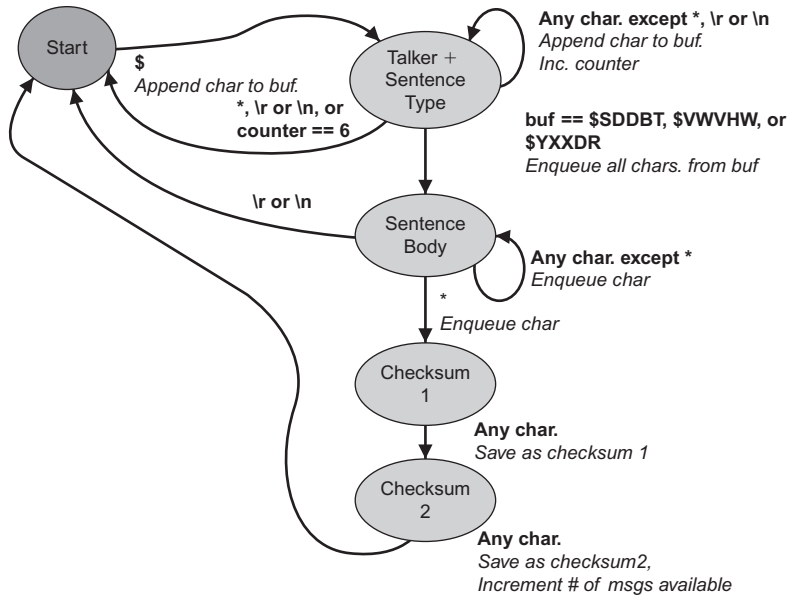


Figure 5.6 Finite state machine design for recognizing NMEA-0183 depth below transducer, heading and speed through water, and battery voltage messages.

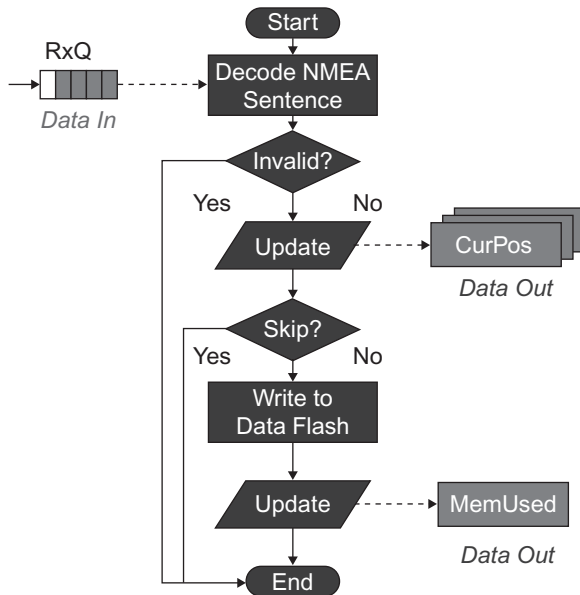


Figure 5.7 Flowchart for decoding NMEA sentence and saving data to flash memory.

There are various other representations available beyond these two workhorses [2], Chapter 12 and 13.

5.3.7 Implementation

Now that we have a detailed design it should be straightforward to proceed to the actual implementation of the code. C is the dominant programming language for embedded systems, followed by C++ and assembly language. C is good enough for the job, even though there are some languages which are much safer. The risk with C is that it allows the creation of all sorts of potentially unsafe code. Ganssle identifies “The Use of C” (or “The Misuse of C”) as reason eight for projects getting into trouble [1]. There are a few points to keep in mind as you develop the code:

- Three fundamental principles should guide your decisions when implementing code: simplicity, generality, and clarity [3].
 - Simplicity is keeping the programs and functions short and manageable.
 - Generality is designing functions that can work, in a broad sense, for a variety of situations and that require minimum alterations to suit a task.
 - Clarity is the concept of keeping the program easy to understand, while remaining technically precise.
- Code should conform to your company’s **coding standards** to ensure that it is easy to read and understand. For more information on why coding style matters see [2], Chapter 17. There are many coding standards examples available [4]. The rules we have seen broken most often, and which have the biggest payoff, are these:
 - Limit function length to what fits onto one screen or page.
 - Use meaningful and consistent function and variable naming conventions.
 - Avoid using global variables.
 - If you find yourself writing the same code with minor variations, it may be worth parameterizing the code so only one version is needed.
- Data sharing in systems with preemption (including ISRs) must be done very carefully to avoid data race vulnerabilities. For more details see [2], Chapter 12.
- **Static analysis** should be used to ensure that your code is not asking for trouble. Most (if not all) compiler warnings should be turned on to identify potential bugs lurking in your source code. Tools such as LINT are also helpful and worth considering.
- **Magic numbers** are hard-coded numeric literals used as constants, array sizes, character positions, conversion factors, and other numeric values that appear directly in programs. They complicate code maintenances because if a magic number is used in multiple places, and if a change is needed, then **each location** must be revised and it is easy to forget about one. Similarly, some magic numbers may

depend on others (e.g., a time delay may depend on the MCU's clock rate). It is much better to use a **const variable** or a **preprocessor #define** to give the value a meaningful name which can be used where needed.

- It is important to **track available design margin** as you build the system up. How much RAM, ROM, and nonvolatile memory are used? How busy is the CPU on average? How close is the system to missing deadlines? The Software Gas Law states that software will expand to fill all available resources. Tracking the resource use helps give an early warning. For more details, see Koopman's discussion on the cost of nearly full resources [2].
- **Software configuration management** should be used as the code is developed and maintained to support evolving code and different configurations as well.

5.3.8 Software Testing

Testing is an important part of software development. It is essentially impossible to develop error-free non-trivial software in a single try. It is especially difficult to design upfront a system which will handle all possible input conditions (including failures) correctly. Ganssle identifies "Inadequate Testing" and "Writing Optimistic Code" as reasons number three and two for projects getting in trouble. Koopman covers verification and validation of systems in detail [1].

Testing the developed software ensures that the product meets the requirements defined. That is, **testing proves that the software does what it is supposed to do**. A corollary is that **testing identifies the software's weaknesses**. These defects are typically prioritized based on their criticality.

Although one can never completely test a program, some tests are more useful and important than others. Hence, it makes sense to think while planning the tests in order to get the biggest return. Testing should be a logical, disciplined, and systematic process, rather than a rote and mechanical process. As with other subjects covered here, there are many excellent texts on software testing for further information [5].

There are several independent dimensions of testing to consider:

- Software tests may or may not depend on the internal details of how the module is built. **Black box testing** assumes no knowledge about the internal structure, and focuses instead on functionality. **White box (or clear box)** testing takes advantage of such knowledge, so it can be more efficient in finding faults.
- Software testing should be done at **various phases** of the development process. **Unit tests** are performed during coding on a per-module basis. **Integration tests** are performed as the system is assembled (integrated) from modules.
- **Regression testing** ensures that past bugs which were fixed have not been re-introduced.

Do We Know How the System is Built?

Black Box Testing tests the functionality of the software by treating it like a black box with unknown contents. **How** the software performs a task **is unknown and unimportant** to the test. The only requirement to pass the test is for the software to do what it should. There are many types of black box testing. Among them are tests for readiness, finite state machine, cause-effect graphing, boundary value testing, and user profile:

- **Readiness:** This test checks if a function is present and functional, and ready for testing. Black box testing should always begin with this form of testing.
- **Finite state machine:** Much software can be considered as finite state machines that transit between different states based on different events. This form of testing tests the transitioning between states and for errors that may occur with them.
- **Cause effect graphing:** This form of testing helps to organize the concepts in other black box techniques. For this test, the tester organizes all possible inputs and outputs of a program. This results in a form of a complete software test and helps to systematically organize test cases.
- **Boundary value testing:** In this form of testing the inputs to the test system are divided into meaningful sets and then tested in groups. One value from each set is then input to the system rather than the whole set. This helps save time.
- **User profile:** This form of testing focuses on how the user intends to use the software and which errors are important to their proper functioning while using the software. This minimizes the amount of time needed to be put into testing. However, learning what part of the program is used often is the difficult part of the test.

White Box Testing relies on knowledge of the structure of the software. It is also known as clear box testing. **How** the software performs a task **is known** to the testers, enabling them to identify probable errors. Important elements of white box testing are coverage and branch and conditioning testing.

- **Coverage:** The aim of white box testing is to cover every statement, state, and path in a program within the constraints of time and money. This can be a daunting task, especially if the program has many conditional statements.
- **Branch and condition testing:** The goal of branch testing is to traverse every path through the program. One way to do this is to use a flow chart of the program. The first test goes through one part of the program. The next one differs from the one before. In this manner, all paths are traversed, even those that share a common part.

How Many Modules Do We Test at a Time?

Individual **unit testing** of modules is typically done by the software developer as the code is created. As the developer has intimate knowledge of the implementation of the module,

this testing is typically white-box testing to maximize the effectiveness. The developer writes test harness code to run the unit under specific conditions and verify the correct responses. Unit testing is quite effective because if there is a bug, it is in that module's code, design, or requirements.

With **integration testing** each module is merged into the main program and is tested to check if it works individually as well as with the rest of the program without causing any errors. There are often scenarios where a subroutine works perfectly on its own, but fails when integrated into the overall system due to unexpected dependencies, requirements, or interactions.

There are various types of integration testing: Bottom up, top down, sandwich, and build. Selecting the type of integration testing depends upon the people and product involved in development.

- **Bottom up:** This is one of the classic approaches for design and testing. Each problem is broken down into smaller parts and solutions are written for them, also called modules. Each module is tested individually and combined into subsystems which in turn are also tested and then combined into a larger system. This goes on till the complete solution is acquired and tested.
- **Top down:** The top down form of integration testing is similar to the bottom up form, but starts with a fully tested main routine. Modules are added to the main routine one after the other and tested as a combination. The process thus continues until all the modules have been added to the main program and tested.
- **Sandwich:** The sandwich testing form combines the bottom up and the top down forms of testing. The top down part tests the main controlling subsystems whereas the bottom up part integrates and tests the individual modules into subsystems.
- **Build:** The build form of integration testing starts with a core system to which functionally related module sets are added consecutively.

There is also a “worst-practice” integration testing method known as **Big Bang** testing. With this form of testing, all modules are combined and tested as a whole. Big bang testing is not advisable with untested modules as diagnosing the error can be very difficult—which of the many modules is really causing the problem? Or is an interaction between two or more modules the cause?

How Do We Keep from Breaking Old Bug Fixes?

The goal of **regression testing** is to ensure that bugs which were found in past testing were fixed and are still fixed. Sometimes an effort to fix a bug introduces other bugs. Regression testing uses a suite of tests which triggered bugs in the past. Automated regression testing allows developers to verify quickly and easily that their bug fix really is a fix. Regression testing may be applied to both unit and integration testing.

5.4 SOFTWARE DEVELOPMENT LIFECYCLE MODELS

We now discuss software development lifecycle models in more detail. We can divide them into two categories: waterfall (big up front design) and everything else (build a piece at a time). The advantage of the latter approaches is that they deliver portions of the implementation to the customer and other stakeholders earlier. This allows problems and misconceptions to be found earlier, and therefore fixed without disrupting the schedule as much. Projects with greater risks will benefit more from more iterative approaches, while less risky projects may be implemented more efficiently with a less iterative approach.

This chapter only provides a general description of these software processes. Further details can be found in the references of this chapter.

5.4.1 Waterfall Process

The waterfall model of software development is an idealized process which assumes that we know everything up front. The process gets its name because the processes flows down the steps like falling water. This process is most appropriate when the problem is very well understood so there is little risk. The following are the steps for the waterfall process:

1. Determine user needs
2. Gather requirements
3. Design
4. Build
5. Test
6. Demonstrate user product

Figure 5.8 illustrates the waterfall process. In practice, there are often arrows jumping back up the waterfall³ which makes this model an idealization.

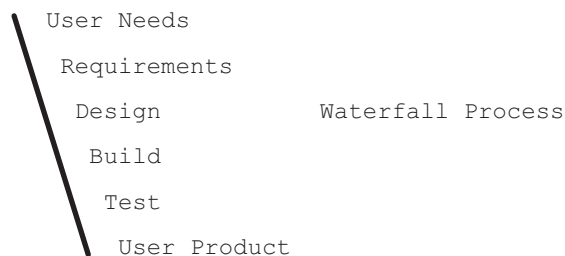


Figure 5.8 The waterfall process expressed as a V-chart.

³ Imagine salmon leaping upstream over the rapids.

5.4.2 Iterative Process

The iterative process is used to deliver a product in increments. The customers define the goals of the product at the beginning of development and are always anxious to have something quickly working. The iterative process provides the product to the customer in parts and provides developers an opportunity to learn about the product and the customer while building the product. This type of process is typically used when there is enough time for developing a project in parts and the customer is eager to provide feedback on the how the product functions while it is being developed. Figure 5.9 illustrates the iterative process.

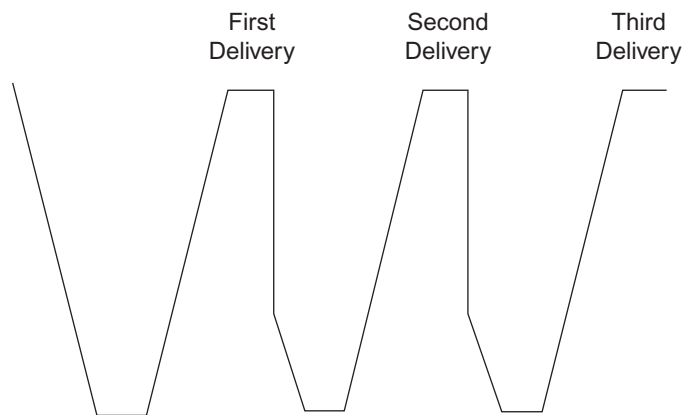


Figure 5.9 Example of an iterative process with one development team, expressed as a V-chart.

5.4.3 Spiral Process

The spiral process combines many fundamental contents of different process models into a single process. This process works best for projects that have a high risk of failure, such as research projects dealing with developing a new technology. Figure 5.10 illustrates the spiral process. Each cycle starts with the steps shown in the upper left quadrant, which are objectives (goals to achieve), constraints (limitations on resources), and alternatives (different approaches to achieve the objectives). The second quadrant (clockwise direction) shows the next steps in the process, which are risk analysis and prototyping. It begins with alternatives produced in the first quadrant. The developers then use the prototypes to analyze each alternative's risks and gain more insight. The third quadrant consists of the evaluation and decision making processes, followed by building the solution. The final quadrant consists of understanding what to do for the next cycle, which is repeated in the first quadrant. The developers revise the previous phases and create a plan for the next quadrant, review the same, and then decide whether to go ahead with the plan or stop building the project.

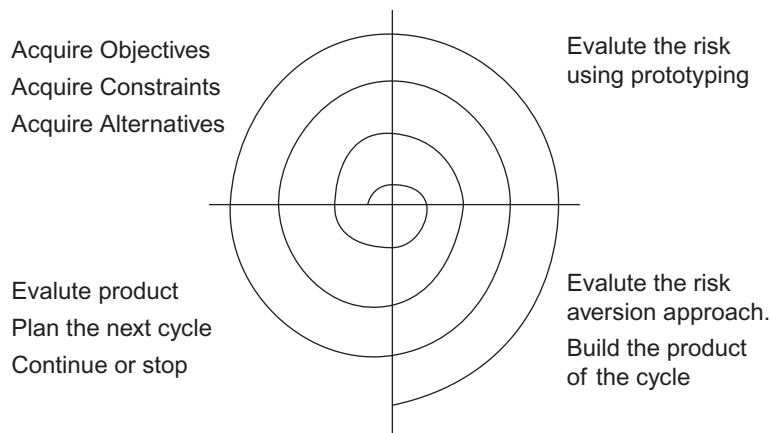


Figure 5.10 The general spiral process.

5.4.4 Agile Development Methods

The most common agile development methods are scrum, extreme programming, and lean development. These methods seek to deliver the product to the customer in satisfactory condition as early as possible in a continuous manner.

Let's examine scrum. With scrum, development activity is divided into a series of sprints lasting two to four weeks. At the end of the sprint the team will have a working, deliverable software product. There are three main types of participants:

- The product owner speaks for the customer.
- The team delivers the product.
- The Scrum Master is responsible for eliminating obstacles from the team's path.

Each sprint begins with the team members and product owner discussing features from a prioritized feature list (the product backlog). The product owner identifies the desired features, and the team estimates which can be delivered within the sprint, adding them to a task list called the sprint backlog. The sprint backlog is frozen for the sprint, so that the team members have clear goals during that development period. Each day during the sprint there is a brief (fifteen minute) status meeting in which each team member answers three specific questions:

- What have you done since yesterday's meeting?
- What are you going to do today?
- Are there any issues keeping you from meeting your goals?

The Scrum Master then seeks to address the issues. Finally, each sprint is time-boxed. If a feature is not completed by the end of the sprint, it goes back into the product backlog. One

of scrum's main strengths is the short development cycle, which improves the speed of feedback. There are other aspects to scrum which we do not cover here, but further details are available in numerous texts on the subject.

5.4.5 Prototyping

Prototyping is a popular and useful software process, especially when determining the look and feel of the software has a higher priority than its basic functions. One of the drawbacks of the prototyped process is that when the waterfall model of development is used the developer may create something completely different from what the customer expected, since the requirements are gathered only at the beginning of the development process. Thus, prototyping is better when it is performed as either an iterative or evolutionary process.

Two basic types of prototypes used are the throw away and evolutionary prototype. In the throw away prototype, developers use a demonstration tool or language. Once the customer is satisfied with the prototype, the developers throw away the prototype and build the actual product with real programming languages. In the evolutionary prototype, the developers use code from the prototype in the actual system.

5.5 RECAP ---

- A major risk of software development is starting coding too early. Designing the system and its components before coding reduces development risks significantly, and also provides other benefits.
- Industry follows many (and sometimes differing) processes when developing software. A process gives a directional path to developing software in an organized manner, and allows the people developing the software and using the software to maintain expectations from the development process at regular intervals.
- Pseudo code and graphical methods to design solutions to a software programming problem allows understanding, resolving, and maintaining logical flow of a program. They can also be directly included in the documentation for the program.
- Testing is an integral part of software testing and software not subjected to testing is bound to fail. There are different techniques available for testing which should be applied as appropriate.

5.6 REFERENCES ---

- [1] Ganssle, Jack. "Breakpoints: Jack's Top Ten." *Embedded Systems Design*, December (2006): 61–63.
- [2] Koopman, Philip J. *Better Embedded System Software*. New Castle, PA., Drumadrochit Education, 2010.

- [3] Kernighan, Brian W., and Rob Pike. *The Practice of Programming*. Indianapolis: Addison-Wesley, 1999.
- [4] Ganssle, Jack. *The Art of Designing Embedded Systems*. 2nd ed. Lawrence, KS: Newnes, 2008.
- [5] Phillips, Dwayne. *The Software Project Manager's Handbook: Principles That Work at Work*. Los Alamitos, CA: John Wiley & Sons, 2004.

5.7 EXERCISES

1. Create a set of requirements for a vending machine which accepts coins and one-dollar bills, and provides change. Assume that each type of item has its own button.
2. Create a set of requirements for a controller for an elevator in a ten-story building.
3. Create a state machine for use in a cellphone to identify local phone numbers, long-distance phone numbers, and invalid phone numbers.
4. Estimate how long it will take you to create a working program to flash the LEDs on your favorite microcontroller board at a frequency proportional to the ambient Celsius temperature. Then go ahead and create the program. Log the time spent for each development activity. Analyze the time required for each activity, the accuracy of your estimations, and finally suggest improvements.
5. Describe the “V” model of software development.
6. What is a flowchart, and how can it be useful in designing software?
7. What is the purpose of integration testing?
8. List the various types of integration testing and briefly describe each type.
9. What can be one of the drawbacks of developing a prototype using the waterfall model?
10. List the two basic types of prototypes and briefly describe each type.
11. Make comparisons between white box (clear box) testing and black box testing with respect to the following parameters:
 - a. Meaning of terms
 - b. Level of application
 - c. Responsibility (engineers involved)
 - d. Need of programming knowledge
 - e. Need of implementation knowledge
12. Compare the following basic software development models:
 - a. Waterfall
 - b. Iterative
 - c. Spiral
13. Compare the following basic software development techniques:
 - a. Prototyping
 - b. Cleanroom
 - c. Object oriented

14. Create a set of software and hardware requirements for a countdown timer which displays: days, hours, minutes, and seconds. The user should be able to set the initial time.
15. Create a state machine for the following two embedded system based appliances:
 - a. Dishwasher
 - b. Washing machine(Create different modes of operation for different loads)
16. List the major advantages and disadvantages of the agile software development method.

Converting Between the Analog and Digital Domains

6.1 LEARNING OBJECTIVES

Embedded systems often measure physical parameters such as light intensity and temperature. These parameters are analog but the embedded system's microcontroller requires digital values to work on. An analog to digital converter (ADC) is used to convert those parameters into a digital form.

In some cases, the microcontroller may need to provide analog signals to another system. For this, the digital output produced by the microcontroller has to be converted to analog before being fed to the interfaced system. A digital to analog converter (DAC) is used for this purpose.

In this chapter we will learn about:

- Converting an analog value to digital, mathematically
- ADCs in the RX63N
- Setting up registers and using the 12-bit and 10-bit ADC
- Using a DAC

6.2 BASIC CONCEPTS

A microcontroller represents information digitally: a voltage less than $V_{cc}/2$ represents a logical 0, while a voltage above $V_{cc}/2$ represents a logical 1. An analog signal can represent an infinite number of possible values. For example, consider an electronic thermometer with an output voltage which is proportional to the temperature in Celsius: $V_{out} = \text{Temperature} \times 0.05 \text{ V}/^\circ\text{C}$. At 5°C , $V_{out} = 0.25 \text{ V}$. At 40°C , $V_{out} = 2.0 \text{ V}$. At 40.1°C , $V_{out} = 2.005 \text{ V}$. If we connect this thermometer directly to a microcontroller's digital input we will not be able to measure temperatures very accurately. In fact, we can only determine if the voltage is above or below $V_{cc}/2$. Assuming a supply voltage of 3.3 V , we can only determine if the temperature is above or below $(3.3 \text{ V}/2)/(0.05 \text{ V}/^\circ\text{C}) = 33^\circ \text{C}$, throwing away all other

temperature information. In order to preserve this information we need a more sophisticated conversion approach.

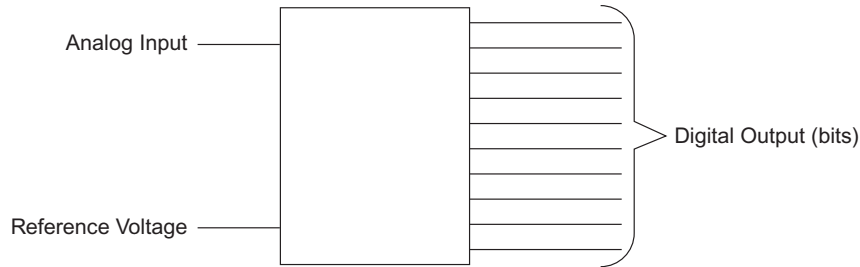


Figure 6.1 Simple ADC.

An ADC measures an analog input voltage and determines a digital (binary) value which represents it best. This measurement process is called *quantization*. The conversion is based on reference voltages which define the high (V_{+Ref}) and low (V_{-Ref}) ends of the input voltage range. Often microcontrollers have V_{-Ref} connected to ground (0 V). An input voltage of V_{+Ref} will result in an output code which is all ones, while an input voltage of V_{-Ref} will result in an output code of all zeroes. An intermediate input voltage will result in the proportional binary code value. This is discussed in more detail in Section 6.2.3.

A block diagram for a simple ADC is shown in Figure 6.1. The number of bits in the digital output is called the *resolution* of the ADC. A 10-bit ADC produces an output with 10 bits, with 1024 (2^{10}) different binary outputs. Thus, in a 10-bit ADC, a range of input voltages (analog) will map/translate to a unique binary output range (0000000000b to 1111111111b). A 12-bit ADC will have 4096 (2^{12}) unique binary outputs values to represent 0 to 100% of an analog input.

Quantization usually introduces some error. A specific code (e.g. 0000101010b) corresponds to a *range* of analog input voltages. The term *quantization error* describes how large the error can be. An ADC with higher resolution has more binary codes possible, which reduces the range of voltages corresponding to each code. This reduces the quantization error.

$$\text{Quantization error} = \frac{1}{(2 * 2^N)}, \text{ where } N = \text{number of quantization levels.}$$

The rate at which new outputs are calculated in an ADC is called the *conversion rate* or *sampling frequency*. Sampling theory states that an input signal with no frequency compo-

nents greater than or equal to one half of the sampling frequency (called the *Nyquist frequency*) will be completely and accurately represented by the samples. If the input signal has any frequency components above the Nyquist frequency, these will be *aliased* by the sampling and appear as noise in the signals (as lower frequency components).

Hence input signals may be bandwidth-limited with a low-pass filter before sampling and quantization. In addition, the system is typically designed so that the Nyquist frequency is well above the filter's corner frequency, allowing the use of less expensive, lower-order filters.

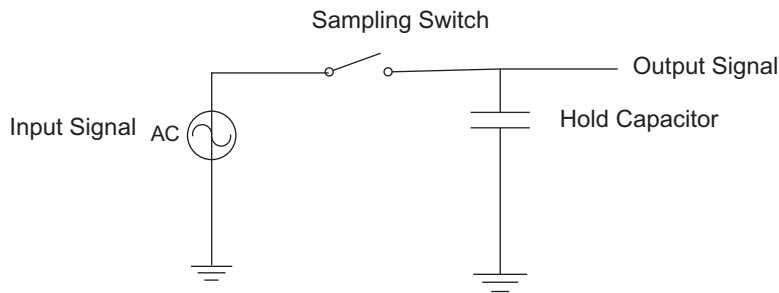


Figure 6.2 Sample and hold circuit.

Some types of ADC will generate incorrect results if the analog input signal changes too much during the conversion time. To avoid this problem, a *sample and hold* circuit (shown in Figure 6.2) can be used to sample the input voltage and save it in a capacitor. The capacitor is then disconnected from the input voltage by opening the sampling switch. The output signal can then be sampled by the ADC without interference from the changing input.

6.2.1 Analog to Digital Conversion by Successive Approximation

Analog to Digital conversion can be performed using many methods, such as Flash Conversion, Dual Slope Integrating, and Successive Approximation. The ADC method used in the RX63N board is Successive Approximation. Conversion using this method gives good resolution and has a wide range.

In the Successive Approximation method, the input voltage is repeatedly compared with the output of a DAC, until the best approximation is achieved. The DAC is fed by the current value of the approximation. The binary value of the approximate is found in every step of this method and is stored in the SAR. The SAR then compares the binary value and the reference

voltage. Successive Approximation requires the same number of clock cycles as the output bits of the ADC; i.e., 12-bit ADC requires 12 clock cycles and 10-bit ADC requires 10 clock cycles (ADC clock cycles, not CPU clock cycles) to perform A/D conversion.

This process can be better understood with an example. The reference voltage for the RX63N board is 3.3 V. Let us assume that an input voltage of 2.5 has to be converted to digital form and the ADC used is 10-bit.

In the first clock cycle, 2.5 V is compared with 1.65 V (voltage is generated by the DAC and is half the reference voltage of 3.3 V). The 2.5 V is greater than 1.65 V and hence a '1' is set at the MSB of the binary value of the approximate, making the value 1xxxxxxx. This value is stored in the SAR.

In the second clock cycle, the input (2.5 V) is compared with 2.47 V (halfway between 1.65 V and 3.3 V). Since the input (2.5 V) is greater than the output from DAC (2.47 V), the next bit of the binary value is set to '1.' The binary value of the approximate is now 11xxxxxxx.

In the third clock cycle, the input (2.5 V) is compared with 2.89 V, (halfway between 2.47 V and 3.3 V). The input (2.5 V) is less than the output from DAC (2.89 V), so the next bit of the binary value is set to '0.' The binary value of the approximate is now 110xxxxxxx.

In the next cycle, the input (2.5 V) is compared with 2.68 V, (halfway between 2.47 V and 2.89 V). The input (2.5 V) is less than the output from DAC (2.68 V), so the next bit of the binary value is set to '0.' The binary value of the approximate is now 1100xxxxxx.

The same process takes place until all the bits of the binary value are found. The final result of this conversion is 1100000111.

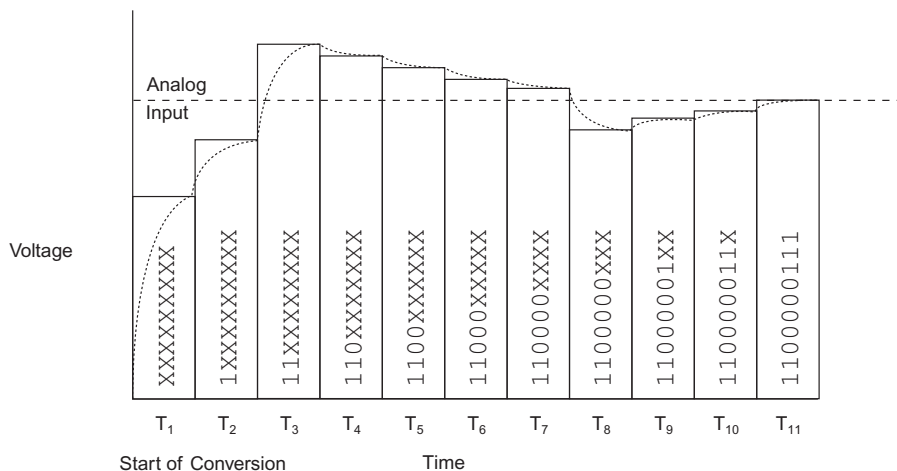
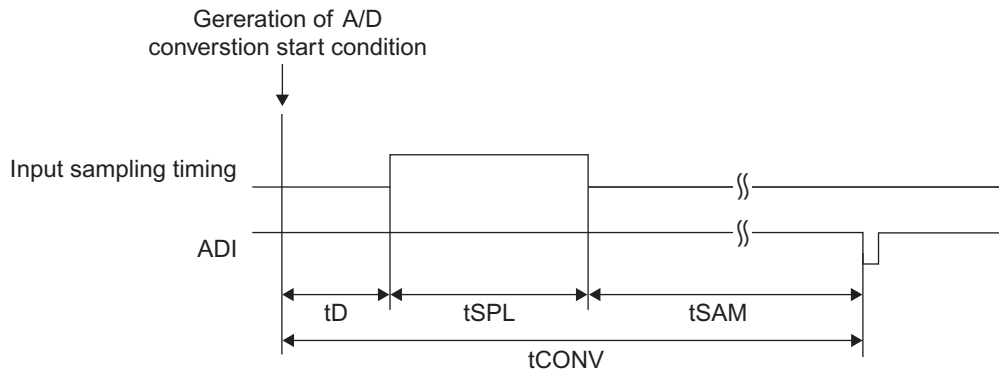


Figure 6.3 A/D conversion using successive approximation.



[Legend]

t_D : A/D conversion start delay time
 t_{SPL} : Input sampling time
 t_{SAM} : Successive conversion time
 t_{CONV} : A/D conversion time

Figure 6.4 ADC conversion timing [1], Figure 42.7, page 1700.

6.2.2 Conversion Speed

The analog input is sampled after A/D conversion start delay time (t_D). Input sampling time (t_{SPL}) is the time that the capacitor in the sample and hold circuit takes to charge. Successive conversion time (t_{SAM}) is the time after which the next conversion can start. It is fixed at 25 ADC clock cycles.

A/D conversion time (t_{CONV}), or sampling time, is the inverse of conversion speed or sampling frequency. Conversion time is the sum of t_D , t_{SPL} , and t_{SAM} only during the first conversion. The following conversions always have a conversion time of t_{SPL} and t_{SAM} .

A/D Sampling State Register 01 (ADSSTR01) is used to set the sampling time for the analog input of the selected channel and A/D Sampling State Register 23 (ADSSTR23) is used to set the sampling time for the temperature sensor output. One may want to alter this if the analog input signal has high-impedance or if the analog input is a fast changing signal and the original sampling time is insufficient, or when the peripheral module clock (PCLK) is slow.

6.2.3 Transfer Function Calculation

The digital value for a particular analog value can be found mathematically. This can be useful as a guide to see if the ADC output obtained is correct.

TABLE 6.1 Example of ADSSTR setting [1], Table 42.6, page 1700.

EXAMPLE OF SETTING	SETTING RANGE	SAMPLE TIME*
Standard (initial value)	19h	0.5 μ s (When PCLK = ADCLK = 50 MHz)
Analog input signal impedance is high and the sampling time may be insufficient	1Ah to FFh	Example: FFh 5.1 μ s (When PCLK = ADCLK = 50 MHz)
Input sampling time is less than the initial value when ADCLK is below 50 MHz.	02h to 18h	Example: 14h 0.5 μ s (When PCLK = ADCLK = 40 MHz)

TABLE 6.2 ADC conversion time [1], Table 42.7, page 1701.

ITEM	SYMBOL	FORMULA	
		MIN	MAX
A/D conversion start delay time (1)	tD	$\frac{3}{\text{PCLK (MHz)}}$	$\frac{1}{\text{ADCLK (MHz)}} + \frac{4}{\text{PCLK (MHz)}}$
Input sampling time (2)	tSPL		$\frac{\text{Setting value of ADSSTR}}{\text{ADCLK (MHz)}}$
Successive conversion time (3)	tSAM		$\frac{25}{\text{ADCLK (MHz)}}$
A/D conversion time* ¹	tCONV		(1) + (2) + (3)
A/D conversion time* ²	tCONV		(2) + (3)

Notes: 1. A/D conversion time in single channel mode and scan mode (first round)
2. A/D conversion time in scan mode (after the second round)

If V_{in} is the sampled input voltage, $V_{+\text{ref}}$ is the upper end of the input voltage range, $V_{-\text{ref}}$ is the lower end of the input voltage range, and n is the number of bits of resolution in ADC, then the digital output (n) can be found using the following formula:

$$n = \left[\frac{(V_{\text{in}} - V_{-\text{ref}})(2^N - 1)}{V_{+\text{ref}} - V_{-\text{ref}}} + \frac{1}{2} \right] \text{int}$$

$$n = \left[\frac{(V_{in})(2^N - 1)}{V_{+ref}} + \frac{1}{2} \right] \text{int} \quad (\text{if } V_{-ref} = 0)$$

6.3 BASIC EXAMPLES

6.3.1 Conversion Speed

Let us calculate the conversion time for the first conversion. Let PCLK = ADCLK = 50 MHz, and ADSSTR is the standard value of 19h.

From Table 6.2, it can be seen that for the first conversion:

$$\begin{aligned} t_{CONV} &= (tD + tSPL + tSAM) \\ t_{CONV} &= (3 / PCLK + ADSSR / ADCLK + 25 / ADCLK) \end{aligned}$$

ADSSTR value is 19h or 25₁₀. Decimal value has to be used for calculation.

$$\begin{aligned} t_{CONV} &= (3 / 50 \text{ MHz} + 25 / 50 \text{ MHz} + 25 / 50 \text{ MHz}) \\ t_{CONV} &= (0.06 \mu\text{s} + 0.5 \mu\text{s} + 0.5 \mu\text{s}) \\ t_{CONV} &= 1.06 \mu\text{s} \end{aligned}$$

While calculating conversion time for the second and subsequent conversions,

$$t_{CONV} = (tSPL + tSAM).$$

6.3.2 Digital Value for a Given Analog Value

Let us assume that the analog voltage to be calculated is 2.7 V and the 12-bit ADC has to be used. The digital value will be:

$$\begin{aligned} n &= \left[\frac{(V_{in})(2^N - 1)}{V_{+ref}} + \frac{1}{2} \right] \text{int} \quad (\text{Since } V_{-ref} = 0) \\ &= \left[\frac{(2.7)(2^{12} - 1)}{3.3} + \frac{1}{2} \right] \\ &= \left[\frac{(2.7)(4095)}{3.3} + \frac{1}{2} \right] \\ n &= 3350_{10} \end{aligned}$$

6.3.3 Step Size

While reference voltage is the maximum analog value that can be converted to digital form, step size is the smallest change in voltage that can be converted. Step size is also known as the resolution of the ADC.

$$\text{Step Size} = \frac{(V_{\text{ref}})}{2^N} \text{ (Since } V_{-\text{ref}} = 0 \text{)}$$

$$\text{The step size for 10-bit ADC} = \frac{(3.3)}{2^{10}} = 3.2 \text{ mV}$$

$$\text{The step size for 12-bit ADC} = \frac{(3.3)}{2^{12}} = 0.8 \text{ mV}$$

The resolution (step size) of the 12-bit ADC is much better than that of the 10-bit ADC. Hence, for applications, which need to detect very small changes in voltage, 12-bit ADC should be used.

6.4 ADVANCED CONCEPTS

The RX63N has 12-bit and 10-bit ADCs. Depending on the resolution the application needs, either the 12-bit or 10-bit ADC should be selected. By default peripherals are in the stop state. They can be enabled using Module Stop Register A (MSTPCRA). To use the 12-bit ADC, SYSTEM.MSTPCRA.BIT.MSTPA17 must be set to 0; and to use the 10-bit ADC, SYSTEM.MSTPCRA.BIT.MSTPA23 must be set to 0.

The 12-bit ADC has 21 channels and the 10-bit A/D converter has eight channels. To use a particular channel, the respective port has to be set up as input. For example, to use AN0, port 4 pin 0 use `PORT4.PDR.BIT.B0 = 0`. For inputs, the Port Mode Register (PMR) also has to be set up. This can be done using `PORT4.PMR.BIT.B0 = 1`.

Next, the ADC registers have to be set up. The 12-bit ADC and the 10-bit ADC have different registers. In this section we shall see how to set the registers and use the different operating modes of the ADCs.

6.4.1 12-Bit A/D Converter

The ADC usually consists of a sample and hold circuit and a comparator. The sample and hold circuit gets a one-time snap shot of the analog input (voltage) and this is compared against a reference voltage using the comparator.

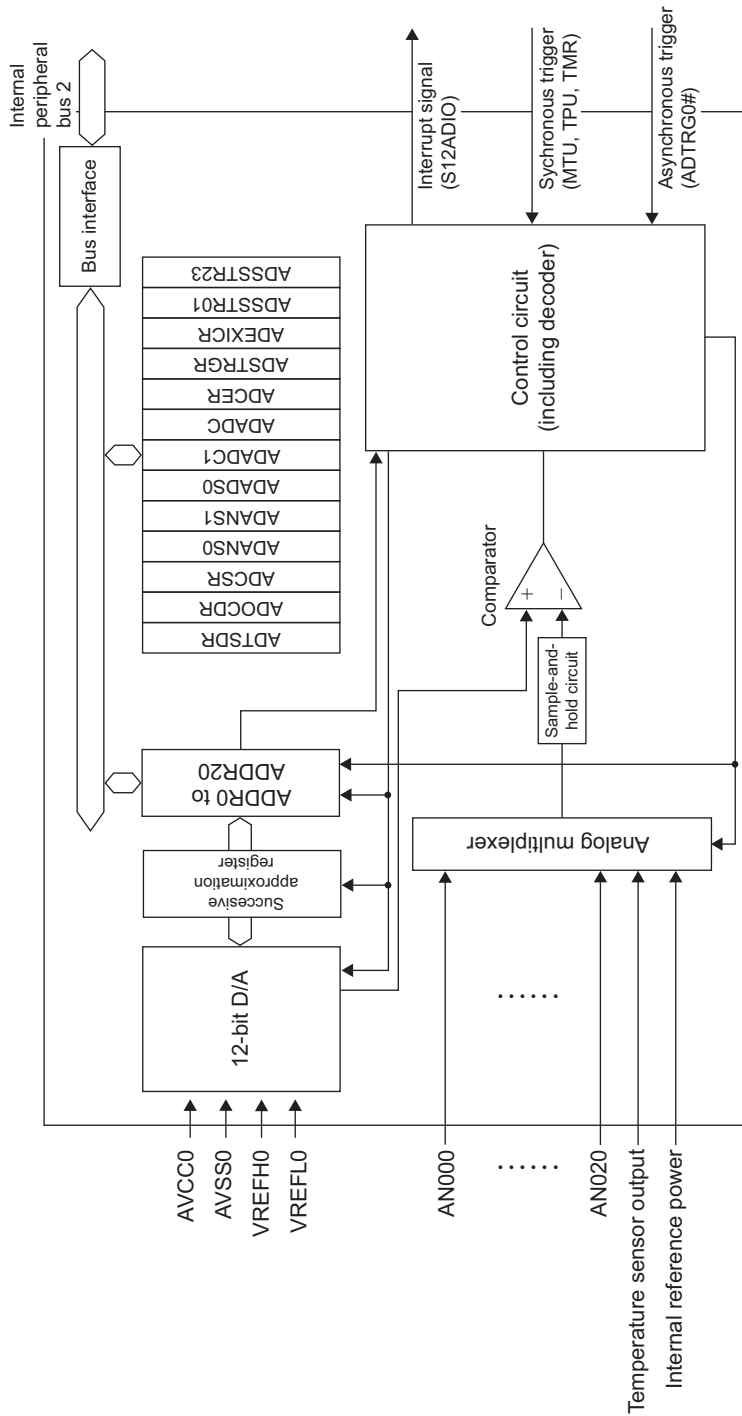


Figure 6.5 Block diagram of 12-bit A/D converter [1], Figure 41.1, page 1659.

Registers

The 12-bit ADC registers are presented as structures and unions for easy manipulation, just like the ports, in the 'iodefine.h' file. The registers can be accessed using the syntax `S12AD.REGISTER.WORD` to set up an entire register or `S12AD.REGISTER.BIT.BIT_NAME` to set up a particular bit of a register.

A/D Data Registers n ($ADDR_n$) ($n = 0$ to 20)

The 12-bit ADC has 21 Data Registers each corresponding to the input channels of the ADC. A/D data registers `ADDR0` to `ADDR20` are 16-bit read-only registers. They store the A/D conversion results of channels `AN000` to `AN020`. The width of the `ADDRn` register (16-bit) is greater than the width of the ADC output (12-bit). To avoid reading wrong data, the output has to be aligned either to the right or left of `ADDRn`. This can be done using the A/D Control Extended Register (`ADCER`). This is explained a little later.

A/D Control Register (`ADCSR`)

The `ADCSR` is used to select different settings of the ADC.

Address: 0008 9000h

	b7	b6	b5	b4	b3	b2	b1	b0
	ADST	ADCS	—	ADIE	CKS[1:0]		TRGE	EXTRG
Value after reset:	0	0	0	0	0	0	0	0

Figure 6.6 A/D control register [1], page 1659.

The `b0` bit is used to specify if an external trigger, `ADTRG0#`, should start A/D conversion. If 1 is set, the microcontroller starts A/D conversion when a trigger is received. The value 0 is set when A/D conversion is to be started by other means.

To receive the external trigger (if `b0 = 0`), the external trigger has to be enabled. This is done by setting `b1` bit to 1. The value 0 disables external trigger.

The frequency of the ADC clock can be selected using the following table. `PCLK` is the peripheral clock.

TABLE 6.3 Clock Selection.

b3	b2	FUNCTION
0	0	PCLK/8
0	1	PCLK/4
1	0	PCLK/2
1	1	PCLK

The scan end interrupt enable (ADIE) bit is used to enable or disable A/D interrupt after A/D conversion has been performed. Setting this bit to 0 disables the interrupt, and setting it to 1 enables this interrupt.

The scan mode select (ADCS) bit is used to select mode of operation of the ADC. Setting this bit to 0 selects Single-Cycle Scan Mode, and setting it to 1 selects continuous scan mode.

The A/D Conversion Start (ADST) bit is used to stop/start the A/D conversion. Setting this bit to 1 starts the ADC and setting it to 0 stops the ADC. If ADC is to be started using a software trigger, ADST must be set to 1 only after all the ADC registers have been configured. Hence set ADST = 0 when setting this register initially.

A/D Channel Select Registers (ADANS_x (x=0 or 1))

These registers are 16 bits wide and are used to select the channel(s) on which A/D conversion should be performed. ADANS0 is used to select channels AN000 to AN015 and ADANS1 is used to select channels AN016 to AN020. The upper 11 bits of ADANS1 are reserved. To select a channel, set the corresponding bit to 1. For example, to select channel 0, set S12AD.ADANS0.WORD = 0x0001; and to select fifteen channels set S12AD.ADANS0.WORD = 0x00FF.

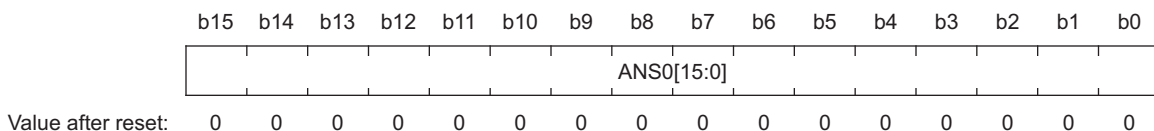


Figure 6.7 A/D Channel Select Register 0 (ADANS0) [1], page 1661.

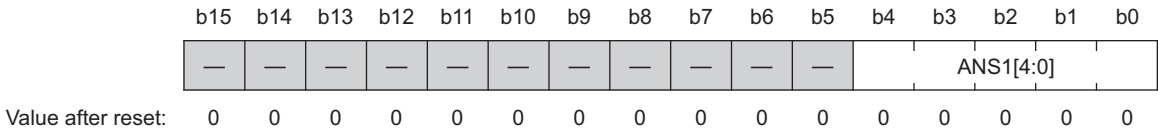


Figure 6.8 A/D Channel Select Register 1 (ADANS1) [1], page 1661.

A/D-Converted Value Addition Mode Select Registers (ADADSx (x=0 or 1))

The 12-bit ADC has a special setting which is called the Converted Value Addition Mode. This setting is used to successively convert and sum two to four times the channels that have been selected using the ADANS register. ADADS0 is used for value addition mode for AN000 to AN015 and ADADS1 is used for value addition mode for AN016 to AN020. The upper eleven bits of ADADS1 are reserved.

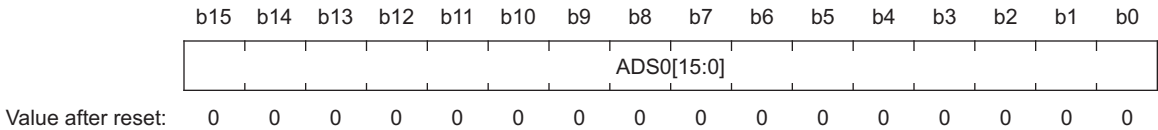


Figure 6.9 A/D-Converted Value Addition Mode Select Register 0 (ADADS0) [1], page 1662.

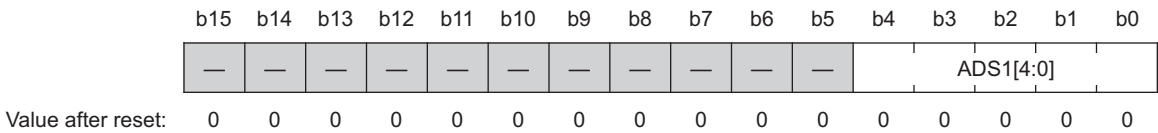


Figure 6.10 A/D-Converted Value Addition Mode Select Register 1 (ADADS1) [1], page 1662.

To understand value addition better, let us consider an example in which eight channels have been selected (S12AD.ADANS0.WORD = 0x00FF) and value addition is to be performed on channels 2 and 6.

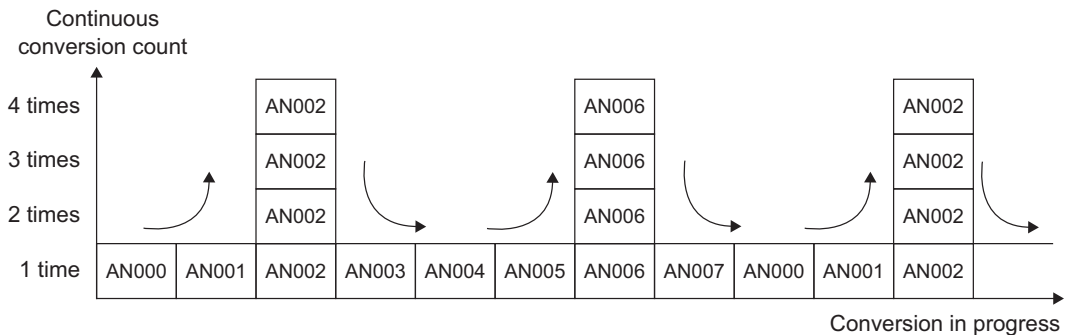


Figure 6.11 A/D converted value addition mode [1], Figure 41.2, page 1663.

According to our example, analog inputs at channels 0, 1, 3, 4, 5, and 7 are A/D converted once, but inputs at channels 2 and 6 are successively converted four times (the number of times can be changed) and added. This added value is stored in the A/D data register. Finding the average of this value can improve A/D conversion accuracy.

A/D-Converted Value Addition Count Select Register (ADADC)

The ADADC is the register that is used to select the number of times the value adding has to be performed. This register is an 8-bit register. The upper 6 bits are reserved and the lower 2 bits (b1, b0) are used to select the value addition count. Value addition can be performed two to four times. The setting for the value addition count can be seen from the following table.

TABLE 6.4 A/D Converted Value Addition Count Setting.

b1	b0	FUNCTION
0	0	1-time conversion (no addition)
0	1	2-time conversion (addition once)
1	0	3-time conversion (addition twice)
1	1	4-time conversion (addition three times)

A/D Control Extended Register (ADCER)

The ADCER is a 16-bit register. All bits except bit 5 and bit 15 of this register are reserved. Bit 5 is for Automatic Clearing Enable (ACE). Thus, setting bit 5 to 1 enables automatic clearing of the Data Register once the A/D value has been read by the microcontroller. This setting makes sure that older A/D values are not read by mistake.

Bit 15 (ADRFMT) of the ADCER is used to select the format of the Data Register. Setting bit 15 to 0 sets the format of the Data Register to right alignment. Setting this bit to 1 selects left alignment of Data Register. However, if the A/D converted value addition mode is selected, this formatting becomes void. Selection of the value addition mode automatically sets left alignment format for the Data Register. Note that the number of bits output after value addition is fourteen and not twelve.

	b15	b14	b13	b12	b11	b10	b9	b8	b7	b6	b5	b4	b3	b2	b1	b0
ADR FMT	—	—	—	—	—	—	—	—	—	—	ACE	—	—	—	—	—
Value after reset:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.12 A/D Control Extended Register (ADCER) [1], page 1664.

A/D Start Trigger Select Register (ADSTRGR)

The ADSTRGR is an 8-bit register. The upper 4 bits (b7 to b4) of this register are reserved and the lower 4 bits (b3 to b0) are used to select the type of trigger that will start the Analog to Digital Conversion process.

Address: 0008 9010h

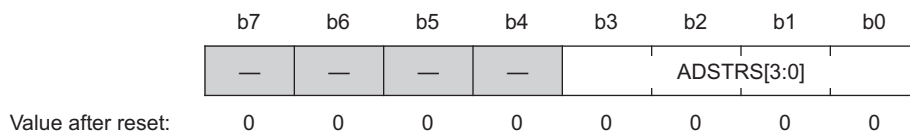


Figure 6.13 A/D start trigger select register [1], page 1665.

A/D conversion can be started by one of three sources. They are a) Multi-function Timer pulse Unit (MTU) and Timer (TMR), b) external trigger (ADTRG0#), and c) Software Trigger. To choose a type of trigger, use the following table.

TABLE 6.5 Trigger Selection [1], Table 41.5, page 1665.

SELECTED SOURCE	ADSTRS[3]	ADSTRS[2]	ADSTRS[1]	ADSTRS[0]	REMARKS
Software trigger	—	—	—	—	
Asynchronous trigger	0	0	0	0	
TRGOAN_0	0	0	0	1	MTU0.TGRA and MTU0.TCNT
TRGOBN_0	0	0	1	0	MTU0.TGRB and MTU0.TCNT
TRGAN_0	0	0	1	1	MTUn.TGRA and MTUn.TCNT (n=0 to 4)
TRGAN_1	0	1	0	0	TPUn.TGRA (n=0 to 4)
TRGOEN_0	0	1	0	1	MTU0.TGRE and MTU0.TCNT
TRGOFN_0	0	1	1	0	MTU0.TGRF and MTU0.TCNT
TRG04ABN_0	0	1	1	1	MTU4.TADCORA and MTU4.TCNT or MTU4.TADCORB and MTU4.TCNT
TRG04ABN_1	1	0	0	0	TPU0.TGRA
TMTRGOAN_0	1	0	0	1	TMR0.TCORA and TMR0.TCNT
TMTRGOAN_1	1	0	1	0	TMR2.TCORA and TMR2.TCNT

When the MTU and TMR are to be used as the trigger, the TRGE bit in ADCSR has to be set to 1 and the EXTRG bit in ADCSR has to be set to 0.

When an external input is to be used as the trigger (ADTRG0#), the TRGE bit in ADCSR has to be set to 1 and the EXTRG bit in ADCSR has to be set to 1. ADTRG0# has to be set up as an input pin and ICR has to be enabled.

Software trigger is enabled at all times irrespective of the values set using TRGE, EXTRG, and ADSTRGR bits in ADCSR.

A/D-Converted Extended Input Control Register (ADEXICR)

The ADEXICR is a 16-bit register whose bits 15 to 10 and 7 to 2 are reserved. The other bits are used to control temperature sensor data conversion and internal reference voltage conversion.

	b15	b14	b13	b12	b11	b10	b9	b8	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	—	—	—	—	OCS	TSS	—	—	—	—	—	—	OCSAD	TSSAD
Value after reset:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.14 A/D-Converted Extended Input Control Register [1], page 1666.

The OCS bit selects A/D conversion for internal reference voltage. Similarly the TSS bit selects A/D conversion of temperature sensor output. The OCSAD bit is the value addition mode select bit for internal reference voltage A/D conversion. The TSSAD bit is the value addition mode select bit for temperature sensor output.

A/D Temperature Sensor Data Register (ADTSDR)

The ADTSDR register is a 16-bit register which stores the 12-bit converted digital value of temperature sensor output. Depending on the ADRFMT bit in ADCER, the result is left or right justified. If value addition mode is selected the result is 14-bit.

A/D Internal Reference Voltage Data Register (ADOCDR)

The ADOCDR register is a 16-bit register which stores the 12-bit converted digital value of A/D internal reference voltage. Depending on the ADRFMT bit in ADCER, the result is left or right justified. If value addition mode is selected the result is 14-bit.

Let us now look at an example of setting up the registers of the 12-bit ADC. It is always better to write register set up as a function.

```
1. void ADC_Init() {
2.     SYSTEM.MSTPCRA.BIT.MSTPA17 = 0;
3.     S12AD.ADCSR.BYTE = 0x0C;
4.     S12AD.ADANS0.WORD = 0x01;
5.     S12AD.ADCER.BIT.ACE = 1;
6.     S12AD.ADCER.BIT.ADRFMT = 0;
7. }
```

The setting up of registers has been written as a function named `ADC_Init()` in line 1. In line 2, the 12-bit ADC has been selected using the Module Stop Control Register A. In line 3, the Control Register is set up—the Software trigger has been enabled (b1 = 0, b0 = 0), the PCLK (b3 = 1, b2 = 1) has been selected, A/D Interrupt Enable has not been enabled (b4 = 0) and Single-Cycle Scan mode has been selected (b6 = 0). In line 4, channel 0 (AN000) has been selected. Next, automatic clearing of `ADDRn` (line 5) and right alignment of `ADDRn` (line 6) is done.

Operation

The 12-bit ADC is capable of operating in two modes: single-cycle scan mode and continuous scan mode.

Single-Cycle Scan Mode

In this mode, one to twenty-one channels (number of channels selected using `ADANS0` and `ADANS1` registers) are scanned/converted to digital once in ascending order and then the ADC is stopped. This can be better understood with the following figure in which conversion is performed on three channels (AN004, AN005 and AN006).

The ADC in Single-Cycle Scan Mode is started (represented by (1) in Figure 6.15) when the `ADST` bit (`ADCSR`) is set to 1. The channels are A/D converted in ascending order (AN004, AN005, AN006) and the converted value is stored in the respective Data Register (represented by (2) in the figure). An ADI interrupt request is raised if `ADIE` bit (`ADCSR`) is enabled (represented by (3) in the figure). Finally, the `ADST` bit gets cleared to 0 when inputs of all the channels have been converted (represented by (4) in the figure).

The ADC operates similarly when ADC is started using `MTU`, `TMR`, or an external trigger input.

The A/D conversion of temperature sensor output and internal reference voltage always operates in single scan mode. For conversion of temperature sensor output set the temperature sensor output A/D conversion select bit (`TSS`) in `ADEXICR` to 1 or for conversion of internal reference voltage set A/D internal reference voltage A/D conversion select bit

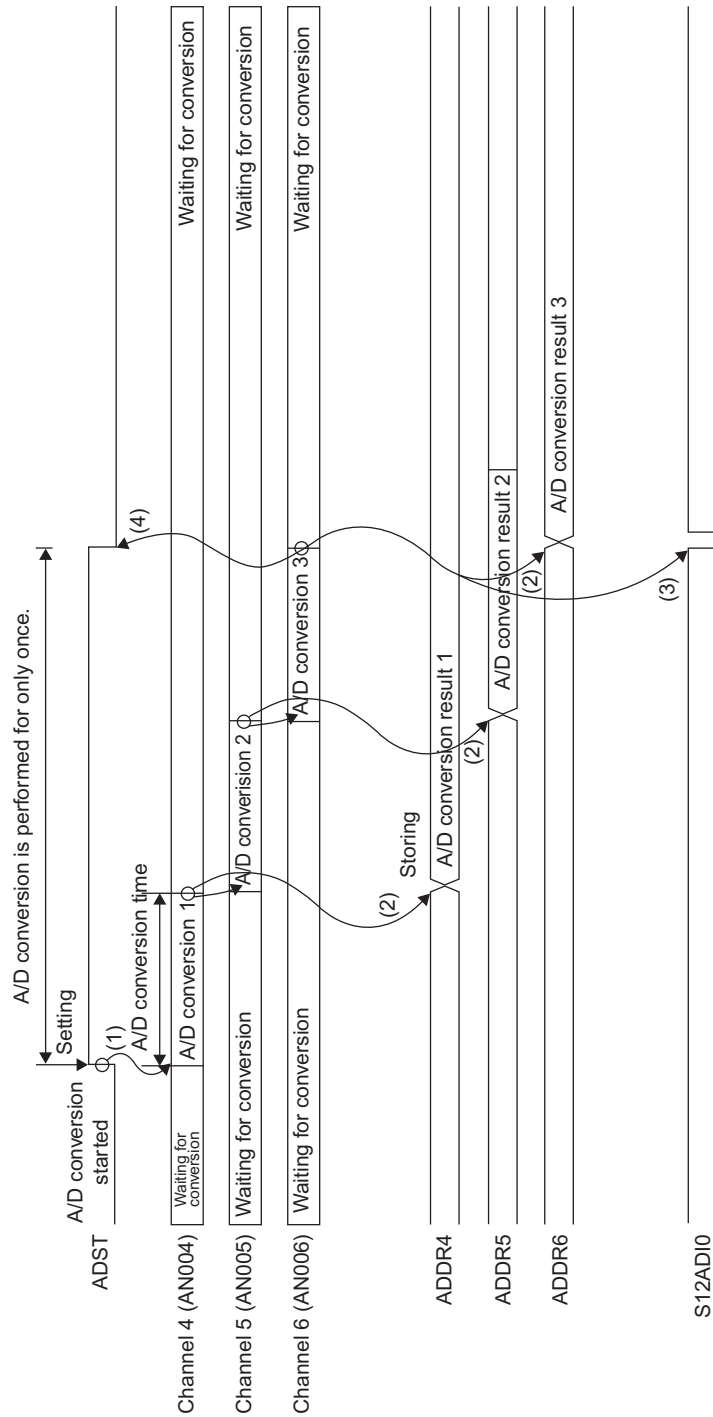


Figure 6.15 Single-cycle scan mode [1], page 1672.

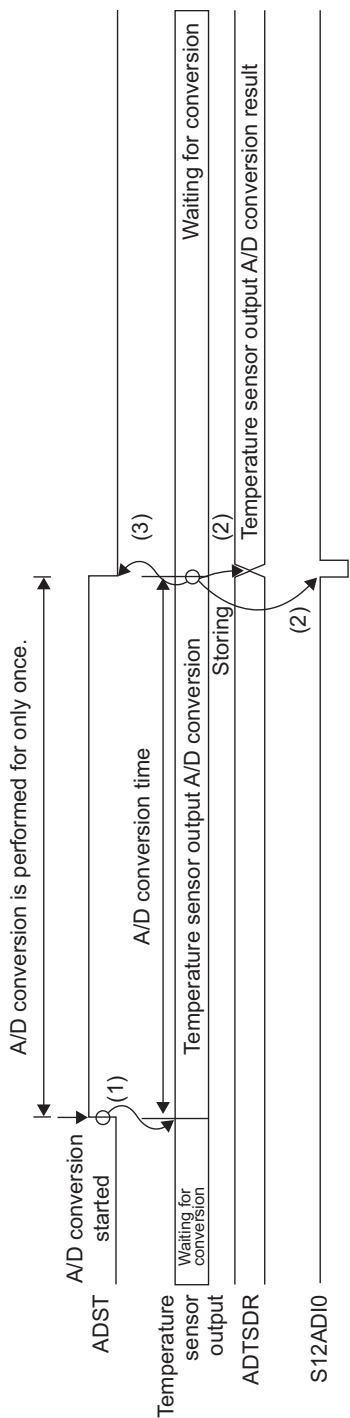


Figure 6.16 Single-cycle scan mode [1], page 1673.

(OCS) in ADEXICR to 1. Both cannot be performed at a time. Once the ADST bit in ADCSR is set to 1 the conversion process is the same as any other analog channel conversion. The result of temperature sensor output conversion is stored in ADTSDR register and that of internal reference voltage conversion is stored in ADOCDR register.

Continuous Scan Mode

In this mode, one to twenty-one channels (number of channels selected using ADANS0 and ADANS1 registers) are scanned/converted to digital continuously in ascending order until the ADC is stopped manually. In continuous scan mode, temperature sensor output A/D conversion select bit (TSS) and A/D internal reference voltage A/D conversion select bit (OCS) in ADEXICR should both be set to 0. This can be better understood with the following figure in which conversion is performed on three channels (AN000, AN001, and AN002).

The ADC in Continuous Scan Mode is started (represented by (1) in Figure 6.17) when the ADST bit (ADCSR) is set to 1.

The channels are A/D converted in ascending order (AN000, AN001, AN002) and the converted value is stored in the respective Data Register (represented by (2) in the figure). An ADI interrupt request is raised if ADIE bit (ADCSR) is enabled (represented by (3) in the figure).

Unlike Single-Cycle Scan Mode, the above two processes ((1) and (2)) are repeated until the ADST is set to 0 manually. When ADST is set to 0, the ADC stops and enters a wait state. When ADSR is set to 1 later, A/D conversion starts again.

The ADC operates similarly when ADC is started using MTU, TMR, or an external trigger input.

6.4.2 10-Bit ADC

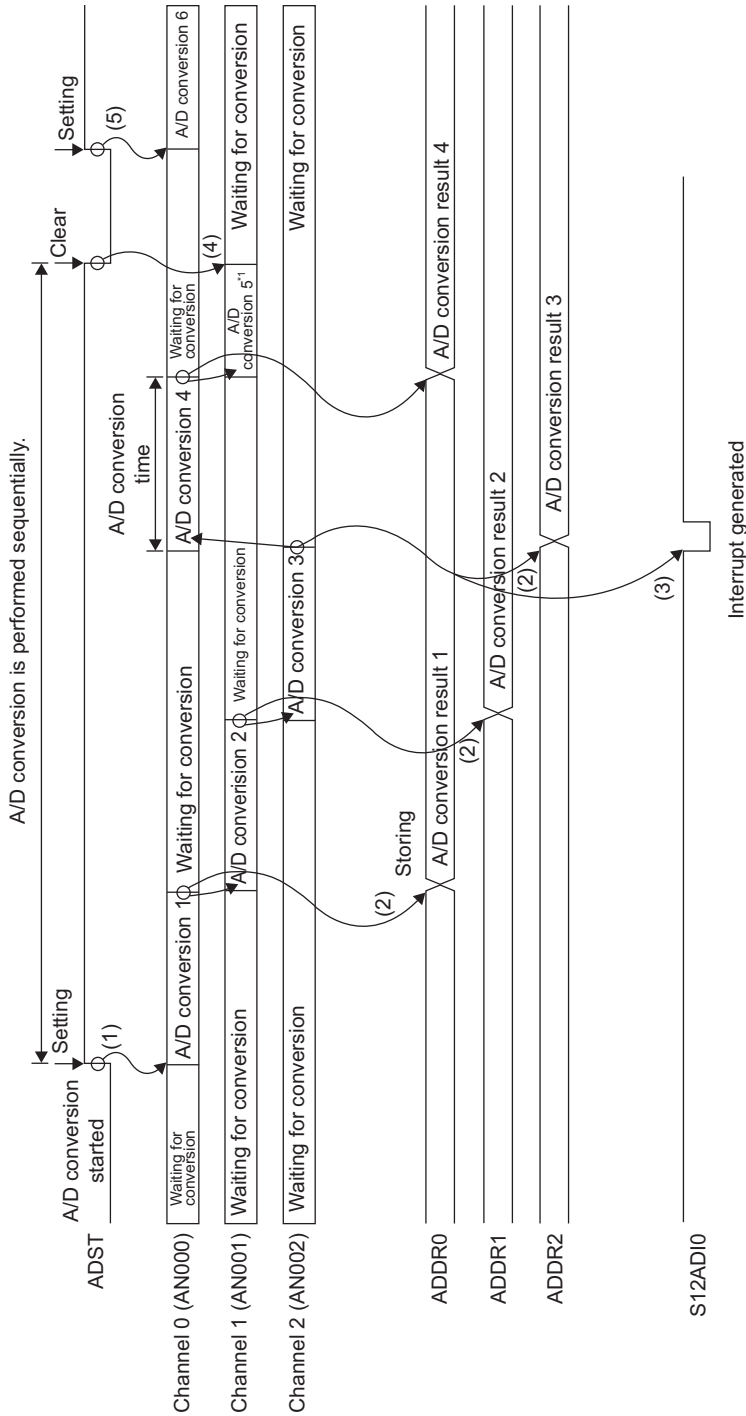
The RX63N has one 10-bit ADC. It can convert up to eight analog input channels. There are eight channels (AN0 to AN7) and an extended analog input channel (ANEX1).

Like the 12-bit ADC, 10-bit ADC registers are also presented as structures and unions for easy manipulation, just like the ports, in the 'iodefine.h' file. The registers can be accessed using the syntax `AD.REGISTER.WORD` to set up an entire register or `AD.REGISTER.BIT.BIT_NAME` to set up a particular bit of a register.

Registers

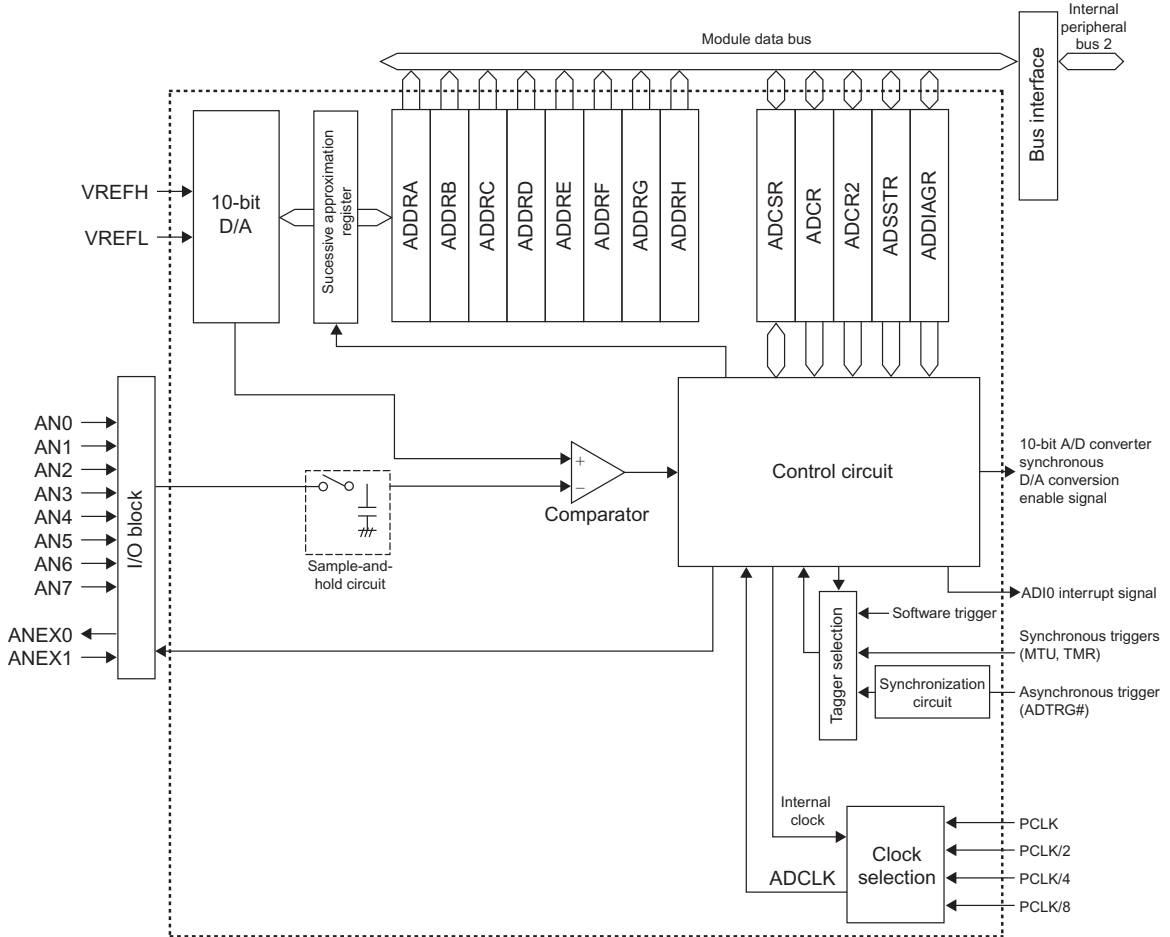
A/D Data Registers (ADDRn) (n = A to H)

The 10-bit ADC has eight Data Registers, each corresponding to the input channels of the ADC. A/D data registers are 16-bit read-only registers. They store the A/D conversion results of channels AN0 to AN7. The width of the ADDRn (16-bit) is greater than the width



Notes: 1. Converted data of A/D conversion 5 are ignored.

Figure 6.17 Continuous scan mode [1], page 1674.



ADDRA: A/D data register A
 ADDR B: A/D data register B
 ADDR C: A/D data register C
 ADDR D: A/D data register D
 ADDR E: A/D data register E
 ADDR F: A/D data register F
 ADDR G: A/D data register G
 ADDR H: A/D data register H
 ADCSR: A/D control/status register
 ADCR: A/D control register
 ADCR2: A/D control register 2
 ADSSTR: A/D sampling state register
 ADDIAGR: A/D self-diagnostic register

Figure 6.18 Block Diagram of 10-bit ADC (Unit 0) [1], page 1688.

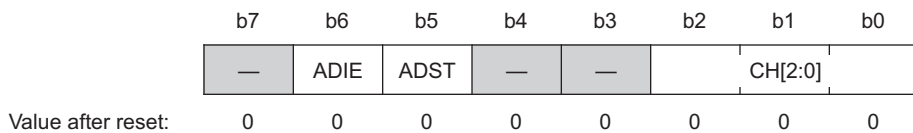


Figure 6.19 A/D control/status register [1], page 1690.

of the ADC output (10-bit). To avoid reading wrong data, the output has to be aligned either to the right or left of ADDRn. This can be done by setting the ADCR2.DPSEL bit. This will be explained a little later.

A/D Control/Status Register (ADCSR)

The Control/Status Register is used to select the input channels, start or stop A/D conversion, and enable or disable ADI interrupt.

The CH[2:0] is used to select the analog channels which have to be A/D converted. The channels can be selected using the following table.

TABLE 6.6 Channel Selection [1], page 1690.

When ADCR.MODE[1:0] = 00b				When ADCR.MODE[1:0] = 10b or 11b			
b2	b1	b0		b2	b1	b0	
0	0	0	AN0	0	0	0	AN0
0	0	1	AN1	0	0	1	AN0, AN1
0	1	0	AN2	0	1	0	AN0 to AN2
0	1	1	AN3	0	1	1	AN0 to AN3
1	0	0	AN4	1	0	0	AN0 to AN4
1	0	1	AN5	1	0	1	AN0 to AN5
1	1	0	AN6	1	1	0	AN0 to AN6
1	1	1	AN7	1	1	1	AN0 to AN7

The A/D Start bit (ADST) is used to start or stop the ADC. Setting this bit to 1 starts the ADC, and setting it to 0 stops the ADC. The A/D Scan Conversion End Interrupt Enable (ADIE) is used to enable or disable the A/D scan conversion end interrupt (ADI). When A/D conversion is complete, an interrupt is generated. Setting the ADIE bit to 1 enables the interrupt and setting it to 0 disables the interrupt.

A/D Control Register (ADCR)

The Control register is used to select the type of A/D conversion mode, clock, and trigger.

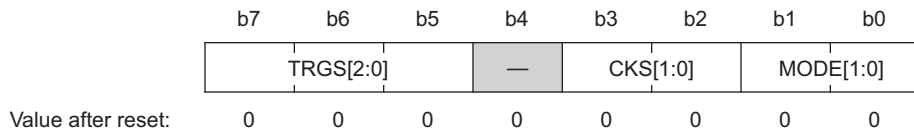


Figure 6.20 A/D control register [1], page 1691.

Like the 12-bit ADC, the 10-bit ADC also has different modes of operation. They are Single mode, Continuous Scan mode, and One-cycle scan mode. Set the MODE[1:0] bits to 00b (single channel mode), 10b (continuous scan mode), or 11b (single scan mode). Do not set the MODE[1:0] bits to 01b. Details of these modes are explained later.

The ADC clock can be set using the CKS[1:0] bits. To select the peripheral module clock (PCLK), set the CKS[1:0] bits to 00b (PCLK/8), 01b (PCLK/4), 10b (PCLK/2), or 11b (PCLK).

The TRGS bits are used to select the type of trigger that will start the A/D conversion process.

TABLE 6.7 Trigger Select for 10-bit ADC.

b7	b6	b5	TRIGGER
0	0	0	Software Trigger
0	0	1	Compare-match/input-capture A from MTU0 to MTU4
0	1	0	Compare-match from TMR0
0	1	1	Trigger from ADTRG#
1	0	0	Compare-match/input-capture A from MTU0
1	0	1	Compare-match/input-capture A from TPU0 to TPU4
1	1	0	Compare-match from MTU4
1	1	1	Compare-match/input-capture A from TPU0

A/D Control Register 2 (ADCR2)

A/D Control Register 2 (ADCR2) is used to select extended analog input channel, extended analog output channel and to select A/D result format. Setting the EXSEL[1:0] bits to 01b selects extended analog input channel. The extended analog input channel should be

input from an external operational amplifier. Setting the EXSEL[1:0] bits to 00b isolates the extended analog input channel from the A/D converter circuit inside the chip. Do not set the EXSEL[1:0] bits to 10b or 11b. Setting the EXOEN bit to 1 enables Extended Analog Output Control. Setting the DPSEL bit to 0 aligns the A/D result to the right and setting it to 1 aligns the A/D result to the left in the ADDR_n register (n = 0 to 20).

A/D Self-Diagnostic Register (ADDIAGR)

This register is used to check if the 10-bit ADC has any defects. This register is an 8-bit register and the lower 2 bits (b1 and b0) are used to set up the test voltage for fault detection. To perform fault detection, do the following:

- Set up the ADC in Single mode (AD.ADCR.BIT.MODE = 00b)
- Enable analog input AN0 (AD.ADCSR.BIT.CH = 000b)
- Set up software trigger for the ADC (AD.ADCR.TRGS = 000b)
- Set the test voltage by setting (AD.ADDIAGR.DIAG) using Table 6.8
- Start conversion (AD.ADCSR.BIT.ADST = 1)

TABLE 6.8 Test Voltage Setting.

b1	b0	FUNCTION
0	0	Self-diagnostic function is off
0	1	A/D conversion of $V_{\text{ref}} \times 0$ voltage value is enabled
1	0	A/D conversion of $V_{\text{ref}} \times 1/2$ voltage value is enabled
1	1	A/D conversion of $V_{\text{ref}} \times 1$ voltage value is enabled

The test voltage (0 V or $V_{\text{ref}}/2$ or V_{ref}) is A/D converted and the result is stored in the ADDRA register. The result should approximately be 0_{10} if 0 V was chosen as test voltage, 1023_{10} if V_{ref} was chosen, and 512_{10} if $V_{\text{ref}}/2$ was chosen. If the result does not correspond to these values then the ADC is at fault.

Self-diagnosis takes the same time as A/D conversion for one channel.

Let us now look at an example of setting up the registers of the 10-bit ADC. It is always better to write register set up as a function.

```

1. void ADC_Init() {
2.     SYSTEM.MSTPCRA.BIT.MSTPA23 = 0;
3.     AD.ADCSR.BYTE = 0x03;

```

```
4.     AD.ADCR.BYTE = 0x0F;
5.     AD.ADCR2.BYTE = 0x00;
6.     AD.ADDIAGR.BYTE = 0x0;
7. }
```

The setting up of registers has been written as a function named `ADC_Init()` in line 1. The 10-bit ADC has been selected using Module Stop Control Register A (lines 2). In line 4, the Control/Status Register is set up—eight channels (AN0 to AN7) have been selected and A/D Interrupt Enable has not been enabled (`b6 = 0`). Next, One-Cycle Scan mode, PCLK, and software trigger have been selected using the A/D Control Register in line 5. The format of the Data Register has been set to right alignment using line 6. In line 7 the A/D self-diagnostic function has been turned off as we are not trying to detect any faults.

Operation

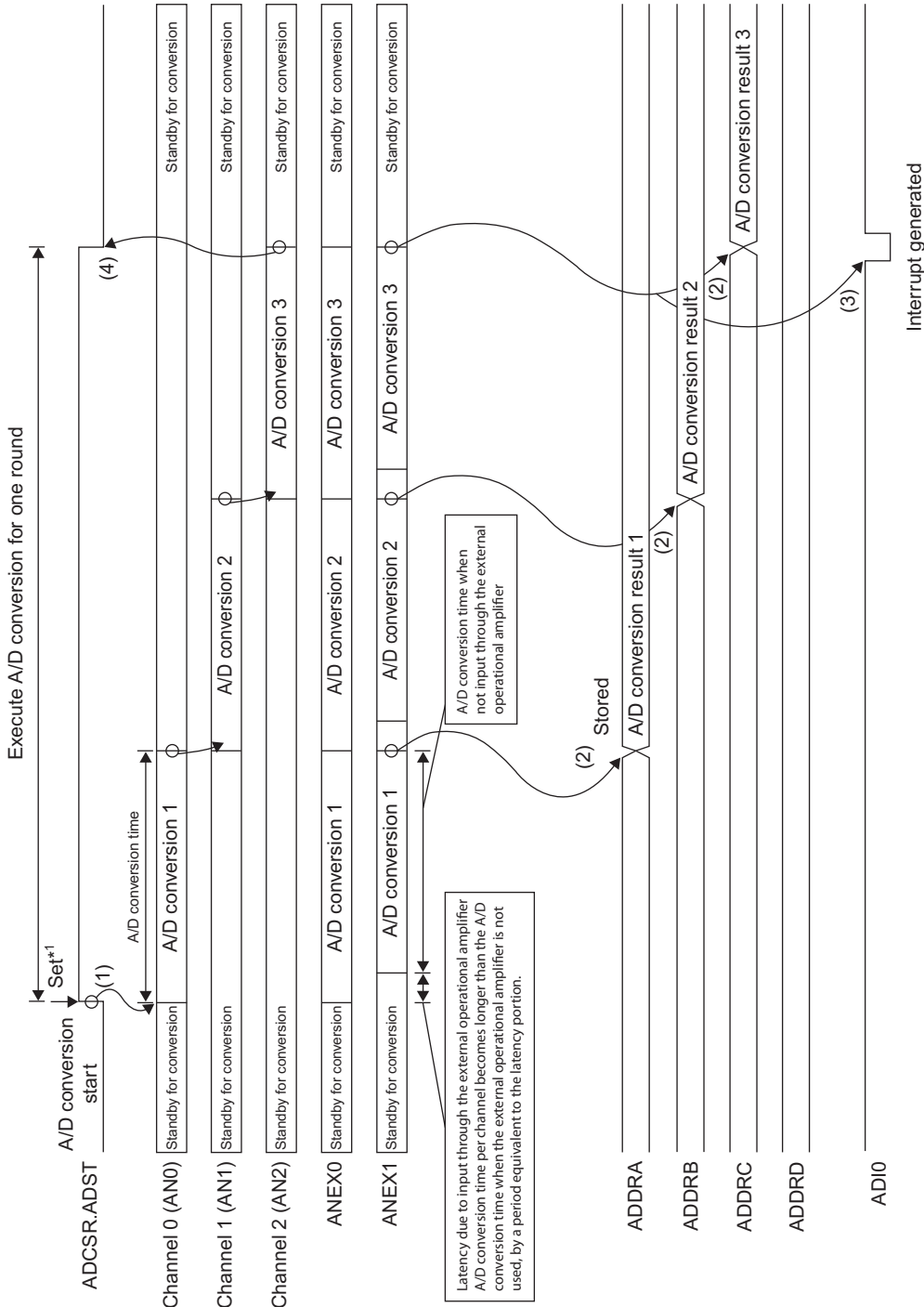
The 10-bit A/D converter has two operating modes: Single Mode and Scan Mode. In the Single Mode, A/D conversion is performed on the specified single channel only once. In the Scan mode, A/D conversion is performed sequentially on the specified channel(s) (up to four). The Scan Mode can be further classified as the One-Cycle Scan mode and the Continuous Scan mode. The operation of the One-Cycle scan mode is the same as the Single-Cycle Scan mode of the 12-bit ADC and the operation of the Continuous Scan mode is the same as the continuous Scan mode of the 12-bit ADC.

There is one extended analog input ANEX1. The ANEX1 is used when an external operational amplifier is connected to the chip to perform A/D conversion for the multiple analog values. Then the time-shared analog values are taken from the extended analog output (ANEX0), and the operational amplifier is connected between ANEX0 and ANEX1. To select ANEX1, set the `ADCR2.EXSEL[1:0]` bits to 01b. To enable ANEX0 output, set the `ADCR2.EXOEN` bit to 1. In addition, select single channel mode or scan mode. This shows the operation when three channels (AN0, AN1, and AN2) and single scan mode are selected.

6.4.3 D/A Converter

The digital to analog converter, as the name suggests, is used to convert digital signals to analog values. A DAC can convert bits to signals only if the Nyquist condition is met. The output of the DAC is in the form of pulses and this could cause harmonics above the Nyquist frequency. This could be avoided by using a low-pass filter. DACs face the issue of high output impedance and slow settling time.

DACs are used in digital devices to play back stored music. The RX63N has a 10-bit DAC. This DAC has two channels.



Note: 1. ↓ indicates an instruction executed by software.

Figure 6.21 ANEX1 Input Operation Example (Single Scan Mode) [1], page 1699.

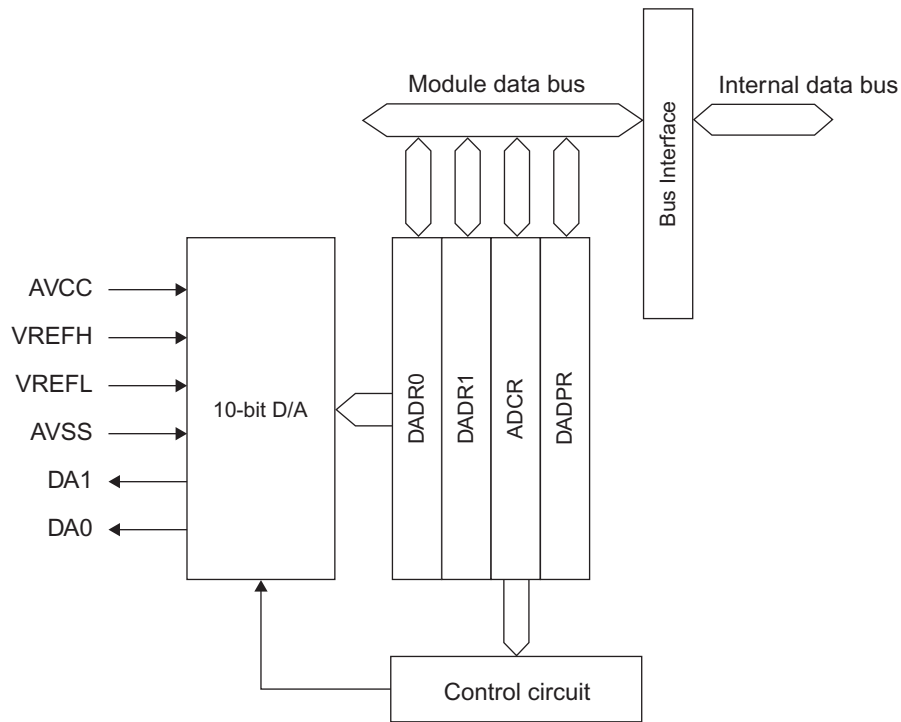


Figure 6.22 Block diagram of DAC [1], Figure 43.1, page 1714.

D/A Registers

The DAC has three registers that have to be set in order to perform D/A conversion. They are D/A Data Register, D/A Control Register, and D/A Data Placement Register.

D/A Data Register (DADR_m) (m = 0, 1)

DADR0 and DADR1 are 16-bit registers which store the digital value that has to be converted to analog. The format of the 10-bit data register can be changed by setting the DPSEL bit (D/A Data Placement Register).

D/A Control Register (DACR)

The D/A Control register is an 8-bit register used to enable or disable D/A conversion. It is also used to select the channel for the D/A operation.

Address: 0008 80C4h

	b7	b6	b5	b4	b3	b2	b1	b0
	DAOE1	DAOE0	DAE	—	—	—	—	—
Value after reset:	0	0	0	0	0	0	0	0

Figure 6.23 D/A control register [1], Section 43.2.2, page 1716.

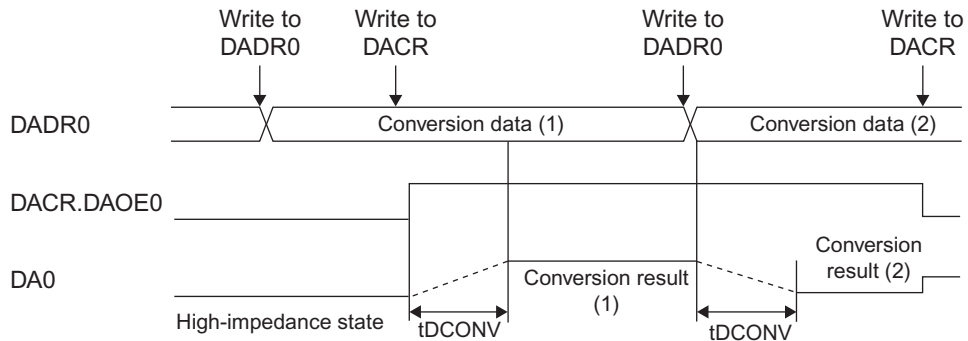
The lower 5 bits (b0 to b4) are reserved. The b5, b6, and b7 bits can be set Table 6.9.

DADRm Format Select Register (DADPR)

The format of the D/A Data Register can be set using this register. This is an 8-bit register. All bits except the eighth bit are reserved. The eighth bit is the Data Placement Selection bit (DPSEL). Setting DPSEL to 0 aligns the D/A Data Register to the right (LSB), and setting it to 1 aligns the D/A Data Register to the left (MSB).

TABLE 6.9 Setting of DACR [1], Section 43.2.2, Page 1716.

BIT	SYMBOL	BIT NAME	DESCRIPTION
b4 to b0	—	Reserved	These bits are read as 1. The write value should always be 1.
b5	DAE* ¹	D/A Enable	0: D/A conversion is independently controlled on channels 0 and 1. 1: D/A conversion on channels 0 and 1 is controlled as a single whole.
b6	DAOE0	D/A Output Enable 0	0: Analog output of channel 0 (DA0) is disabled. 1: D/A conversion of channel 0 is enabled. Analog output of channel 0 (DA0) is enabled.* ²
b7	DAOE1	D/A Output Enable 1	0: Analog output of channel 1 (DA1) is disabled. 1: D/A conversion of channel 1 is enabled. Analog output of channel 1 (DA1) is enabled.* ²



[Legend]

tDCONV: D/A conversion time

Figure 6.24 Operation of DAC [1], Figure 43.2, page 1719.

Operation

The RX63N has two circuits for D/A conversion and they can operate independently. To perform D/A conversion:

- Port 0 pin 5 or Port 0 pin 3 has to be set up as the output port (PORT0.DDR.BIT.B3 = 1) and disable ICR (PORT0.ICR.BIT.B3 = 0) for channel 0 (DA0) and PORT0.DDR.BIT.B5 = 1 and PORT0.ICR.BIT.B5 = 0 for channel 1 (DA1).
- The value to be converted has to be written into the D/A Data Register.
- DAOEn bit ($n = 0$ or 1) in DACR has to be set to 1.

If a new value is written to DADR n ($n = 0$ or 1), conversion takes place again. Conversion takes place until DAOEn bit ($n = 0$ or 1) is cleared.

$$\text{Analog value} = \frac{\text{Setting value of DADR}_n}{1024} \times V_{+\text{ref}}$$

6.5 ADVANCED EXAMPLES

6.5.1 12-Bit ADC

Let us consider the example of a simple 12-bit ADC. A DC voltage supply of 3 V is converted to its corresponding digital code and displayed on the LCD. To perform this Single-Cycle Scan mode an AN000 will be used. Software trigger will be used to start the ADC.

```
1. #include <stdio.h>
2. #include "iodefine.h"
3. #include "lcd.h"
4. void ADC_Init();
5. void main(void){
6.     unsigned int ADC_out;
7.     int i = 0;
8.     char ADC_OUT [13 ];
9.     PORT4.PDR.BIT.B0 = 0;
10.     PORT4.PMR.BIT.B0 = 1;
11.     lcd_initialize();
12.     lcd_display(LCD_LINE1, "12-bit ADC");
13.     ADC_Init();
14.     while(1){
15.         if(S12AD.ADCSR.BIT.ADST == 0 && i == 0){
16.             ADC_out = S12AD.ADDR0 & 0X0FFF;
17.             sprintf(ADC_OUT,"%d",ADC_out);
18.             lcd_display(LCD_LINE2,ADC_OUT );
19.             i++;
20.         }
21.     }
22. }
23. void ADC_Init()
24. {
25.     SYSTEM.MSTPCRA.BIT.MSTPA17 = 0;
26.     S12AD.ADCSR.BYTE = 0x0C;
27.     S12AD.ADANS0.WORD = 0x01;
28.     S12AD.ADCER.BIT.ACE = 1;
29.     S12AD.ADCER.BIT.ADRFMT = 0;
30.     S12AD.ADSTRGR.BIT.ADSTRS = 0x0;
31.     S12AD.ADCSR.BIT.ADST = 1;
32. }
```

The `iodefine.h` in line 2 defines the ports and the ADC registers which need to be set for the ADC operation. The `lcd.h` file (line 3) includes all the LCD functions that are used for displaying. The `ADC_Init` function (lines 23 to 32) is used to set up 12-bit ADC in Single scan mode on AN000 and software start to trigger the conversion. The Module Stop Control Register A (MSTPCRA) is set such that the 12-bit ADC is selected (line 25). The A/D Control register (ADCSR) is set for software trigger, PCLK, and Single-cycle scan mode (line 26). Channel AN0 is selected and the A/D Channel Select register 0 (ADANS0) is set accordingly (line 27). Automatic clearing of the data registers and

right alignment of the data register is selected (lines 28 and 29). The A/D Start Trigger Select register (ADSTRGR) is set for software trigger (line 30). The A/D conversion is then started (line 31). On lines 6 to 8 the variables are declared. Port 4 pin 0 is initialized as analog input on lines 9 and 10.

In the main program, three variables have been used: `ADC_out`, `ADC_OUT`, and `i`. `ADC_out` declared in line 6 is used to get the ADC value from the data register. `ADC_OUT` declared in line 8, is a string which contains the `ADC_out` in string form so that it can be displayed on the LCD. The variable `i`, declared in line 7, is used to print the A/D value once on the LCD. The ADC initialization function is called on line 13. After conversion is complete, the ADST bit of the ADCSR gets cleared to 0. This condition is checked (line 15) and the next few lines are executed only once using the variable `i`, if the conversion is complete, the A/D converted value is written to the variable `ADC_out` (line 16). The ADC data register was set to be right aligned. To avoid reading wrong bits, the value `0X0FFF` is used to mask the upper 4 bits (using zeros) and read the lower 12 bits (right bits). `ADC_out` is then converted into a string `ADC_OUT` (line 17) and displayed on the LCD (line 18).

Output

When a 3 V input was given to channel AN000, the A/D conversion result displayed was 3720. Using the formula, the A/D value is 3723.

6.5.2 10-Bit ADC

```
1. #include <stdio.h>
2. #include "iodefine.h"
3. #include "lcd.h"
4. void ADC_Init();
5. void main(void){
6.     unsigned short ADC_value;
7.     int i = 0;
8.     char ADC_OUT [13];
9.     PORTE.PDR.BIT.B0 = 0;
10.    PORTE.PMR.BIT.B0 = 1;
11.    lcd_initialize();
12.    lcd_display(LCD_LINE1,"10-bit ADC");
13.    ADC_Init();
14.        while(1){
15.            if(AD.ADCSR.BIT.ADST == 0 && i == 0){
16.                ADC_value = AD.ADDRA & 0x0FFF;
```

```
17.             sprintf (ADC_OUT,"%d",ADC_value);
18.             lcd_display(LCD_LINE2,ADC_OUT);
19.             i++;
20.             }
21.         }
22. }
23. void ADC_Init(){
24.     SYSTEM.MSTPCRA.BIT.MSTPA23 = 0;
25.     AD.ADCSR.BYTE = 0x00;
26.     AD.ADCR.BYTE = 0x0C;
27.     AD.ADCR2.BYTE = 0x00;
28.     AD.ADDIAGR.BYTE = 0x0;
29.     AD.ADCSR.BIT.ADST = 1;
30. }
```

The `iodefine.h` in line 2 defines the ports and the ADC registers which need to be set for the ADC operation. The `lcd.h` file (line 3) contains functions to use LCD. `ADC_Init` function initializes the ADC module. The function is defined in lines 23 to 30. The A/D Control/Status register (ADCSR) is set to select channel AN0 and disable interrupt (line 25). The A/D Control Register (ADCR) is used to select single mode, PCLK and software trigger (line 26). The ADCR2 register is used to select right alignment (line 27). The Self-Diagnostic function is set to off (line 28). The ADC is started on line 29.

In the main program three variables have been used: `ADC_value`, `ADC_OUT`, and `i`. `ADC_value` declared in line 6 is used to get the ADC value from the data register. `ADC_OUT` declared in line 8 is a string which contains the `ADC_value` in string form so that it can be displayed on the LCD. The variable `i`, declared in line 7, is used to print the A/D converted value once on the LCD. Port E pin 0 is set as analog input on lines 9 and 10. The LCD is initialized using built-in function (line 11). The program name is displayed on LCD (line 12) and ADC is initialized (line 13). After conversion is complete, the ADST bit of the ADCSR gets cleared to 0. This condition is checked (line 15) and the next few lines are executed only once using the variable `i`. If conversion is complete, the A/D converted value is written to the variable `ADC_value` (line 16). The Data Register was set to be right aligned. Hence, to avoid reading wrong bits, the value `0X0FFF` is used to mask the upper 4 bits (using zeros) and read the lower twelve bits (right bits). `ADC_value` is then converted into a string `ADC_OUT` (line 17) and displayed on the LCD (line 18).

Output

When a 3 V input was given to channel AN0, the A/D conversion result displayed was 1007. Using the formula, the A/D value is 930.

6.5.3 DAC

To understand how to program DACs let us look at an example in which DAC unit1 has been used.

```
1. #include "iodef.h"
2. #define "lcd.h"
3. void DAC_Init();
4. void main(void){
5.     PORT0.PDR.BIT.B5 = 1;
6.     PORT0.PMR.BIT.B5 = 0;
7.     lcd_initialize();
8.     lcd_display(LCD_LINE1, "DAC");
9.     DAC_Init();
10.    while(1){
11.    }
12.
13. void DAC_Init(){
14.     SYSTEM.MSTPCRA.BIT.MSTPA19 = 0;
15.     DA.DADR1 = 102;
16.     DA.DACR.BYTE = 0x9F;
17. }
```

The header files `iodef.h` and `lcd.h` (lines 1 and 2) are needed as they contain definitions of registers and the LCD functions respectively. `DAC_Init` function initializes the DAC module. Its definition is on lines 13 to 17. The right aligned value in D/A Data register (`DADR1`) is 102 (line 15). The D/A Control Register (`DACR`) selects channel 1 (line 16).

In the main function, Port 0 pin 5 is set as output (lines 5 and 6). The LCD is initialized using `lcd_initialize` function (line 7) written in `lcd.c`. The name of the program is displayed on LCD line 1 (line 8). The `DAC_Init` function is called (line 13) to set up and start the D/A conversion. The while loop (line 10) is used to let the analog value on the pin forever. The analog value can be checked by a multimeter.

6.6 RECAP

Thus we have seen how the ADC and DAC of the RX63N board can be programmed. The methods discussed above have been using polling. Polling is not very efficient. An efficient method of using these features would be using interrupts. Interrupts are discussed in detail in Chapter 9.

6.7 REFERENCES

[1] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013

6.8 EXERCISES

1. What is the output code (in decimal) of a 12-bit ADC with $V_{in} = 2.7\text{ V}$? $V_{+ref} = 5\text{ V}$? $V_{-ref} = -5\text{ V}$?
2. What is the output code (in decimal) of a 10-bit ADC with $V_{in} = 3\text{ V}$? $V_{+ref} = 5\text{ V}$? $V_{-ref} = 0\text{ V}$?
3. Given the following information of a particular analog to digital converter, determine the value of the digitally represented voltage and the step size of the converter:
 - The device is 10-bit ADC with a V_{+ref} —reference voltage of 3.3 volts and a V_{-ref} reference voltage of 0 volts.
 - The digital representation is: 0100110010.
4. What is the maximum quantization error for a 10-bit ADC with $V_{+ref} = 3.3\text{ V}$, $V_{-ref} = 0\text{ V}$?
5. Write a simple subroutine to set up the ADC registers for a 12-bit ADC operation of the following specifications: continuous scan mode, software triggered, PCLK/4, and Channel AN3.
6. Identify the modifications to be made if the above problem works on the value addition mode (3—time conversion).
7. Write a subroutine to set up the registers for a 10-bit ADC operation of the following specifications: continuous scan mode on channels AN1 and AN2, software triggered, PCLK/2, and data aligned to the LSB end.
8. Write a program to display the percentage of light intensity given a light sensor circuit. Record the ‘darkness’ (cover the sensor to make it dark) and ‘brightness’ (shine a bright LED or other light on the sensor) values. Identify the correct calibration such that the average room light lies between these values.

Serial Communications

7.1 LEARNING OBJECTIVES

Microcontrollers often need to communicate with other devices. Sending information serially (rather than in parallel) reduces the number of signal connections needed, saving space and cost. This chapter introduces how microcontrollers can exchange information serially using the UART, SPI, and I²C communication controllers.

7.2 BASIC CONCEPTS OF SERIAL COMMUNICATIONS

Communication is the exchange of information between entities. In computers, information can be of any form which can be represented in a digital form. The medium of communication is electrical signals that vary continuously between high and low. The patterns in which they vary follow a set of rules that dictate the information the two entities want to exchange. Also these signals can be communicated one at a time, or as we are familiar with by now, bit by bit; or all at the same time on a single set of wires. The former is called serial communication wherein the information/data is sent 1 bit at a time, and the latter is called parallel communication where more than a single bit of data is shifted out at the same time from one side of the communication channel. Also there can be information channels where both ends can send as well as receive information at the same time. Such channels are called full duplex channels.

Parallel communication is primarily used when there is a need to transfer data at a very high speed over short distances, such as inside a computer from one peripheral to another. In such cases, the data and its delivery is of utmost importance. Parallel forms of communication are usually implemented using a bus. You may already be familiar with commonly used terms when talking about computer peripherals such as the IDE bus or the PCI bus. A fact to note is that these are low capacitance wires bundled together to form the bus and are usually not extremely long. Among other factors which affect the choice of parallel or serial communication are: the PCB board space, number of I/O pins, density, capacitance, signal integrity, and optical/electrical.

Serial communication, on the other hand, is a preferred medium when data is to be transferred over long distances. This may include a range of a couple hundred feet, from

one building to another, or one computer to another. Serial communication is usually much slower than parallel. However, with the advent of time and technology, serial busses are becoming more and more high speed and are now also being used for short distances; i.e., internal communication mechanisms of computers.

In this chapter, we will primarily deal with serial communication only to establish data transfer between the Renesas microcontroller and a PC or other microcontroller boards or devices using various protocols such as USART, SPI, and I²C. It should be noted that there are other protocols beyond these that are also available with the RX63N; however, they require implementation using complex techniques. As you go through this chapter you will learn:

- The basics of each technique for serial communication, through polling; since polling is the best way to understand the exact details of the working of the peripheral device.
- The practical working of each technique through guided and intricately explained examples.
- How to distinguish between the implementation of each technique and the overheads of communication along with necessary precautions.

Before we jump into understanding the working of each serial communication interfacing technique, it is necessary to understand the terminologies that are used while talking about serial communication, and also understand the need for communication. So why would we need communication between different peripherals? A few examples are mentioned below:

- **Parallel Computation:** In these cases, a complex problem is broken down into smaller, less complex parts and is distributed to other computers on a network, solved and then returned back to the source. The result is a reduction in the time taken to solve the problem, full use of available resources, etc.
- **Data acquisition from remote locations:** This is prominent in industrial applications where there are sensors deployed in the field or inside a factory. The sensors continuously gather data and send it to a central controller which monitors them and controls the overall system.
- **Control of remote devices such as smart transducers.**
- **Developing fault tolerant systems.**

Terminologies

Serial Port: A communication junction that provides for connecting a cable responsible for conducting electrical signals between the communicating entities, usually a 9 pin DBI male/female header.

Bus: One or more wires shared between devices in order to communicate electrical signals.

Baud Rate: Number of symbols transferred per second. A symbol may represent one or more bits of data through its encoding.

Bit Rate: Number of bits of information transferred per second.

Start Bit: Initial bit sent on the communication channel before communication begins.

Stop Bit: Final bit sent on the communication channel before communication terminates.

Parity Bit: A bit included in the communicated data whose status determines the parity (even/odd) of the information/data byte transferred.

Simplex Communication: A communication channel that can perform communication in only one direction, for example, family radios and walkie-talkies.

Full Duplex Communication: A communication channel is considered to be full duplex if both entities at the end of the channel can communicate in both directions simultaneously; i.e., transmit and receive data.

Half Duplex Communication: A communication channel/port is said to be half duplex if it can either transmit or receive data at an instant of time, but not simultaneously.

Synchronous: A clock signal accompanies the data being transmitted on a separate line thereby synchronizing the two end processors. Examples of such buses are HDMI and DVI for video signals.

Asynchronous: A clock signal does not accompany the data being transmitted. Instead an internal clock is maintained on both ends of the communicating modules to assist in synchronizing the data transfer. Typical PC serial port communications devices are an example of such transfers.

Now that we are familiar with some of the terms and needs of serial communication, we are ready to learn a few of the different interfaces available with the RX63N in detail. **Section 7.2** will introduce basic concepts applicable to each serial communication interface. **Section 7.3** will demonstrate the concepts of **Section 7.2** by providing an example for each interface. **Section 7.4** will describe advanced concepts of serial communication and **Section 7.5** will demonstrate them with more complex examples.

7.2.1 Introduction to the RX63N Serial Communication Interfacing

In order to fulfill the previously mentioned needs for communication between the processor and its desired peripherals or other devices, the RX63N has been provided with various mechanisms. These include the serial communication interface (SCI), Renesas serial peripheral interface (RSPI), and the Renesas Inter Integrated Chip (RIIC) bus interface. All three interfaces perform the same task of communicating data between various entities serially; i.e., one 1 every cycle, however, the manner in which they do so is different for each interface. Depending upon the different requirements of communication, such as speed, number of devices needed to connect to, or topography of the communication, you may choose between the three different interfaces as desired. The three interfaces along with their features are described in the following:

Serial Communication Interface (SCI): This interface provides for one of the oldest and most fundamental methods in serial communication, the Universal Synchronous/Asynchronous Receiver/Transmitter (USART). The RX63N microcontroller has a total of six of these interfaces available which support USART communication as well as provide an interface to smart cards. The SCI has a variable transfer speed due to the availability of an on-chip bit-rate generator and can transfer data with either the MSB or LSB leading the communication. It also provides for multi-processor communication functions. Other available functions include data length selection (i.e., 7 or 8 bits), number of stop bits, parity selection, clock source selection, receive error detection, and break detection. Details of the SCI are further discussed in **Section 7.2.2**.

Serial Peripheral Interface (RSPI): The Renesas SPI is a means for high-speed synchronous data transfer between the microcontroller and other connected serial peripherals, such as an SD card or other Renesas microcontrollers. The RSPI provides two channels for serial transfer. Each channel has either 3 or 4 pins; i.e., MISO, MOSI, SPCK, and SSL depending upon the mode of operation. The RSPI also has interchangeable data formats with which one can transmit either the LSB or MSB at the start of communication. The RSPI is also capable of handling data as either a master or slave. These shall be further discussed in **Section 7.2.3**. The number of bits transferred by the RSPI can be varied between 8 to 32 bits. The RSPI operates through the means of a double buffer for both transmission and reception; each of which is 128-bits long, thereby permitting storage of four 32-bit long frames.

I²C Bus Interface (RIIC): The RIIC is a simple, powerful, and flexible serial transmission method that generally operates using only two wires with a well-defined protocol. The RIIC provides for two channels with variable communication formats and transfer rates up

to 1 Mbps. Also a total of 128 devices may be connected on a single RIIC bus may be connected at a time with only the requirement of a pull up resistor. Details of the RIIC bus are discussed in **Section 7.2.4**.

Table 7.1 provides for a comparison between the mentioned interfaces:

TABLE 7.1 Comparison Between Different Interfaces.

	SERIAL COMMUNICATION INTERFACE	RENESAS SERIAL PERIPHERAL INTERFACE	RENESAS INTER INTEGRATED CHIP BUS
Modes	USART/Smart Card interface	Four wire/Three wire mode	I ² C mode or SM bus mode
Max transfer speed	1.92 Mbps with PCLK @ 50 MHz	Up to 25 Mbps	Up to 1 Mbps
Max. number of devices/slaves connected per bus	1	8 SPI integrated channels for slave selection	127
Number of wires required for communication (not including ground)	2 to 3	3 to 4	2
Max. length of wires [1], page 9.	40 meters @ 1 Mbps	10 feet with clock speed of few kHz	10 meters @ 100 kbps
Number of bits per unit transfer (excluding start and stop)	7 or 8	Up to 32 bits	8
Slave selection method	Addressed during communication when in multi-processor communication mode, or else not available.	Using slave select line	Through addressing

Now that we have an idea of some of the different available techniques of serial communication available on the Renesas board and the differences between each of them, we can proceed to the details of operation for each interface available.

7.2.2 Universal Asynchronous Receiver and Transmitter

The UART/USART is one of the oldest mechanisms available for the serial transmission of data. The idea of a UART was developed in order to convert parallel data into serial data to be transmitted over large distances. This is usually done by means of a shift register which shifts out a 1 bit per clock cycle. Given the premise that the shift register clocks out a 1 bit per clock cycle, it requires one clock cycle to fill the shift register in parallel; and where the clock provided to both the CPU and the shift register is the same, one can easily determine that serial transmission is at least N times slower than parallel transmission, where N is the number of bits available in the serial register; i.e., if the size of the shift register is 8 bits, serial communication is at least eight times slower than parallel communication. Before we jump into detailed concepts of the Renesas UART, let us look at the mechanism of a shift register.

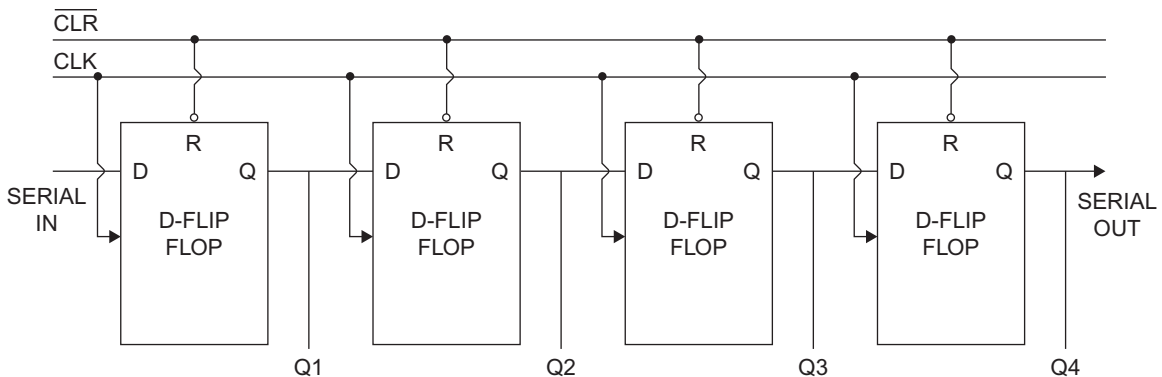


Figure 7.1 Serial Input Parallel Output (SIPO) shift register.

If one is familiar with digital circuits, one may easily note from Figure 7.1 that a shift register is nothing but a series of cascaded flip-flops that share the same clock. The most commonly used flip-flop for shift registers is the D flip-flop where the D stands for Delayed. More detailed information on the D flip-flop can be found in [2], but in essence it is enough to know that the flip-flop outputs the state of the input (D), or data, for every rising edge of the clock, and maintains it until the next rising edge. Depending on the configuration, there

can be two types of shift registers, Parallel In Serial Out (PISO) and Serial In Parallel Out (SIPO). A PISO type shift register shifts out data serially, that is, the data is input to the shift register through a parallel bus and gets shifted out onto the serial bus, and is therefore used on the transmitter side of the interface; whereas the SIPO type shift register takes data in serially and converts it to parallel form, and is thus used at the receiver side of the interface. The two types of shift registers are shown in Figure 7.1 and Figure 7.2 respectively. This is the basis of operation for the UART. More reading on the electronics part of the flip-flops can be found at [2].

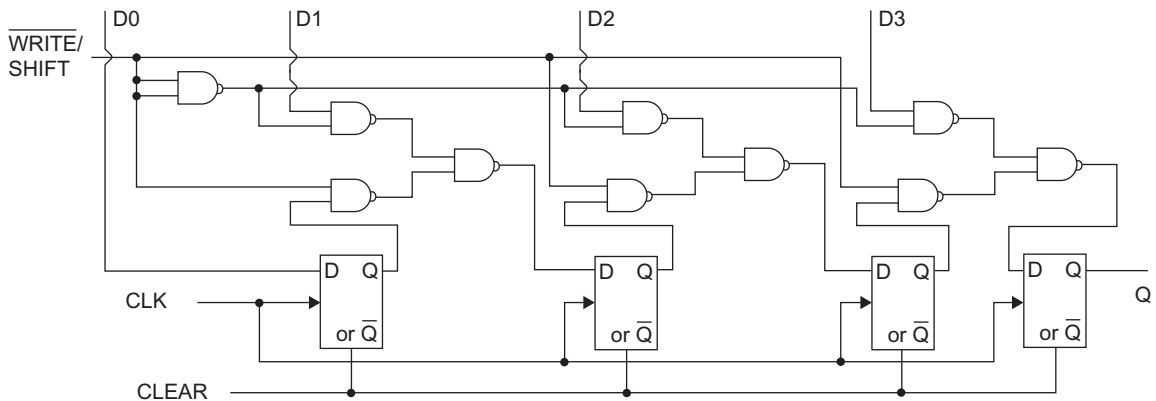


Figure 7.2 Parallel Input Serial Output (PISO) shift register.

Now that we are aware of the basic mechanism of UART serial communication, it is worthwhile to notice that there are various other overheads to communication that are required, such as ensuring that the data has been communicated properly and identified. These are usually done by addition of extra bits in the communication process. Additional bits are padded to the 8 bits of data, and then the data is transmitted. The additional bits padded are the START, PARITY and STOP bits. When not communicating, both the TX(transmit) and RX(receive) lines are held in the high-impedance state. When transmission/reception of data is about to occur, the line is first pulled low. This period is called the START bit and is maintained for one clock cycle. After 8 bits of data transmission, the line is pulled high again and maintained high. This is the STOP bit and is maintained for at least one clock cycle before the next byte of data can be communicated. In this manner data is recognized over the channel for reception. But this

does not yet resolve the problem of incorrect data transmission. Over distances, electrical signals have a tendency to weaken, reduce in amplitude, and also pick up noise. This may result in data corruption. This is checked by the addition of an extra bit to the data, also called the parity. The parity bit is set to 1 or 0 in order to make the total number of 1 bits even (for even parity) or odd (for odd parity). One more note is that all the above mentioned transactions are performed at logic levels; i.e., voltages range from 0 to 3 V at most 5 V. These voltages are very much susceptible to noise and signal corruption over long distances. To prevent this, an amplifier circuit boosts and inverts the voltages so that they vary from -15 V (logical high) to $+15$ V (logical low). These are the voltage levels for the telecommunications Recommended Standard 232(RS-232). A level-shifting inverter circuit converts the RS232 voltages back to logic levels at each receiver. More information regarding the RS-232 standard can be found in [3]. This concludes the basic working mechanism of the UART. Now we come to the control part of the UART, which is essentially done by means of a few special function registers (SFRs) that are linked to the serial communications interface available with the Renesas Microcontroller.

Registers Related to the SCI in UART Mode

The Serial Communications Interface provides for a Universal Synchronous Transmitter/Receiver, a Universal Asynchronous Transmitter/Receiver, a Smart Card interface, simple I2C bus, and simple SPI bus. The Renesas Microcontroller has 13 independent serial communication interface channels. The SCI is configured as SCIC module (SCI0 to SCI11) and SCID module (SCI12). However, before one can use the SCI it needs to be properly configured to work in one of the five modes. We shall be configuring the SCI to work as a UART, and therefore we would be talking about the special function registers and the values to be injected into them to make the UART work successfully. Finally, we will discuss how to test the configured UART and the physical variations possible to the communication signals.

The special function registers related to the UART are:

- Smart Card Mode Register (SCMR)
- Serial Mode Register (SMR)
- Serial Control Register (SCR)
- Serial Status Register (SSR)
- Bit Rate Register (BRR)
- Transmit Data Register (TDR)
- Receive Data Register (RDR)
- Serial Extended Mode Register (SEMR)
- Noise Filter Setting Register (SNFR)

Smart Card Mode Register (SCMR): This is the register that selects whether the SCI is going to be in either the Smart Card Interface mode or act as a UART or USART. It has 4 bits that need to be assigned values. However, since we are only concerned with setting up the SCI as a UART, the only bit we need to be concerned with is the SMIF bit. Setting this bit to 1 causes the particular SCI to enter smart card interface mode else the SCI can behave as either a synchronous or asynchronous transmitter/receiver. Hence we always set it to 0.

	b7	b6	b5	b4	b3	b2	b1	b0
	BCP2	—	—	—	SDIR	SINV	—	SMIF
Value after reset:	1	1	1	1	0	0	1	0

Figure 7.3 The SCI Smart card mode register [4], page 1311.

Serial Mode Register (SMR)

This special function register is concerned with operational variations of the UART. The register details are as follows:

	b7	b6	b5	b4	b3	b2	b1	b0
	CM	CHR	PE	PM	STOP	MP	CKS[1:0]	
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.4 The SCI Serial mode register [4], page 1300.

- **CKS[1:0]:** These bits selects the clock speed applied to the shift register, which is related to the TDR is the PCLK. The frequency of this clock can be reduced by means of a frequency divider. This is selectable by the CKS1 and CKS0 bits which give combinations to divide the PCLK frequency by 1, 4, 16, or 64. Refer to Table 7.2 for details. These bits usually depend upon the acceptable baud rate error and the value of the BRR register.
- **MP:** This bit enables or disables the multi-processor communications function. Setting the multi-processor mode bit MP in the SMR causes the UART to become aware of multi-processor communication taking place on the channel. If one is not using multi-processor communication, this bit is set to 0. Multi-processor mode (or 9 bit wake-up mode, or multidrop mode) was a very common way of placing more than one slave on an UART bus or giving it multi-drop capability. In these systems when the ninth bit was set as a high this indicated that the remaining 8 bits were the address of the device that the Master wanted to communicate with. All

devices processed the address field. Only the device with the corresponding address continued to communicate, all other devices went back to “sleep” waiting for the next address command. In most devices that support MP the UART peripheral will create an interrupt when the ninth bit is high. This allows the devices that are not actively communicating with the Master to ignore all other traffic on the bus, reducing the overhead on those MCUs.

- **STOP:** This bit determines the length of the stop bit, whether it is either 1 or 2 bits wide. Setting this bit to 0 selects length of stop bit as 1 whereas setting it to 1 causes the length of stop bit to be 2 bits wide.
- **PM:** Setting this bit to 1 causes the parity bit to be high when the parity of the data is odd; whereas, setting this bit to 0 causes the parity bit to be high if the parity of the data is even.
- **PE:** Setting this bit to 1 enables the transmission of the parity bit and disables otherwise.
- **CHR:** Setting this bit to 1 truncates the size of the data being transmitted to 7 bits, or else 8-bit long data is transmitted.
- **CM:** This bit determines the operation of the SCI, whether it is operating in synchronous or asynchronous mode. If this bit is set to 1, the interfaces act in the clock synchronous mode, or else it enters the clock asynchronous mode. If operating in the clock synchronous mode, a clock signal can be generated on the SCLK line by the transmitter which also acts as the clock input to the shift register on the receiver end of the module. Selection whether the clock is input or output is dependent on the state of the CKE bit in register SCR.

Serial Control Register (SCR)

This register is responsible for controlling the Serial Communications Interface; whether it is turned on or off, the choice of input clock to the shift register, and function of the SCK pin. The register details are as follows:

b7	b6	b5	b4	b3	b2	b1	b0
TIE	RIE	TE	RE	MPIE	TEIE	CKE[1:0]	
Value after reset:	0	0	0	0	0	0	0

Figure 7.5 The SCI serial control register [4], page 1303.

- **CKE[1:0]:** These bits determine which clock is to be used when transferring data, internal or external, and the function of the SCKn pin corresponding to the SCIn module. The Table 7.2 determines the functions depending on each of the four combinations of the 2 bits when the SCI is in Asynchronous mode.

- TEIE: Setting this bit to 1 and 0 enables and disables the transmit end interrupt that is generated every time a byte is transmitted from the SCI.
- MPIE: This bit is related to multi-processor communication and is usually set to 0 when there is no multi-processor communication occurring on the bus.
- RE: Setting this bit to 0 and 1 disables and enables reception of data on the Rxn pin, respectively.
- TE: Setting this bit to 0 and 1 disables and enables transmission of data on the Txn pin, respectively.
- RIE: Setting this bit to 1 and 0 enables and disables the generation of a receive interrupt, respectively.
- TIE: Setting this bit to 1 and 0 enables and disables the generation of a transmit interrupt, respectively.

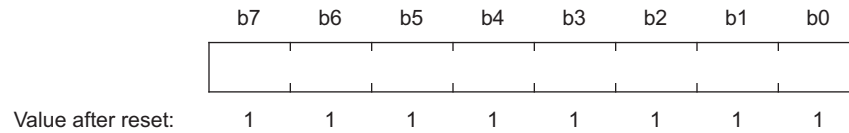
Serial Status Register (SSR)

This is a read only type of register (except for bit 0) which determines the condition of the currently received byte over the corresponding SCI by means of various flag bits.

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	ORER	FER	PER	TEND	MPB	MPBT
Value after reset:	x	x	0	0	0	1	0	0

Figure 7.6 The SCI serial status register [4], page 1307.

- MPBT: This bit sets the value of the multi-processor bit for adding to the transmission frame
- MPB: This bit holds the value of the multi-processor bit in the reception frame. Note that the value of this bit does not change when RE bit in SCR is kept as 0. This is a read only type bit.
- TEND: This flag is set at the end of transmission of a byte from the TDR or in case the serial transmission is disabled. Resetting this flag requires one to write data to the TDR.
- PER: This bit indicates a parity error has occurred during reception in asynchronous mode and reception ends abnormally. When a parity error occurs, data is maintained in the RDR and the parity error flag is set but subsequent reception is terminated until PER is reset
- FER: This flag is set when a low error signal and reset after clearing to 0 manually
- ORER: This flag is set if data is received in RDR before the previous data has been read. The flag is cleared when 0 is written to it.

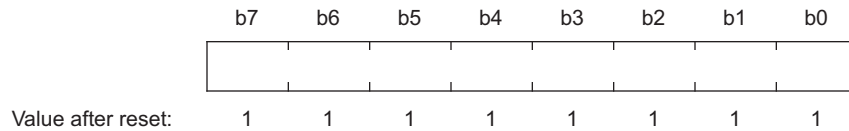
Bit Rate Register (BRR)**Figure 7.7** The SCI bit rate register [4], page 1312.

This is the register that controls the generation of the clock signal to be provided to the shift registers. Table 7.2 shows the relation between the value N input into the BRR and the bit rate B for normal asynchronous mode. In asynchronous mode, one should note that there is always a minor difference in timings between the two processors involved in communication, due to the minor differences in parts (oscillator circuits). The actual bit rate may not exactly meet the desired rate because only rates which can be generated by dividing PCLK by multiples of 16 are possible. Therefore, an error in communication, such as loss of reception of a bit, may occur if the bit rate mismatch (error) between the transmitter and receiver is too large. Table 7.2 defines a few standard values of BRR along with the generated bit rate's percentage error for each case.

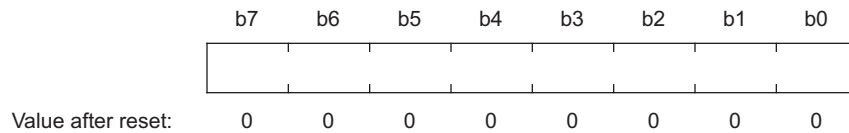
TABLE 7.2 Bit Rates and Percent Errors

(N = BRR value, n = Clock source setting with CKS bits in SMR).

BIT RATE (bit/s)	OPERATING FREQUENCY PCLK (MHz)											
	25			30			33			50		
	n	N	ERROR (%)	n	N	ERROR (%)	n	N	ERROR (%)	n	N	ERROR (%)
110	3	110	-0.02	3	132	0.13	3	145	0.33	3	221	-0.02
150	3	80	0.47	3	97	-0.35	3	106	0.39	3	162	-0.15
300	2	162	-0.15	2	194	0.16	2	214	-0.07	3	80	0.47
600	2	80	0.47	2	97	-0.35	2	106	0.39	2	162	-0.15
1200	1	162	-0.15	1	194	0.16	1	214	-0.07	2	80	0.47
2400	1	80	0.47	1	97	-0.35	1	106	0.39	1	162	-0.15
4800	0	162	-0.15	0	194	0.16	0	214	-0.07	1	80	0.47
9600	0	80	0.47	0	97	-0.35	0	106	0.39	1	40	-0.77
19200	0	40	-0.76	0	48	-0.35	0	53	-0.54	0	80	0.47
31250	0	24	0.00	0	29	0.00	0	32	0	0	49	0.00
38400	0	19	1.73	0	23	1.73	0	26	-0.54	0	40	-0.77

Transmit Data Register (TDR)**Figure 7.8** The SCI transmit data register [4], page 1299.

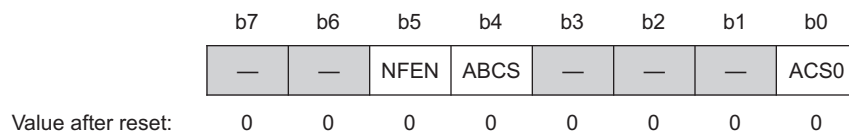
This register stores the data to be transmitted. When the SCI detects that the TSR register is empty, it transfers the data written in the TDR to TSR registers and starts transmission. The double-buffered structures of TDR and TSR registers enable continuous serial transmission. If the next frame of transmit data has already been written to the TDR register when one frame of data is transmitted, the SCI transfers the written data to the TSR register to continue transmission. Data for transmission should only be written to the TDR register once after each instance of the transmit data empty interrupt (TXI).

Receive Data Register (RDR)**Figure 7.9** The SCI receive data register [4], page 1299.

This register stores data received. When the SCI has received one frame of serial data, it transfers the received serial data from the RSR register to the RDR register where it is stored. This allows the RSR register to receive the next frame of serial data. Since the RSR and RDR registers function as a double buffer in this way, continuous receive operations can be performed. RDR should only be read once after a receive data full interrupt (RXI) has occurred. Note that if the next frame of data is received before the previously received frame of data is read from the RDR register, an overrun error will occur.

Serial Extended Mode Register (SEMR)

This register selects the clock source for the 1-bit period when operating in asynchronous mode.

**Figure 7.10** The SCI serial extended mode register [4], page 1320.

- **ACSO:** This bit selects the clock source. Setting this bit to 0 enables an external clock input. Setting this bit to 1 selects the TMR clock input. When operating in UART mode we are not concerned with enabling the TMR clock input, thus this bit should always be set to 0 when operating the SCI in UART mode.
- **ABCS:** This bit selects between 16 base and 8 base clock cycles for the 1-bit period. Setting this bit to 0 selects 16 base clock cycles, while setting this bit to 1 selects 8 base clock cycles. This bit is only valid in asynchronous mode.
- **NFEN:** This bit enables or disables the digital noise filtering function. Setting this bit to 0 disables the noise filtering function for the RXDn input signal, while setting this bit to 1 enables the noise filtering function for the RXDn signal.

Noise Filter Setting Register (SNFR)

This register selects the sampling clock for the digital noise filter. When operating in asynchronous mode, the NFCS[2:0] bits are set to 0 resulting in the clock signal divided by 1 being used with the noise filter. Writing to these bits is only possible when the RE and TE bits in the SCR register are set to 0.

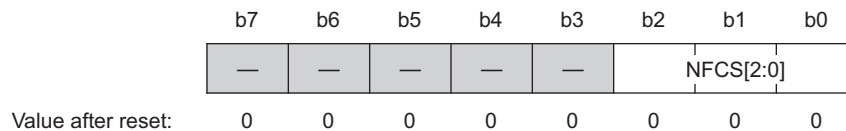


Figure 7.11 The SCI noise filter setting register [4], page 1322.

- **NFCS[2:0]:** These bits select the sampling clock for the digital noise filter. To use the noise filter in asynchronous mode, set these bits to 000b.

Variations to the UART

Before we move on to other techniques of serial communication, it is worthwhile to mention that there are other UART-based communication standards which use different types of voltage signaling, such as the RS-422, RS-423, RS-449, and RS-485. More readings on these can be found at [5].

7.2.3 Renesas Serial Peripheral Interface

Serial Peripheral Interface (SPI) uses synchronous communication, so a dedicated clock signal must be transmitted in addition to the serial data. Providing this clock signal lets us simplify the hardware down to just the shift registers and some minor supporting logic. This is

much simpler than the USART, as there is no need for a bit rate generator, start and stop bits, and other modules. The dedicated clock signal determines the bit rate. This interface is similar to the USART. SPI is a full duplex mode of communication in which data can be transmitted and received simultaneously. The SPI was designed by Motorola to achieve high speed data transfer between peripherals of a microcontroller, and generally requires three wires for communication. In case multiple slave devices (devices to communicate with) are attached on the SPI bus, additional lines for selecting the device are required. However if not more than one slave device is connected on the bus, communication may be performed with only three wires. A typical SPI set up between a microcontroller and a peripheral is shown in Figure 7.12. As seen in the figure, the devices connected on the SPI bus usually have one master and one or more slave peripherals. However a multi-master mode may also be used. Master devices are usually microcontrollers or processors that control the flow of data to and from the slave peripheral device. The four required lines for communication are Serial Clock (SCLK), Master In Slave Out (MISO), Master Out Slave In (MOSI), and Slave Select (SSL).

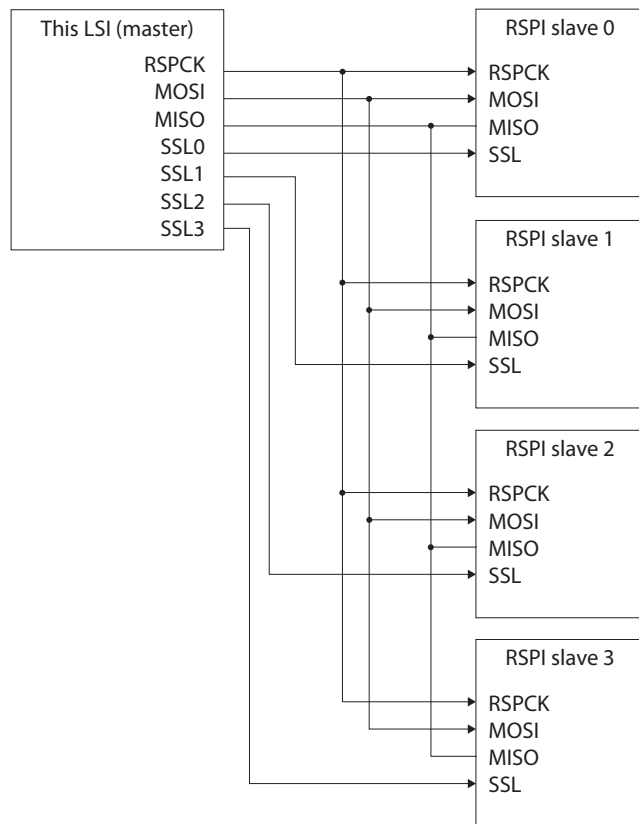


Figure 7.12 Serial Peripheral Interface bus; Single master with multiple slaves connected [4], page 1559.

Serial Clock: Accompanying each data transfer is a clock signal that synchronizes the Master and Slave device. The length of the clock signal also determines the amount of data transferred on the MISO and MOSI pins. The serial clock is always generated by the master device and the slave synchronizes itself and the data transfer using the same clock.

Master Out Slave In: This line is similar to the transmit line of the USART, provided the Master device remains the same.

Master In Slave Out: This line is similar to the receive line of the USART, provided the Master device remains the same.

Slave Select: This pin, when acting as an output pin, provides for an active low signal that activates or de-activates the slave. The slave is usually in sleep mode until this line is toggled to the desired state (low or high) for activating the device. When in multi master mode, this pin acts as an input, and when pulled low indicates that another master is trying to communicate on the SPI bus.

Now that we have an introduction to the physical part of the SPI interface, it is time to understand the working. But before we move on, it is worthwhile to note some of the features of the Renesas SPI that are different from most other microcontrollers. The Renesas Microcontroller has two independent SPI modules with multiple (four) slave select lines for each channel. The important features of the Renesas Serial Peripheral Interface are:

- Transmit only operation available.
- Switching of phase and polarity of the serial clock.
- LSB/MSB first option.
- 128-bit transmit/receive buffers.
- Transfer bit length is selectable as 8, 9, 10, 11, 12, 13, 14, 15, 16, 20, 24, or 32 bits.
- Up to four frames can be transferred in one round of transmission/reception (each frame consisting of up to 32 bits).
- Mode fault error, overrun error, and parity error detection.
- A transfer of up to eight commands can be executed sequentially in looped execution with SSL signal value, bit rate, RSPCK polarity/phase, transfer data length, LSB/MSB-first, burst, RSPCK delay, SSL negation delay, and next-access delay which can be changed for each command.
- A transfer can be initiated by simply writing to the transmit buffer.

General Working of SPI Modules

During every SPI transfer, there always exists a Master device and a slave device. The master device is the one responsible for performing the transfer of data and generating the clock signal for performing the synchronous transfer of data. The slave device, while receiving data also sends out data of its own to the master over the MISO line. Thus full

duplex communication occurs. The slave is active only when the master pulls the corresponding Slave Select Line low. This results in a “chip select” and activates the slave device.

Events take place in this sequence:

- Master selects slave by pulling SSL low, thereby activating the slave device for communicating data.
- Master starts synchronous transfer of data by sending out a clock signal over the SCLK pin and the data over the MOSI line. The master waits until the data transfer completes.
- On reception of the serial clock signal from the master, the slave device starts outputting data that it might want to transfer to the master.
- Data transfer halts as soon as the clock signal stops.
- Master deselects the slave by pulling the SSL line high.

Configurations of the Renesas SPI

The Renesas microcontroller SPI bus can be configured to have:

- Single Master Single Slave
- Single Master Multiple Slaves
- Multiple Masters Multiple Slaves

For the sake of simplicity, and understanding the basics of SPI, we shall consider only the Single Master Single Slave configuration. These configurations are shown in Figures 7.13 to 7.15.

Registers Related to the Renesas Serial Peripheral Interface

The following describes the registers that are responsible for control of the RSPI with a short explanation, and the values to be assigned to each bit for setting up the SPI in the single master single slave configuration with the RX63N functioning as the master device.

Serial Peripheral Control Register (SPCR): This register controls the operating mode of the RSPI. The functions of the bits are as follows:

- SPMS: This is the RSPI mode select bit which determines whether the SPI will act as a three wire (SCLK, MOSI, MISO) or a four wire interface (SCLK, MOSI, MISO, and SSL_n). Setting this bit to 0 makes the RSPI operate in four wire mode whereas setting it to 1 makes the RSPI function in three wire clock synchronous mode. When operating in four wire mode, the pins SSL0 to SSL3 become available for chip selection; the default chip (slave) select pin being SSL0. When

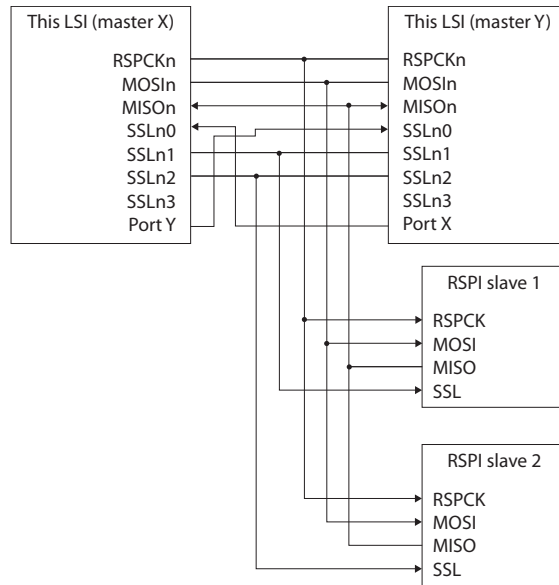


Figure 7.13 Multiple Masters Multiple Slaves [4], page 1561.

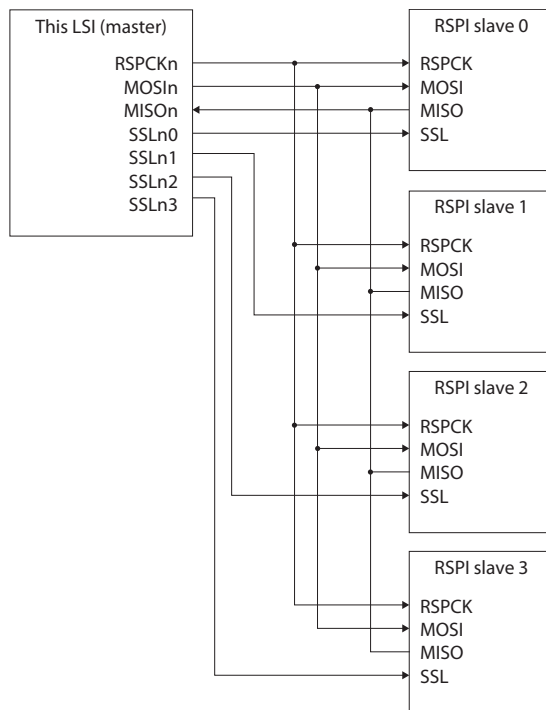


Figure 7.14 Single Master Multiple Slaves [4], page 1559.

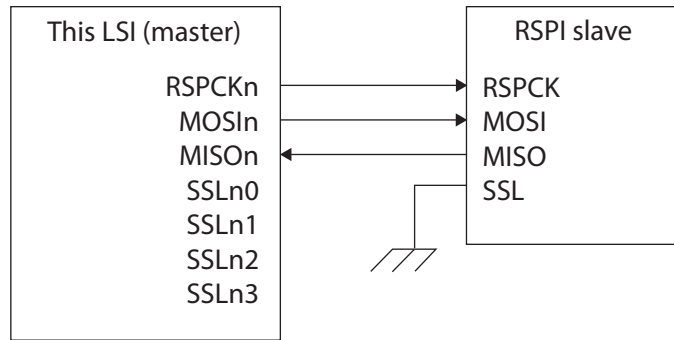


Figure 7.15 Single Master Single Slave (also shows clock synchronous configuration) [4], page 1557.

	b7	b6	b5	b4	b3	b2	b1	b0
	SPRIE	SPE	SPTIE	SPEIE	MSTR	MODFEN	TXMD	SPMS
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.16 The SPI serial peripheral control register [4], page 1537.

operating in three wire mode, it is assumed that either the desired chip is selected manually or there is only one active SPI slave on the device.

- **TXMD:** This is the Communications Operating Mode Select bit that determines whether the SPI will be acting in full duplex mode or perform transmit operations only.
- **MODFEN:** This bit enables or disables mode fault error detection. Mode fault error occurs when the SPI is in master mode and an external device drives a slave select pin low.
- **MSTR:** This bit determines whether the microcontroller acts as a master or a slave.
- **SPEIE:** Setting this bit to 1 enables the generation SPI error interrupt. This interrupt occurs when the RSPI module detects a mode fault or an overrun error, and sets the corresponding bits in the status register SPSR to 1.
- **SPTIE:** Setting this bit to 1 enables SPI transmit interrupt to indicate that the transmit buffer is empty.
- **SPE:** Setting this bit to 1 enables the SPI module.
- **SPRIE:** Setting this bit to 1 enables SPI receive interrupt. The interrupt occurs whenever the receive buffer is successfully written without errors.

Serial Peripheral Control Register (SPCR2): This register adds to the controllability of the operating mode of the Renesas SPI. The functions of the bits are as follows:

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	—	—	PTE	SPIIE	SPOE	SPPE
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.17 SPI serial peripheral control register 2 [4], page 1551.

- **SPPE:** This bit enables or disables the parity function. The parity bit is added to transmit data, and parity checking is performed for receive data when the communications operating mode select bit (TXMD) in the RSPI control register (SPCR) is 0 and the SPPE bit in SPCR2 is 1. The parity bit is added to transmit data but parity checking is not performed for receive data when the SPCR.TXMD bit is 1 and the SPPE bit in SPCR2 is 1.
- **SPOE:** When even parity is set, parity bit addition is performed so that the total number of 1-bits in the transmit/receive character plus the parity bit is even. Similarly, when odd parity is set, parity bit addition is performed so that the total number of 1-bits in the transmit/receive character plus the parity bit is odd. The SPOE bit is valid only when the SPPE bit is 1.
- **SPIIE:** The SPIIE bit enables or disables the generation of RSPI idle interrupt requests when the RSPI being in the idle state is detected and the IDLNF flag in the RSPI status register (SPSR) is cleared to 0.
- **PTE:** This bit enables the self-diagnosis function of the parity circuit in order to check whether the parity function is operating correctly.

Slave Select Polarity (SSLP): This register sets the polarity of the slave select lines SSL0 to SSL3 of the Renesas SPI module. SSLP has four usable bits that select the polarity (active low/active high) for the corresponding slave select lines.

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	—	—	SSL3P	SSL2P	SSL1P	SSL0P
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.18 The SPI slave select polarity register [4], page 1538.

Setting the SSLxP bits to 0 sets the SSLx pin to active low, while setting SSLxP bit to 1 sets the SSLx pin to active high ($x = 0$ or 1 or 2 or 3).

Serial Peripheral Pin Control Register (SPPCR): This register sets the modes of the RSPI pins.

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	MOIFE	MOIFV	—	—	SPLP2	SPLP
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.19 The SPI pin control register [4], page 1539.

- **SPLP:** When the SPLP (SPI Loopback) bit is set to 1, the RSPI shuts off the path between the MISO pin and the shift register, and between the MOSI pin and the shift register, and connects (reverses) the input path and output path for the shift register (loopback mode).
- **SPLP2:** The function of this bit is the same as the SPLP. When the SPLP2 bit is set to 1, the RSPI shuts off the path between the MISO pin and the shift register, and between the MOSI pin and the shift register, and connects (reverses) the input path and output path for the shift register (loopback mode).
- **MOIFV:** If the MOSI Idle Fixed Value bit is 1 in master mode, the MOIFV bit determines the MOSI pin output value during the SSL negation period (including the SSL retention period during a burst transfer).
- **MOIFE:** The MOSI Idle Value Fixing Enable bit fixes the MOSI output value when the RSPI in master mode is in an SSL negation period (including the SSL retention period during a burst transfer). When the MOIFE bit is 0, the RSPI outputs the last data from the previous serial transfer during the SSL negation period. When the MOIFE bit is 1, the RSPI outputs the fixed value set in the MOIFV bit to the MOSI bit.

Serial Peripheral Status (SPSR): This register is an indicator of the current operating status of the RSPI.

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	—	—	PERF	MODF	IDLNF	OVRF
Value after reset:	x	0	x	0	0	0	0	0

Figure 7.20 The SPI serial peripheral status register [4], page 1540.

- **OVRF:** This Overrun error flag is set when a serial transfer ends while the SPCR.TXMD bit is 0 and the receive buffer holds data that has not yet been read, thereby indicating an overrun error. It is cleared when the CPU writes the value 0 to the OVRF bit.
- **IDLNF:** The RSPI Idle Flag indicates the transfer status of the RSPI. The IDLNF, when in master mode, is cleared when all of the following conditions are satisfied:
 - The SPCR.SPE bit is 0 (RSPI is initialized).
 - The transmit buffer (SPTX) is empty (data for the next transfer is not set).
 - The SPSSR.SPCP[2:0] bits are 000 (beginning of sequence control).
 - The RSPI internal sequencer has entered the idle state (status in which operations up to the next-access delay have finished).

The IDLNF bit, when in master mode, is set when any of the above conditions are not satisfied, thereby indicating a non-idle state.

When acting as a slave, this bit is set when the SPCR.SPE bit is 1 (RSPI function is enabled) and cleared when SPCR.SPE bit is 0 (RSPI is initialized).

- **MODF:** A SPI Mode Fault is detected in a multi master mode when the input level of the SSLn pin changes to the active level while the SPCR.MSTR bit is 1 (master mode) and the SPCR.MODFEN bit is 1 (mode fault error detection is enabled). When in slave mode, a mode fault is detected when the SSLn pin is negated before the RSPCK cycle necessary for data transfer ends while the SPCR.MSTR bit is 0 (slave mode) and the SPCR.MODFEN bit is 1 (mode fault error detection is enabled), the RSPI detects a mode fault error. The MODF flag is cleared by writing 0 to the MODF bit.
- **PERF:** The Parity Error Flag is set when a serial transfer ends while the SPCR.TXMD bit is 0 and the SPCR2.SPPE bit is 1. This bit is cleared when CPU reads SPSR when the PERF bit is 1, and then writes the value 0 to the PERF bit.

Serial Peripheral Data Register (SPDR): This register contains data to be transmitted and data received over the SPI channel. Data written to this register is transmitted over the SPI channel. When this register is read from it returns the data received over the transmission channel.

	b31	b30	b29	b28	b27	b26	b25	b24	b23	b22	b21	b20	b19	b18	b17	b16
	SPD31	SPD30	SPD29	SPD28	SPD27	SPD26	SPD25	SPD24	SPD23	SPD22	SPD21	SPD20	SPD19	SPD18	SPD17	SPD16
Value after reset:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	b15	b14	b13	b12	b11	b10	b9	b8	b7	b6	b5	b4	b3	b2	b1	b0
	SPD15	SPD14	SPD13	SPD12	SPD11	SPD10	SPD9	SPD8	SPD7	SPD6	SPD5	SPD4	SPD3	SPD2	SPD1	SPD0
Value after reset:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7.21 The SPI serial peripheral data register [4], page 1542.

The frame length and the number of bits transferred from this register depends upon the setting of the SPFC[1:0] and SPB[3:0] bits.

Serial Peripheral Sequence Control (SPSCR): This register sets the sequence method when the RSPI operates in master mode.

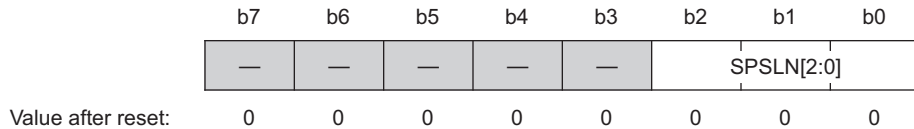


Figure 7.22 The SPI serial peripheral sequence control register [4], page 1545.

- SPSLN[2:0]: The SPI Sequence Length Specification bits specify a sequence length when the RSPI performs sequential operations in master mode. When in slave mode, the RSPI always refers to SPCMD0.

Serial Peripheral Sequence Status (SPSSR): This register indicates the sequence control status when the RSPI operates in master mode.

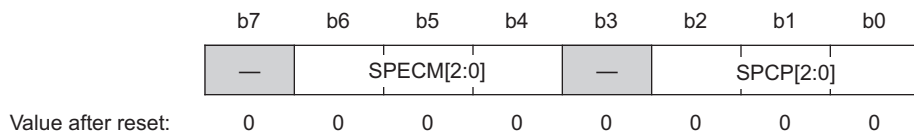


Figure 7.23 The SPI serial peripheral sequence status register [4], page 1546.

- SPCP[2:0]: The RSPI command pointer bits point to the SPCMDn currently being executed.
- SPEM[2:0]: The RSPI Error command in conjunction with the SPSR register points to the command SPCMDn which caused an error.

Serial Peripheral Bit Rate Register (SPBR): The value of this register determines the rate of data transfer.

	b7	b6	b5	b4	b3	b2	b1	b0
	SPR7	SPR6	SPR5	SPR4	SPR3	SPR2	SPR1	SPR0
Value after reset:	1	1	1	1	1	1	1	1

Figure 7.24 The SPI bit rate register [4], page 1547.

The SPBR register can have any value from 0 to 255. The following table shows a few example bit rate settings.

TABLE 7.3 Example Bit Rate Settings for the SPBR Register [4], page 1547.

SPBR (n)	BRDV[1:0] Bits (N)	DIVISION RATIO	BIT RATE			
			PCLK = 32 MHz	PCLK = 36 MHz	PCLK = 40 MHz	PCLK = 50 MHz
0	0	2	16.0 Mbps*	18.0 Mbps*	20.0 Mbps*	25.0 Mbps*
1	0	4	8.00 Mbps	9.00 Mbps	10.0 Mbps	12.5 Mbps
2	0	6	5.33 Mbps	6.00 Mbps	6.67 Mbps	8.33 Mbps
3	0	8	4.00 Mbps	4.50 Mbps	5.00 Mbps	6.25 Mbps
4	0	10	3.20 Mbps	3.60 Mbps	4.00 Mbps	5.00 Mbps
5	0	12	2.67 Mbps	3.00 Mbps	3.33 Mbps	4.16 Mbps
5	1	24	1.33 Mbps	1.50 Mbps	1.67 Mbps	2.08 Mbps
5	2	48	667 kbps	750 kbps	833 kbps	1.04 Mbps
5	3	96	333 kbps	375 kbps	417 kbps	521 kbps
255	3	4096	7.81 kbps	8.80 kbps	9.78 kbps	12.2 kbps

Serial Peripheral Data Control Register (SPDCR): This register determines the number of frames that can be stored in SPDR, controls the SSLn pin output reading from SPDR, and selects width access to SPDR.

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	SPLW	SPRDTD	—	—	SPFC[1:0]	
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.25 The SPI serial peripheral data control register [4], page 1548.

- **SPLW**: This bit specifies the access width for the SPDR. Setting this bit to 1 selects longwords while setting this bit to 0 selects words.
- **SPRDTD**: This bit specifies whether the SPDR reads data from the receive buffer or from the transmit buffer. Setting this bit to 1 selects the transmit buffer, while setting this bit to 0 selects the receive buffer.
- **SPFC[1:0]**: These bits specify the number of frames that can be stored in SPDR. Up to four frames can be transmitted or received in one round of transmission or reception, and the amount of data is determined by the combination of the RSPI data length specification bits (SPB[3:0]) in the RSPI command register (SPCMD), the RSPI sequence length specification bits (SPSLN[2:0]) in the RSPI sequence control register (SPSCR), and the number of frames specification bits (SPFC[1:0]) in the RSPI data control register (SPDCR). Also, the SPFC[1:0] bits specify the number of received data at which the RSPI receive buffer full interrupt is requested. The following table shows the frame configurations that can be stored in SPDR and examples of combinations of settings for transmission and reception.

TABLE 7.4 Settings for the Number of Frames Transmitted from SPDR [4], page 1549.

SETTING	SPSLN[2:0]	SPFC[1:0]	NUMBER OF FRAMES FOR TRANSFER	NUMBER OF FRAMES AT WHICH RECEIVE BUFFER FULL INTERRUPT OCCURS OR TRANSMIT BUFFER HOLDING DATA IS RECOGNIZED
1-1	000	00	1	1
1-2	000	01	2	2
1-3	000	10	3	3
1-4	000	11	4	4
2-1	001	01	2	2
2-2	001	11	4	4
3	010	10	3	3
4	011	11	4	4
5	100	00	5	1
6	101	00	6	1
7	110	00	7	1
8	111	00	8	1

Serial Peripheral Clock Delay Register (SPCKD): The value of this register sets a period from the beginning of SSL signal assertion to the clock oscillations on the RSPK line.

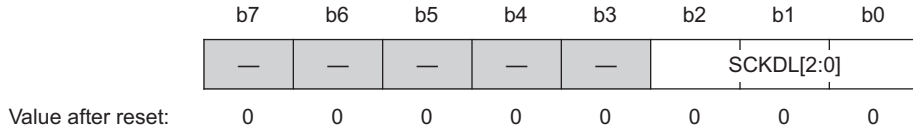


Figure 7.26 The SPI serial peripheral clock delay register [4], page 1549.

- SCKDL[2:0]: These bits set an RSPCK delay value when the SPCMDm.SCKDEN bit is 1. When using the RSPI in slave mode, set the SCKDL[2:0] bits to 000b.

Slave Select Line Negation Delay (SSLND): This register sets a period/delay from the transmission of final RSPCK edge to the negation of the SSL signal during a serial transfer by the RSPI in master mode.

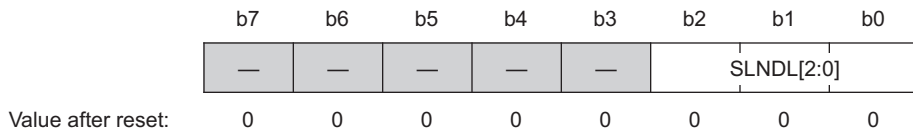


Figure 7.27 The SPI serial peripheral slave select negation delay register [4], page 1550.

- SLNDL[2:0]: These bits set a SSL negation delay value when the RSPI is in master mode. When using the RSPI in slave mode, set the SLNDL[2:0] bits to 000b.

Serial Peripheral Next Access Delay Register (SPND): This register sets a non-active period after termination of a serial transfer.

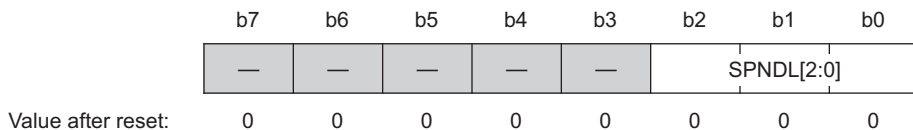


Figure 7.28 The SPI serial peripheral next access delay register [4], page 1550.

- SPNDL[2:0]: These bits set a next-access delay when the SPCMDm.SPNDEN bit is 1. When using the RSPI in slave mode, set the SPNDL[2:0] bits to 000b.

Serial Peripheral Command Register (SPCMDx): SPCMD0 to SPCMD7 are used to set a transfer format/method for the RSPI in master mode. The SPCMDx register has various fields that can be set to control the corresponding feature of the RSPI.

	b15	b14	b13	b12	b11	b10	b9	b8
	SCKDEN	SLNDEN	SPNDEN	LSBF		SPB[3:0]		
Value after reset:	0	0	0	0	0	1	1	1
	b7	b6	b5	b4	b3	b2	b1	b0
	SSLKP		SSLA[2:0]		BRDV[1:0]		CPOL	CPHA
Value after reset:	0	0	0	0	1	1	0	1

Figure 7.29 The SPI serial peripheral command register [4], page 1552.

- **CPHA:** This bit sets an RSPCK phase of the RSPI in master mode or slave mode. Data communications between RSPI modules require the same RSPCK phase setting between the modules.
- **CPOL:** This bit selects the RSPCK polarity. Setting this bit to 1 will make the RSPCK low when idle, while setting this bit to 0 will make the RSPCK high when idle.
- **BRDV[1:0]:** These bits are used to determine the bit rate. A bit rate is determined by combinations of the settings in the BRDV[1:0] bits and SPBR see [4], page 1547 table 38.3. The settings in SPBR determine the base bit rate. The settings in the BRDV[1:0] bits are used to select a bit rate, which is obtained by dividing the base bit rate by 1, 2, 4, or 8. In SPCMD0 to SPCMD7, different BRDV[1:0] bit settings can be specified. This permits the execution of serial transfers at a different bit rate for each command.
- **SSLA[2:0]:** These bits control the SSL signal assertion when the RSPI performs serial transfers in master mode. Setting the SSLA[2:0] bits controls the assertion for the SSL0 to SSL3 signals. When an SSL signal is asserted, its polarity is determined by the set value in the corresponding SSLP. When the SSLA[2:0] bits are set to 000 in multi-master mode, serial transfers are performed with all the SSL signals in the negated state (as the SSLn0 pin acts as input). When using the RSPI in slave mode, set the SSLA[2:0] bits to 000b.
- **SSLKP:** This bit RSPI in master mode performs a serial transfer, the SSLKP bit specifies whether the SSL signal level for the current command is to be kept or negated between the SSL negation timing associated with the current command

and the SSL assertion timing associated with the next command. When using the RSPI in slave mode, the SSLKP bit should be set to 0.

- SPB[3:0]: These bits set a transfer data length for the RSPI in master mode or slave mode.
- LSBF: This bit sets the data format of the RSPI in master mode or slave mode to MSB first or LSB first.
- SPNDEN: This bit sets the next-access delay enable. Setting this bit to 0 enables a next-access delay of $1 \text{ RSPCK} + 2 \text{ PCLK}$, while setting this bit to 1 enables a next-access delay equal to the setting of the SPND register.
- SCKDEN: This bit sets the period from the time when the RSPI in master mode activates the SSL signal until the RSPCK starts oscillation, also known as RSPI clock delay. Setting this bit to 0 sets the delay to 1 RSPCK. If this bit is set to 1 the delay of RSPCK will be in compliance with the settings of the SPCKD register. When using the RSPI in slave mode, the SCKDEN bit should be set to 0.

Configuring the RSPI to Function in Single Master Single Slave Mode

This is the simplest configuration possible in which we have 1 slave device connected to the Renesas Serial Peripheral Interface. **Section 7.3.2** describes the setup of the aforementioned RSPI registers for the Single Master Single Slave configuration as shown in Figure 7.30.

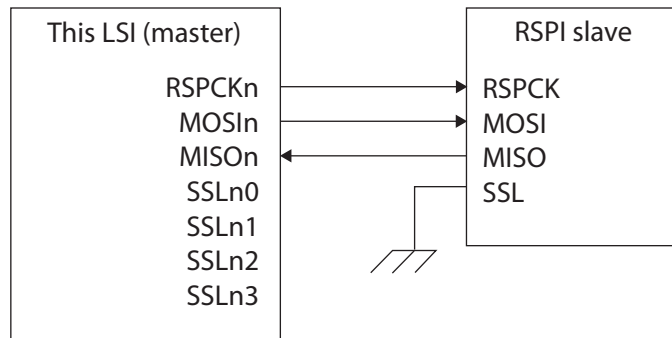


Figure 7.30 Single Master Single Slave Configuration [4], page 1557.

7.2.4 Renesas Inter Integrated Circuit Bus

The Inter Integrated Circuit (I²C) bus was invented by Philips Electronics for serial communications between low speed peripherals in an embedded system. The bus allows multi-

ple peripheral devices to be connected on the same set of wires to communicate with each other with only two devices, one master device and one slave device, communicating with each other at a given time. The bus mainly consists of two wires Serial Clock (SCL) and Serial Data (SDA) that are responsible for transferring the data from one end to the other. These lines are constantly held high by pull up resistors when the bus is inactive. All devices connected on these lines need to communicate with the I²C protocol. Figure 7.31 illustrates devices connected on an I²C bus.

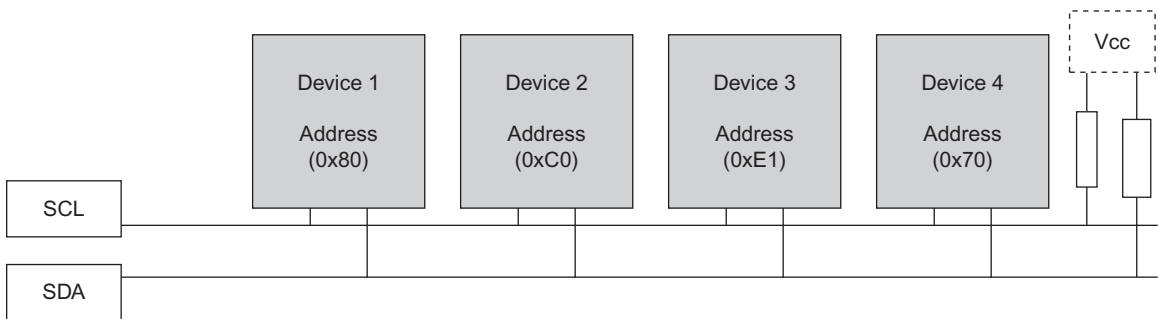


Figure 7.31 Four Devices Connected on the I²C Bus with pull up resistors. 128 such devices can be connected on a single bus.

I²C Bus Protocol

Each device connected on the bus is assigned a 7-bit address. Data is usually transferred as a byte plus an additional bit and is accompanied by a clock signal that synchronizes the data transfer between the communicating devices. The device that takes control of the bus at the beginning of communication is usually the master device, and is responsible for addressing the slave device and generating a clock signal during data transmission.

Before any form of data transfer takes place, a device wanting to transfer data must take control of the bus. This is done by monitoring the bus. If the bus is currently held high (both SDA and SCL are at a high voltage), it implies that the bus is currently free. Otherwise the bus is assumed to be busy and the device must wait for the bus to be free in order to transmit data. When the bus becomes free, the master acquires the control of the bus by sending a START condition in which the device pulls the SDA line low while keeping the SCL line high and thus becomes the current master of the bus. Figure 7.32 (A) illustrates a START condition. The generation of the START condition also informs the other devices that the bus is currently busy, and the other devices start listening to the next byte to be transferred on the bus.

When the current master of the bus is ready to release the bus from its control, it transmits a STOP condition in which the SDA line gets pulled high while the SCL line is high.

During the entire period in which the master is in control of the bus, the SDA line is constantly held low, except that when there is data being transmitted there is toggling of both lines. Figure 7.32 (B) shows a STOP condition.



Figure 7.32 (A) START condition; (B) STOP condition.

Once control of the bus is obtained, the next priority for the master is to address the slave device by transmitting 1 byte which consists of a 7-bit address and 1 bit that specifies if the master device wants to read from or write to the slave device. This bit is called the Read/Write bit (R/W). If this bit is low, it indicates that the master wants to write to the slave device; if high, the master device wishes to read from the slave. The status of the R/W bit determines whether the next transactions are going to be read from or written to the slave devices. After transfer of these 8 bits, the master clocks out an additional pulse while keeping the SDA high. If a device with the transmitted 7-bit address is presently listening on the bus, it responds immediately on the ninth clock pulse by pulling the SDA line low. This is an ACK bit signaling an acknowledgement, and the slave device becomes an active listener on the bus while other devices stop listening to the bus. Thus the master is now ready to transfer more data to the slave. If the SDA line remains low during the ninth clock pulse, the master gets a “no acknowledgement” (NACK) indication and stops transfer of data by sending a STOP bit.

I²C Communication Modes

Depending upon the initial transactions mentioned above, a device can be set up in any of the four following modes:

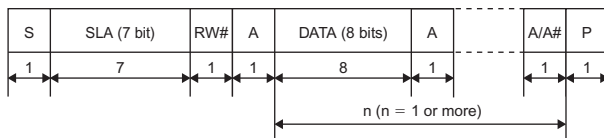
- **Master Transmitter:** In this mode, the device functions as a master and transmits data to a slave after acquiring the control of the bus. This device usually transmits the 7-bit address with the R/W bit set to write. It may also transmit additional bytes if an ACK is received for every byte it transfers.
- **Master Receiver:** In this mode, the device functions as a master and clocks out data from the slave. In this case, the master generates the clock pulses to which the

slave toggles data on the SDA pin. Before any reception can take place, the master must output the slave device address with the R/W bit set to R and then output the desired number of clock cycles with pseudo data (usually 0xFF). On every ninth clock pulse, the master receiver is required to send an ACK pulse to the slave device acknowledging the reception of data. Slave device stops transmitting the data to the master receiver as soon as the master clocks a NACK as the ninth bit on the most recent 8-byte data.

- **Slave Transmitter:** A device enters this mode when another device gains control of the bus and addresses the device with the address assigned to it with the R/W bit set to R. Such a device works in conjunction with a master receiver and responds to commands sent to it by the master receiver. The slave device stops transmitting the data to the master receiver as soon as the master clocks a NACK as the ninth bit on the most recent 8-byte data.
- **Slave Receiver:** A device enters this mode as soon as it is successfully addressed by a master transmitter with the R/W bit transmitted as W. The slave device is required to clock out an ACK bit for every relevant byte it successfully received.

Now that we understand some of the basics of the I²C protocol, we can move on to understand the detailed working of the I²C interface provided by Renesas; i.e., the Renesas Inter Integrated Circuit bus interface and the registers related to it. Figure 7.33 shows the typical transfers supported by the RIIC interface.

[7-bit address format]



[10-bit address format]

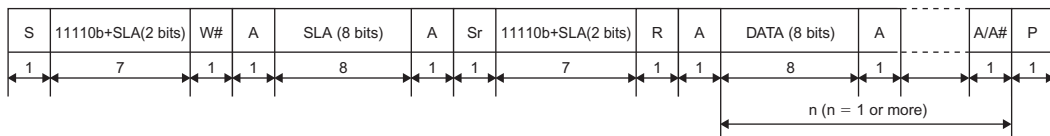
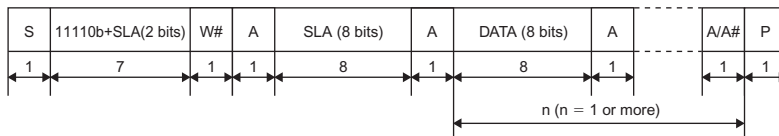


Figure 7.33 Typical data transfers supported by the Renesas I2C Interface [4], page 1440.

Registers related to the RIIC interface:

I²C Bus Control Register 1 (ICCR1): ICCR1 enables or disables the RIIC, resets the internal state of the RIIC, outputs an extra SCL clock cycle, and manipulates and monitors the SCLn pin and SDAn pin.

Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	ICE	IICRST	CLO	SOWP	SCLO	SDAO	SCLI	SDAI
Value after reset:	0	0	0	1	1	1	1	1

Figure 7.34 The ICCR1 register [4], page 1414.

- **ICE:** Setting this pin to 1 enables the RIIC transfer function (the SCLn pin and SDAn pin drive the bus) and vice versa.
- **IICRST:** Setting this bit to 1 initiates the RIIC reset resulting in all control, mode, and status registers resetting to default values. This bit needs to be manually cleared to finish the reset. The bit should usually be set when the ICE bit is set to 0. If this bit is set when ICE is 1, it resets the BC[2:0] bits in ICMR1; the ICSR1, ICSR2, ICDRS registers; and the internal states of the RIIC.
- **CLO:** Setting this bit to 1 causes the RIIC interface to output an extra SCL clock cycle (the CLO bit is cleared automatically after one clock cycle is output).
- **SOWP:** This bit controls the modification of the SCLO and SDAO bits. Setting this bit to 0 allows the SCLO and SDAO bits to be rewritten. This bit is always written as 1.
- **SCLO:** This bit controls the output level of the SCLn pin. This bit also monitors the output state of the SCLn pin. Setting this bit to 0 sets the SCLn pin to low level, and vice versa.
- **SDAO:** This bit controls the output level of the SDAn pin. This bit also monitors the output state of the SDAn pin. Setting this bit to 0 sets the SDAn pin to low level, and vice versa.
- **SCLI:** This bit monitors the input level of the SCLn pin. If this bit is high, it implies that the SCL pin is acting as input and is high. If this bit is low, it implies that the SCL pin is acting as input and is low.
- **SDAI:** This bit monitors the input level of the SDAn pin. If this bit is high, it implies that the SDA pin is acting as input and is high. If this bit is low, it implies that the SDA pin is acting as input and is low.

I²C Bus Control Register 2 (ICCR2): ICCR2 has a flag function that indicates whether or not the I²C bus is occupied and whether the RIIC is in transmit/receive or master/slave mode, as well as a function to issue a start or stop condition. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	BBSY	MST	TRS	—	SP	RS	ST	—
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.35 The ICCR2 register [4], page 1416.

- **BBSY:** The BBSY flag indicates whether the I²C bus is occupied (bus busy) or released (bus free). This bit is set to 1 when the SDAn line changes from high to low under the condition of SCLn = high, assuming that a start condition has been issued. When the SDAn line changes from low to high under the condition of SCLn = high, this bit is cleared to 0 after the bus free time (specified in ICBRL) start condition is not detected, assuming that a stop condition has been issued or if an Internal Interface Reset occurs.
- **MST:** This bit indicates whether the RIIC interface is acting as a master or slave mode. This bit is set when:
 - A start condition is issued normally according to the start condition issuance request (when a start condition is detected with the ST bit set to 1).
 - A 1 is written to the MST bit with the MTWP bit in ICMR1 set to 1.
 It is reset when:
 - A stop condition is detected.
 - The AL (arbitration lost) flag in ICSR2 is set to 1.
 - A 0 is written to the MST bit with the MTWP bit in ICMR1 set to 1.
 - A 1 is written to the IICRST bit in ICCR1 to apply an RIIC reset or an internal reset.
 Manual setting of this is permitted only when MTWP in ICMR1 is 1.
- **TRS:** This bit indicates transmit or receive mode. This bit is set when:
 - A start condition is issued normally according to the start condition issuance request (when a start condition is detected with the ST bit set to 1).
 - The R/W# bit added to the slave address is set to 0 in master mode.
 - The address received in slave mode matches the address enabled in ICSEr, with the R/W# bit set to 1.
 - A 1 is written to the TRS bit with the MTWP bit in ICMR1 set to 1.

This bit is cleared when:

- A stop condition is detected.
- The AL (arbitration lost) flag in ICSR2 being set to 1.
- In master mode, reception of a slave address to which an R/W# bit with the value 1 is appended.
- In slave mode, a match between the received address and the address enabled in ICSEER, when the value of the received R/W# bit is 0 (including cases where the received address is the general call address).
- In slave mode, a restart condition is detected (a start condition is detected with ICCR2.BBSY = 1 and ICCR2.MST = 0).
- When 0 is written to the TRS bit with the MTWP bit in ICMR1 set to 1.
- When 1 is written to the IICRST bit in ICCR1 to apply an RIIC reset or an internal reset.

A combination of this bit and the MST bit indicates the operating mode of the RIIC. Also, writing to this bit is not necessary during normal usage.

- **SP:** This bit is used to request that a stop condition be issued in master mode. This bit is manually set to 1 to request to issue a stop condition, a stop condition is issued only when the BBSY flag is set to 1 (bus busy) and the MST bit is set to 1 (master mode). This bit is set when a 1 is written to it and cleared when any of the following conditions occur:
 - A 0 is written to the SP bit after reading SP = 1.
 - A stop condition has been issued or a stop condition is detected.
 - The AL (arbitration lost) flag in ICSR2 is set to 1.
 - A start condition and a restart condition are detected.
 - A 1 is written to the IICRST bit in ICCR1 to apply an RIIC reset or an internal reset.
- **RS:** This bit is used to request that a restart condition be issued in master mode. When this bit is set to 1 to request to issue a restart condition, a restart condition is issued when the BBSY flag is set to 1 (bus busy) and the MST bit is set to 1 (master mode). This bit is set when a 1 is written to it and cleared when any of the following conditions occur:
 - A 0 is written to the RS bit.
 - A restart condition has been issued or a start condition is detected.
 - The AL (arbitration lost) flag in ICSR2 is set to 1.
 - A 1 is written to the IICRST bit in ICCR1 to apply an RIIC reset or an internal reset.
- **ST:** This bit is used to request transition to master mode and issuance of a start condition. When this bit is set to 1 to request to issue a start condition, a start condition is issued when the BBSY flag is set to 0 indicating that the bus is free. This bit is set when a 1 is written to it and cleared when any of the following conditions occur:
 - A 0 is written to the ST bit.

- A start condition has been issued.
- The AL (arbitration lost) flag in ICSR2 is set to 1.
- A 1 is written to the IICRST bit in ICCR1 to apply an RIIC reset or an internal reset.

I²C Mode Register 1 (ICMR1): ICMR1 specifies the internal reference clock source within the RIIC, indicates the number of bits to be transferred, and protects the MST and TRS bits in ICCR2 from being written. Bits in this register are:

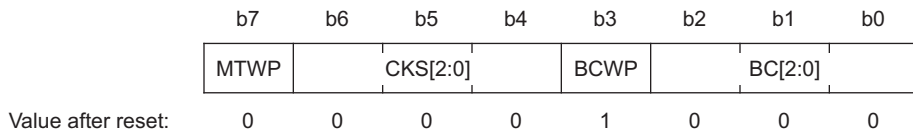


Figure 7.36 The ICMR1 register [4], page 1419.

- **MTWP:** This bit controls the modification of the MST and TRS bits in ICCR2. Setting this bit enables writing to the MST and TRS bits in ICCR2.
- **CKS[2:0]:** These bits select a reference clock source (IIC ϕ) inside the RIIC. Table 7.5 shows the selections possible:

TABLE 7.5 Clock Source Selection for the RIIC Interface [4], page 1419.

CKS2	CKS1	CKS0	CLOCK SOURCE TO RIIC
0	0	0	PCLK/1 clock
0	0	1	PCLK/2 clock
0	1	0	PCLK/4 clock
0	1	1	PCLK/8 clock
1	0	0	PCLK/16 clock
1	0	1	PCLK/32 clock
1	1	0	PCLK/64 clock
1	1	1	PCLK/128 clock

- BCWP: Clearing this bit to 0 enables a value to be written in the BC[2:0] bits.
- BC[2:0]: These bits function as a counter that indicates the number of bits remaining to be transferred at the detection of a rising edge on the SCLn line. Although these bits are writable and readable, it is not necessary to access these bits under normal conditions. To write to these bits, specify the number of bits to be transferred plus one (data is transferred with an additional acknowledge bit) between transferred frames when the SCLn line is at a low level. Table 7.6 shows how the Bit counter indicates the number of bits remaining:

TABLE 7.6 Bit Counter Indications [4], page 1419.

BC2	BC1	BC0	NUMBER OF BITS REMAINING
0	0	0	9
0	0	1	2
0	1	0	3
0	1	1	4
1	0	0	5
1	0	1	6
1	1	0	7
1	1	1	8

I²C Mode Register 2 (ICMR2): ICMR2 has a timeout function and an SDA output delay function. Bits in this register are:

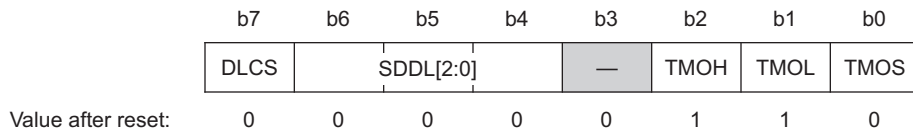


Figure 7.37 The ICMR2 register [4], page 1420.

- DLCS: This bit is used to select the internal reference clock (IIC ϕ) if set to 0, or the internal reference clock divided by 2 (IIC ϕ /2) if set to 1, as the clock source of the SDA output delay time.
- SDDL[2:0]: The SDA output can be delayed by the SDDL[2:0] setting. This counter works with the clock source selected by the DLCS bit. The setting of this function can be used for all types of SDA output, including the transmission of the acknowledge bit.

TABLE 7.7 SDA Output Delay Counter Settings [4], page 1420.

SDDL2	SDDL1	SDDL0	DELAY TIME WHEN DCLS = 0	DELAY TIME WHEN DCLS = 1
0	0	0	No delay in output	No delay in output
0	0	1	1 IIC ϕ cycle	1 or 2 IIC ϕ cycles
0	1	0	2 IIC ϕ cycle	3 or 2 IIC ϕ cycles
0	1	1	3IIC ϕ cycle	5 or 2 IIC ϕ cycles
1	0	0	4 IIC ϕ cycle	7 or 2 IIC ϕ cycles
1	0	1	5 IIC ϕ cycle	9 or 2 IIC ϕ cycles
1	1	0	6 IIC ϕ cycle	11 or 2 IIC ϕ cycles
1	1	1	7 IIC ϕ cycle	13 or 2 IIC ϕ cycles

- **TMOH:** This bit is used to enable (when set to 1) or disable (when set to 0) the internal counter of the timeout function to count up while the SCLn line is held high when the timeout function is enabled (TMOE bit = 1 in ICFER).
- **TMOL:** This bit is used to enable (when set to 1) or disable (when set to 0) the internal counter of the timeout function to count up while the SCLn line is held low when the timeout function is enabled (TMOE bit = 1 in ICFER).
- **TMOS:** This bit is used to select long mode or short mode for the timeout detection time when the timeout function is enabled (TMOE bit = 1 in ICFER). When this bit is set to 0, long mode is selected. When this bit is set to 1, short mode is selected. In long mode, the timeout detection internal counter functions as a 16 bit-counter. In short mode, the counter functions as a 14 bit-counter. While the SCLn line is in the state that enables this counter as specified by bits TMOH and TMOL, the counter counts up in synchronization with the internal reference clock (IIC ϕ) as a count source.

I²C Mode Register 3 (ICMR3): ICMR3 has functions to send/receive acknowledge and to select the RDRF set timing in RIIC receive operation, WAIT operation, and the SCLn pin and SDAn pin input level of the RIIC. Bits in this register are:

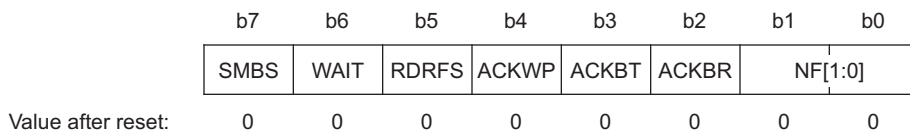


Figure 7.38 The ICMR3 register [4], page 1422.

- **SMBS:** Setting this bit to 1 selects the SMBus and enables the IC SER.HOAE bit. Otherwise the interface acts as the standard I²C interface.
- **WAIT:** This bit is valid only in receive mode and is used to control whether to hold the period between the ninth SCL clock cycle and the first SCL clock cycle low until the receive data buffer (ICDRR) is completely read each time single-byte data is received in receive mode.
- **RDRFS:** This bit is used to select the RDRF flag set timing in receive mode and also to select whether to hold the SCLn line low at the falling edge of the eighth SCL clock cycle. When the RDRFS bit is 0, the SCLn line is not held low at the falling edge of the eighth SCL clock cycle, and the RDRF flag is set to 1 at the rising edge of the ninth SCL clock cycle. When the RDRFS bit is 1, the RDRF flag is set to 1 at the rising edge of the eighth SCL clock cycle and the SCLn line is held low at the falling edge of the eighth SCL clock cycle. The low-hold of the SCLn line is released by writing a value to the ACKBT bit. After data is received with this setting, the SCLn line is automatically held low before the acknowledge bit is sent. This enables processing to send ACK (ACKBT = 0) or NACK (ACKBT = 1) according to receive data.
- **ACKWP:** This bit is used to control the modification of the ACKBT bit.
- **ACKBT:** This bit holds the acknowledgement to be sent in receive mode. When set to 0, ACK is transmitted as 0, and vice versa.
- **ACKBR:** This bit is used to store the acknowledge bit information received from the receive device in transmit mode. This bit is set to 1 when a 1 is received as the acknowledge bit with the ICCR2.TRIS bit set to 1. This bit is set to 0 when a 0 is received as the acknowledge bit with the ICCR2.TRIS bit set to 1, or an interface internal reset occurs.
- **NF[1:0]:** These bits are used to select the number of stages (1, 2, 3, or 4) of the digital noise filter.

I²C Bus Function Enable Register (ICFER): ICFER enables or disables the timeout function, the arbitration lost detection function, and the receive operation suspension function during NACK reception, and selects the use of a digital noise filter circuit and SCL synchronous circuit. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	FMPE	SCLE	NFE	NACKE	SALE	NALE	MALE	TMOE
Value after reset:	0	1	1	1	0	0	1	0

Figure 7.39 The ICFER register [4], page 1424.

- **FMPE:** This bit is used to specify whether to use a slope control circuit for Fast-mode Plus[fm+].

- **SCLE:** This bit is used to specify whether to synchronize the SCL clock with the SCL input clock. Normally, set this bit to 1.
- **NFE:** This bit is used to specify whether to use a digital noise filter circuit.
- **NACKE:** This bit is used to specify whether to continue or discontinue the transfer operation when NACK is received from the slave device in transmit mode. Normally, set this bit to 1.
- **SALE:** This bit is used to specify whether to cause arbitration to be lost when a value different from the value being transmitted is detected on the bus in slave transmit mode (such as when slaves with the same address exist on the bus, or when a mismatch with the transmit data occurs due to noise).
- **NALE:** This bit is used to specify whether to cause arbitration to be lost when ACK is detected during transmission of NACK in receive mode (such as when slaves with the same address exist on the bus, or when two or more masters select the same slave device simultaneously with a different number of receive bytes).
- **MALE:** This bit is used to specify whether to use the arbitration lost detection function in master mode. Normally, set this bit to 1.
- **TMOE:** This bit is used to enable or disable the timeout function.

I²C Bus Status Enable Register (ICSER): IC SER enables or disables comparison of slave addresses, general call address detection, device-ID command detection, and host address detection. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	HOAE	—	DIDE	—	GCAE	SAR2E	SAR1E	SAR0E
Value after reset:	0	0	0	0	1	0	0	1

Figure 7.40 The IC SER register [4], page 1426.

- **HOAE:** This bit is used to specify whether to ignore a received host address (0001 000b) when the SMBS bit in ICMR3 is 1.
- **DIDE:** This bit is used to specify whether to recognize and execute the Device-ID address when a device ID (1111 100b) is received in the first frame after a start condition or restart condition is detected. Setting this bit to 1 enables Device ID detection.
- **GCAE:** This bit is used to specify whether to ignore the general call address (0000 000b + 0 [W]: All 0) when it is received. When this bit is set to 1, if the received slave address matches the general call address as the first frame received after the START condition, the GCA bit is set in the I²C status register 1.
- **SAR2E:** This bit is used to enable or disable the received slave address and the slave address set in SARL2 and SARU2.

- SAR1E: This bit is used to enable or disable the received slave address and the slave address set in SARL1 and SARU1.
- SAR0E: This bit is used to enable or disable the received slave address and the slave address set in SARL0 and SARU0.

I²C Bus Interrupt Enable Register (ICIER): ICIER enables or disables various interrupt sources. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	TIE	TEIE	RIE	NAKIE	SPIE	STIE	ALIE	TMOIE
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.41 The ICIER register [4], page 1427.

- TIE: This bit is used to enable or disable transmit data empty interrupts (ICTXI) when the TDRE flag in ICSR2 is set to 1.
- TEIE: This bit is used to enable or disable transmit end interrupts (ICTEI) when the TDRE flag in ICSR2 is set to 1. An ICTEI interrupt request is canceled by clearing the TEND flag or the TEIE bit to 0.
- RIE: This bit is used to enable or disable receive data full interrupt requests (ICRXI) when the RDRF flag in ICSR2 is set to 1.
- NAKIE: This bit is used to enable or disable NACK reception interrupt requests (NAKI) when the NACKF flag in ICSR2 is set to 1. A NAKI interrupt request is canceled by clearing the NACKF flag or the NAKIE bit to 0.
- SPIE: This bit is used to enable or disable stop condition detection interrupt requests (SPI) when the STOP flag in ICSR2 is set to 1. An SPI interrupt request is canceled by clearing the STOP flag or the SPIE bit to 0.
- STIE: This bit is used to enable or disable start condition detection interrupt requests (STI) when the START flag in ICSR2 is set to 1. An STI interrupt request is canceled by clearing the START flag or the STIE bit to 0.
- ALIE: This bit is used to enable or disable arbitration lost interrupt requests (ALI) when the AL flag in ICSR2 is set to 1. An ALI interrupt request is canceled by clearing the AL flag or the ALIE bit to 0.
- TMOIE: This bit is used to enable or disable timeout interrupt requests (TMOI) when the TMOF flag in ICSR2 is set to 1. TMOI interrupt request is canceled by clearing the TMOF flag or the TMOIE bit to 0.

I²C Bus Status Register 1 (ICSR1): ICSR1 indicates various address detection status. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	HOA	—	DID	—	GCA	AAS2	AAS1	AAS0
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.42 The ICSR1 register [4], page 1428.

- **HOA:** When the received slave address matches the host address (0001 000b) with the HOAE bit in ICSESR set to 1 (host address detection enabled).
- **DID:** This bit is set when the first frame received immediately after a start condition or restart condition is detected matches a value of (device ID (1111 100b) + 0 [W]) with the DIDE bit in ICSESR set to 1 (Device-ID address detection enabled), and is cleared when 0 is written to the DID bit after reading DID = 1, when a stop condition is detected, or when the first frame received immediately after a start condition or restart condition is detected does not match a value of the device IDs assigned to the device.
- **GCA:** When the received slave address matches the general call address with the GCAE bit in ICSESR set to 1 (general call address detection enabled). This flag is set to 1 at the rising edge of the ninth SCL clock cycle in the frame. This bit is cleared when a stop condition is detected, an internal interface reset occurs, the address does not match the general call address (0b0000000 + [0]), or if 0 is written to the GCA bit after reading GCA = 1.
- **AAS2:** This bit is set if either the 7-bit or 10-bit slave address is received/addressed by the master transmitter. This bit is cleared when a stop condition is detected, an internal interface reset occurs, an address mismatch has occurred, or if 0 is written to the AAS0 bit after reading it.
- **AAS1:** This bit is set if either the 7-bit or 10-bit slave address is received/addressed by the master transmitter. This bit is cleared when a stop condition is detected, an internal interface reset occurs, an address mismatch has occurred, or if 0 is written to the AAS0 bit after reading it.
- **AAS0:** This bit is set if either the 7-bit or 10-bit slave address is received/addressed by the master transmitter. This bit is cleared when a stop condition is detected, an internal interface reset occurs, an address mismatch has occurred, or if 0 is written to the AAS0 bit after reading it.

I²C Bus Status Register 2 (ICSR2): ICSR2 indicates various interrupt request flags and statuses. Bits in this register are:

	b7	b6	b5	b4	b3	b2	b1	b0
	TDRE	TEND	RDRF	NACKF	STOP	START	AL	TMOF
Value after reset:	0	0	0	0	0	0	0	0

Figure 7.43 The ICSR2 register [4], page 1431.

- TDRE: This flag when set to 1 indicates that ICDRT contains no transmit data.
- TEND: This flag when set to 1 indicates that data has been transmitted.
- RDRF: This flag when set to 1 indicates that ICDRR contains receive data.
- NACKF: This flag when set to 1 indicates that NACK is detected.
- STOP: This flag when set to 1 indicates that stop condition is detected.
- START: This flag when set to 1 indicates that start condition is detected.
- AL: This flag when set to 1 indicates that arbitration is lost.
- TMOF: This flag when set to 1 indicates that timeout is detected.

Slave Address Register Upper (SARUy): SARUy selects 7-bit address format or 10-bit address format and sets the upper bits of a 10-bit slave address. Bits in this register are:

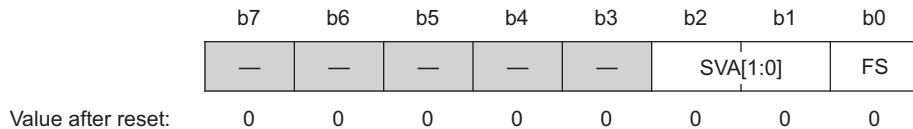


Figure 7.44 The SARUy register [4], page 1435.

- SVA[1:0]: These 2 bits are the upper bits 10-bit address.
- FS: This bit, when set to 0 selects the 7-bit address format and when set to 1 selects the 10-bit addressing format for the device.

Slave Address Register Lower (SARLy): SARLy sets slave address y (7-bit address or lower eight 8 of 10-bit address). Bits in this register are:

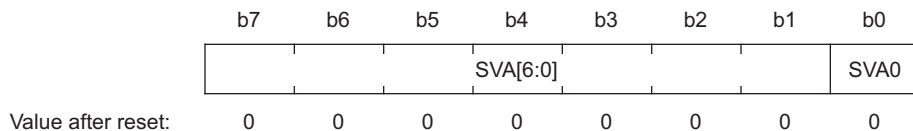


Figure 7.45 The SARLy register [4], page 1434.

- SVA[6:0]: When the 7-bit address format is selected (SARUy.FS = 0), these bits function as a 7-bit address. When the 10-bit address format is selected (SARUy.FS = 1), these bits function as the lower 8 bits of a 10-bit address in combination with the SVA0 bit. While the ICSEr.SARyE bit is 0, the setting of these bits is ignored.
- SVA0: This bit forms the LSB whenever the 10-bit address format is selected. Whenever the 7-bit address format is selected, this bit is invalid.

I²C Bus Bit Rate Low Level Register (ICBRL): ICBRL is a 5-bit (BRL[4:0]) register used to set the low-level period of the SCL clock. It also works to generate the data setup time for automatic SCL low-hold operation. ICBRL counts the low-level period with the internal reference clock source (IIC ϕ) specified by the CKS[2:0] bits in ICMR1. When the RIIC is used only in slave mode, this register needs to be set to a value longer than the data setup time. Bits in this register are:

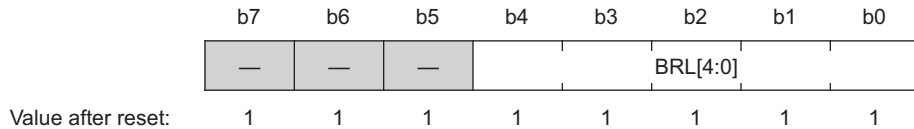


Figure 7.46 The ICBRL register [4], page 1436.

I²C Bus Bit Rate High Level Register (ICBRH): ICBRH is a 5-bit (BRH[4:0]) register used to set the high-level period of SCL clock. ICBRH is valid in master mode. If the RIIC is used only in slave mode, this register need not be set. ICBRH counts the high-level period with the internal reference clock source (IIC ϕ) specified by the CKS[2:0] bits in ICMR1. Bits in this register are:

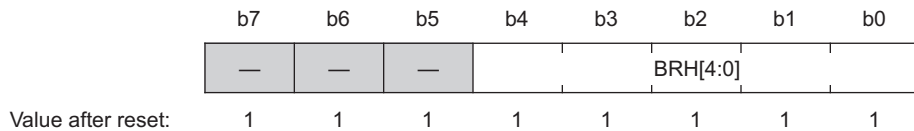


Figure 7.47 The ICBRH register [4], page 1437.

I²C Bus Transmit Data Register (ICDRT): ICDRT is an 8-bit readable/writable register that stores transmit data. When ICDRT detects a space in the I²C bus shift register (ICDRS), it transfers the transmit data that has been written to ICDRT to ICDRS and starts transmitting data in transmit mode. ICDRT can always be read and written. Write transmit data to ICDRT once when a transmit data empty interrupt (ICTXI) request is generated. Bits in this register are:

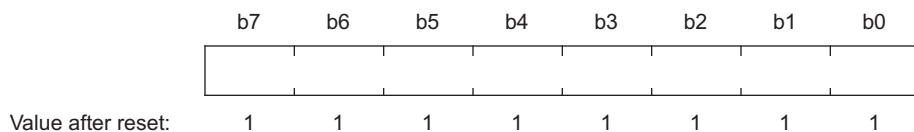


Figure 7.48 The ICDRT [4], page 1439.

I²C Bus Receive Data Register (ICDRR): ICDRR is an 8-bit read-only register that stores received data. When 1 byte of data has been received, the received data is transferred from the I²C bus shift register (ICDRS) to ICDRR to enable the next data to be received. ICDRR cannot be written. Read data from ICDRR once when a receive data full interrupt (ICRXI) request is generated. Bits in this register are:

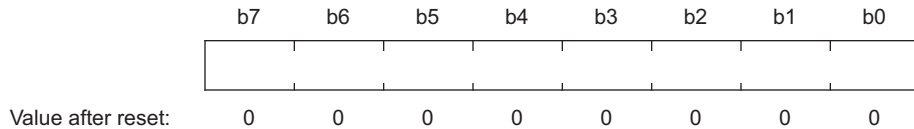


Figure 7.49 The ICDRR register [4], page 1439.

I²C Bus Shift Register (ICDRS): ICDRS is an 8-bit shift register used to transmit and receive data as shown below. ICDRS cannot be accessed directly.

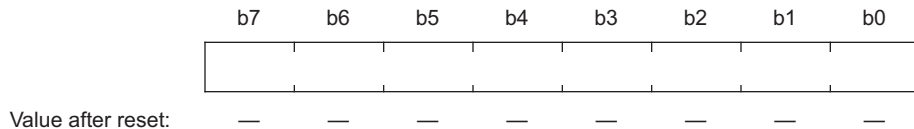


Figure 7.50 The ICDRS register [4], page 1439.

7.3 BASIC EXAMPLES

In this section we shall put into implementation the theoretical concepts learned in **Section 7.1** and **Section 7.2**, the process of setting up the interfaces, and understand the practical working of each of the communication interfaces. Interfaces studied so far include the USART using the SCI, SPI using the RSPI, and the two wire serial interface using the RIIC interface. **Sections 7.3.1 to 7.3.3** demonstrate the procedures to setup communication using each of the aforementioned interfaces by means of simple examples.

7.3.1 Basic Transmission/Receiving of Serial Data via UART

Aim: Demonstration of only transmission and only reception using the UART interface of SCI.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit, PC with RS-232 communication port.

Details: In this example, we will setup the RX63N processor to transmit a single byte of information and receive a single byte of information at 115200 baud, no parity, and 1 stop bit via polling.

Procedure: The process of transmitting and receiving a data byte from the SCI ports can be divided into three parts: Initialization, Transmitting/Receiving the actual data, Getting ready to transmit the next byte/saving the received data into the desired location.

Figure 7.51 illustrates the block diagram of the serial communication channels listed as well as the registers related to those channels, which are: Bit Rate Register (BRR), Serial Control Mode Register (SCMR), Serial Status Register (SSR), Serial Control Register (SCR), Serial Mode Register (SMR), Serial Extended Mode Register (SEMR), Noise Filter Setting Register (SNFR), I2C Mode Register 1 (SIMR1), I2C Mode Register 2 (SIMR2), I2C Mode Register 3 (SIMR3), I2C Status Register (SISR), and SPI Mode Register (SPMR). Upon proper configuration of the values of each of these registers, the SCI can be set up in the desired USART mode with a given baud rate. Note that all these registers do not have to be modified in order for the SCI to operate in USART mode, certain registers are related to the simple I2C interface as well as optional noise filtering. The step of Initialization consists of setting up the initial values of these registers.

In the next step, for transmission, Transmit Data Register (TDR) is filled with the desired value of the data and on the few next clock cycles the data is output on the corresponding SCI port. This concludes the process of transmitting data. In the case of receiving data, a flag is raised whenever a data byte is received in the Receive Data Register (RDR). This may cause an interrupt to occur. When the receive flag is raised, we need to copy the contents of the RDR into the desired location and conclude the process of reception.

The following code snippets show the process for setting up the SCI 2 of RX63N for initialization, transmission, and reception:

```

1. void init_SCI2(void){
2.     SYSTEM.MSTPCRA.BIT.ACSE = 0;
3.     MSTP(SCI2) = 0;
4.     SCI2.SCR.BYTE = 0x00;
5.     MPC.P50PFS.BYTE = 0x4A;
6.     MPC.P52PFS.BYTE = 0x4A;
7.     PORT5.PDR.BIT.B0 = 1;
8.     PORT5.PDR.BIT.B2 = 0;
9.     PORT5.PMR.BIT.B0 = 1;
10.    PORT5.PMR.BIT.B2 = 1;
11.    SCI2.SMR.BYTE = 0x00;
12.    SCI2.SCMR.BIT.SMIF = 0;
13.    SCI2.BRR = 12;
14.    SCI2.SCR.BIT.RIE = 1;
15.    SCI2.SCR.BIT.TIE = 1;
16.    SCI2.SCR.BIT.TEIE = 1;
17.    IR(SCI2, RXI2) = 0;
18.    IR(SCI2, TXI2) = 0;
19.    SCI2.SCR.BYTE |= 0x30;
20. }
```

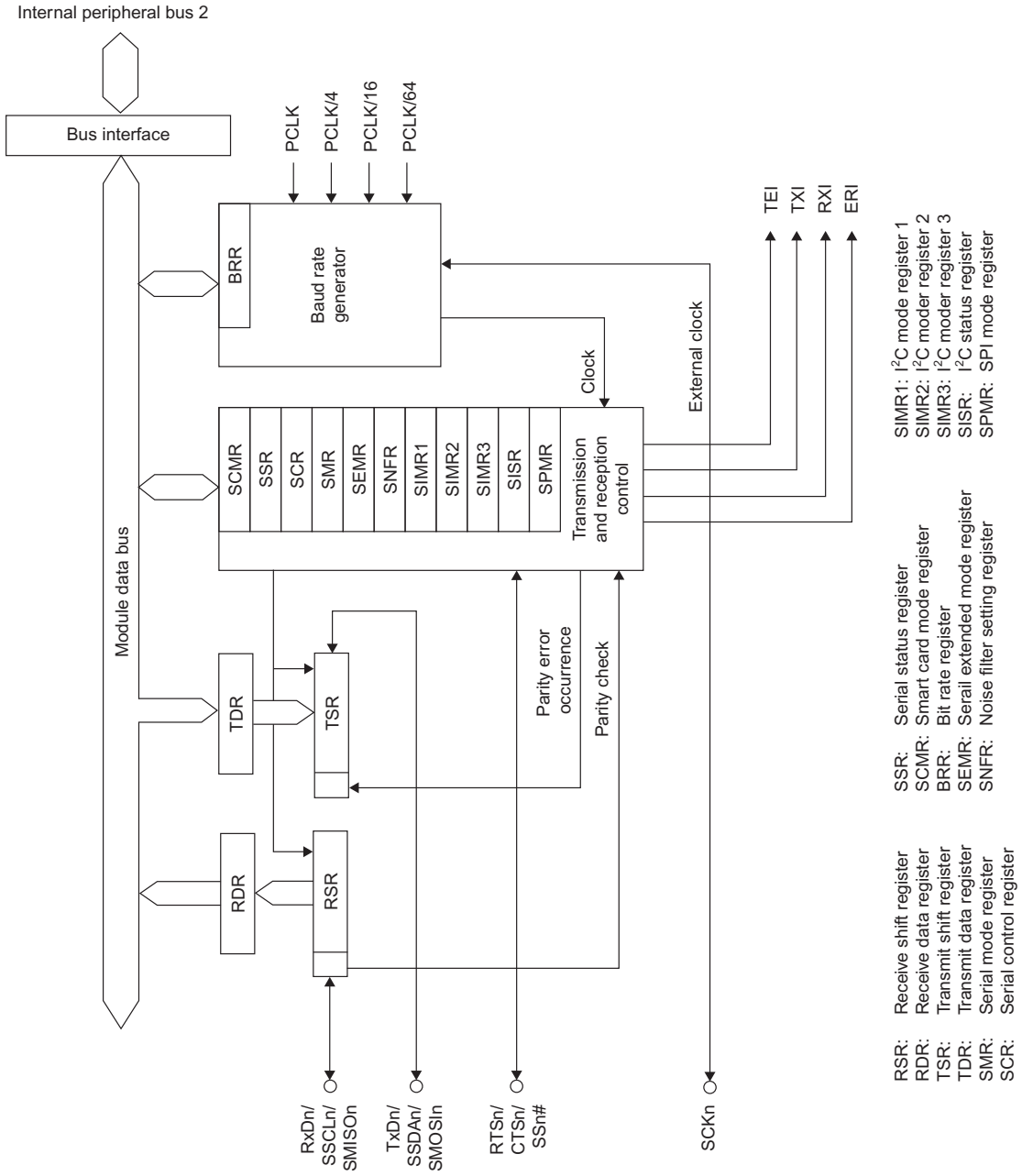


Figure 7.51 Block Diagram of Serial Communications Channels SCI0 to SCI4 and SCI7 to SCI11 [4], page 1293.

Explanation of Initialization Code

- Line 2: `SYSTEM.MSTPCRA.BIT.ACSE = 0;`
Disable all-module clock stop mode.
- Line 3: `MSTP(SCI2) = 0;`
This line of code enables the SCI2 module on the Renesas Microcontroller.
- Line 4: `SCI2.SCR.BYTE = 0x00;`
This line of code disables the transmission and reception.
- Line 5: `MPC.P50PFS.BYTE = 0x4A;`
Enable TxD2 on pin P50.
- Line 6: `MPC.P52PFS.BYTE = 0x4A;`
Enable RxD2 on pin P50.
- Line 7: `PORT5.PDR.BIT.B0 = 1;`
Set TxD2 as output.
- Line 8: `PORT5.PDR.BIT.B2 = 0;`
Set RxD2 as input.
- Line 9: `PORT5.PMR.BIT.B0 = 1;`
Set TxD2 as peripheral.
- Line 10: `PORT5.PMR.BIT.B2 = 1;`
Set RxD2 as peripheral.
- Line 11: `SCI2.SMR.BYTE = 0x00;`
This line of code sets the data transfer format in Serial Mode Register (SMR) to Asynchronous Mode, 8 bits, no parity, 1 stop bit, and PCLK ($n = 0$).
- Line 12: `SCI2.SCMR.BIT.SMIF = 0;`
this line of code selects SCI mode.
- Line 13: `SCI2.BRR = 12;`
This line of code sets the bit rate to 115400 baud.
- Line 14: `SCI2.SCR.BIT.RIE = 1;`
Enable the receive buffer full interrupt.
- Line 15: `SCI2.SCR.BIT.TIE = 1;`
Enable the transmit register empty interrupt.
- Line 16: `SCI2.SCR.BIT.TEIE = 1;`
enable the transmit end interrupt.
- Line 17: `IR(SCI2, RXI2) = 0;`
Clear interrupt request bits for RXI2.

- Line 18: `IR(SCI2, TXI2) = 0;`
Clear interrupt request bits for TXI2.
- Line 19: `SCI2.SCR.BYTE |= 0x30;`
Enable transmission and reception. We are now ready to transmit and receive data.

The following code snippet shows the process for transmitting data from the SCI2 of RX63N:

```
1. void transmit_data(unsigned char data){
2.     while(IEN(SCI2, TXI2) == 0)
3.         ;
4.     IEN(SCI2, TXI2) = 0;
5.     SCI2.TDR = data;
6. }
```

Explanation of Transmission Code

- Line 2: `while(IEN(SCI2, TXI2) == 0);`
This line of code makes the microcontroller enter a wait state until the transmit buffer becomes empty and generates an interrupt request.
- Line 4: `IEN(SCI2, TXI2) = 0;`
This line of code clears the interrupt request generated when the transmit buffer becomes empty.
- Line 5: `SCI2.TDR = data;`
This line of code copies the 1-byte data passed as an argument to the function in to the transmit data register.

The following code snippet shows the process for receiving data from the SCI2 of RX63N:

```
1. unsigned char receive_data(void){
2.     unsigned char rcvd_data = 0;
3.     while(IEN(SCI2, RXI2) != 0)
4.         ;
5.     rcvd_data = SCI2.RDR;
6.     IEN(SCI2, RXI2) = 1;
7.     return(rcvd_data);
8. }
```

Explanation of Reception Code

- Line 2: `unsigned char rcvd_data = 0;`
 Here we initialize an unsigned character variable “rcvd_data” to hold the data received from the SCI2 RxD2-B pin.
- Line 3: `while(IEN(SCI2, RXI2) != 0)`
 This line of code makes the microcontroller enter a wait state until an interrupt request is generated after data is successfully received in the RDR.
- Line 5: `rcvd_data = SCI2.RDR;`
 Here we copy the contents of the data received in the receive data register RDR into the variable rcvd_data.
- Line 6: `IEN(SCI2, RXI2) = 1;`
 We now re-enable interrupt request flag generated due to reception of data, and make the SCI2 interface ready to receive data again.
- Line 7: `return(rcvd_data);`
 Here we return the received data back to the main program/function.

Putting it together:

```

1. int main(void){
2.     init_SCI2();
3.     transmit_data('A');
4.     unsigned char data = 0;
5.     data = receive_data();
6.     printf("\ndata = %c",data);
7.     return 0;
8. }
```

Explanation of Main Program

- Line 2: `init_SCI2;`
 We call and execute the initialization function so that the SCI 2 gets set up as a UART functioning at 115200 baud, no parity, 1 stop bit, and clocking with no frequency division of PCLK.
- Line 3: `transmit_data('A');`
 We call and execute the transmit_data function to transmit a character “A” over the transmission line.
- Line 4: `unsigned char data = 0;`
 Here a unsigned character variable “data” is declared and initialized to 0.

Line 5: `data = receive_data();`

Here we call the function `receive_data` to receive data from the SCI2. The function returns a character when data is received from SCI2 and is stored in the variable “data.”

Line 6: `printf("\ndata = %c",data);`

Here we print the value of the variable `data` as a character over the standard output of the microcontroller.

Line 7: `return 0;`

This line of code terminates the program and the microcontroller comes to a halt.

7.3.2 Basic Transmission of Data Using Serial Peripheral Interface Bus

Aim: Demonstration of transmitting data with the serial peripheral interface bus.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit, Digital Oscilloscope, Oscilloscope probes.

Details: In this example, we will set up the RX63N processor to transmit a single byte of information using the clock synchronous serial peripheral interface bus.

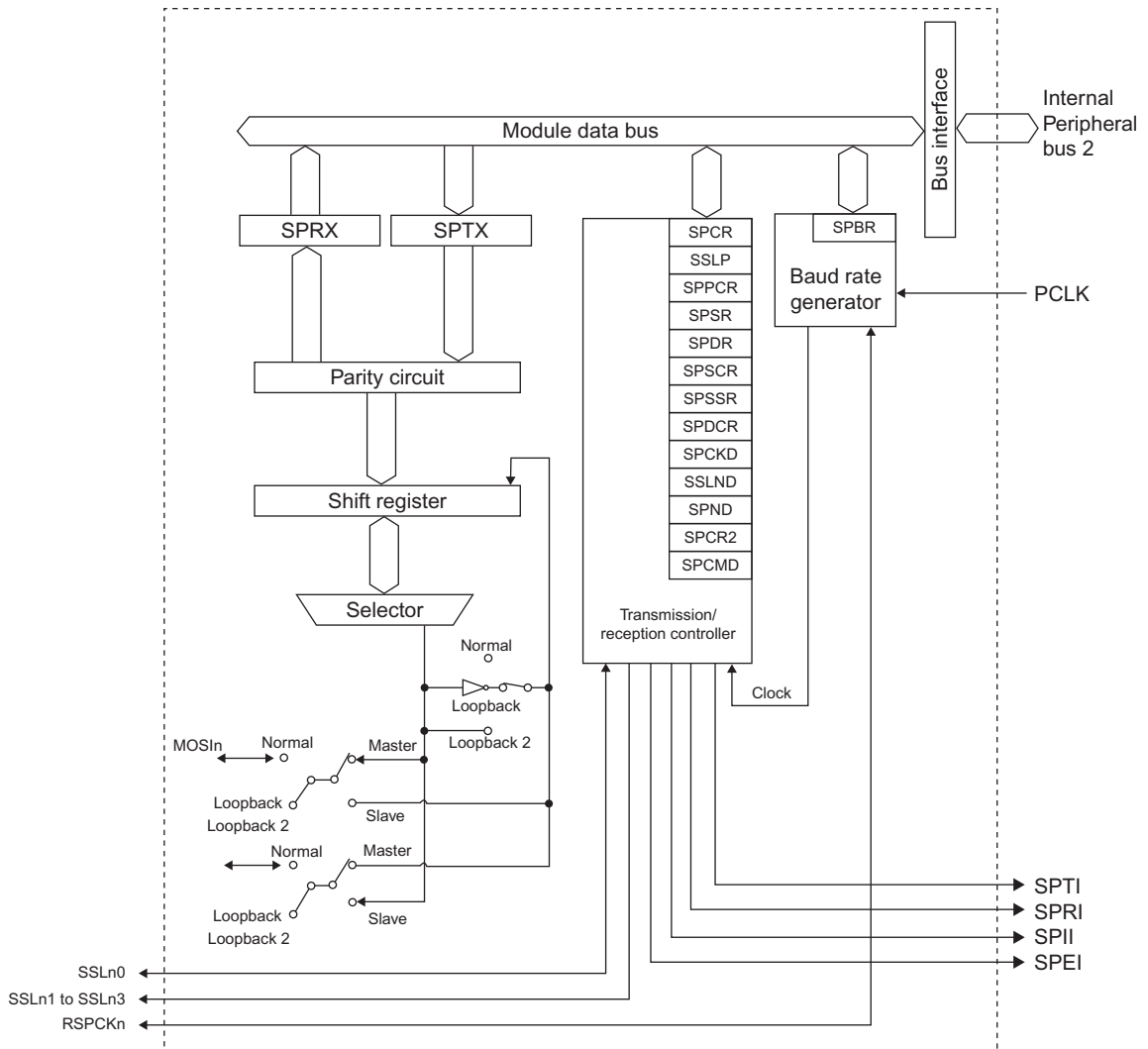
Procedure: The process of transmitting and receiving a data byte from the RSPI ports can be divided in to three parts; namely: initialization, selection of a slave device, and transmitting/receiving the actual data.

As seen in Figure 7.52 the registers required to control the RSPI are: SPCR, SPCR2, SSLP, SPPCR, SPSR, SPDR, SPSSR, SPDCR, SSLND, SPCKD, SPND, SPCMD, and SPBR. Upon proper configuration of the values of each of these registers, the RSPI can be set up in the desired clock synchronous mode with a given bit rate. The step of Initialization consists of setting up the initial values of these registers.

In the next step for slave selection, a chip select/active low signal is output from one of the SSL pins, or any other digital I/O pins, bringing the device out of the sleep state.

Next, the SPDR and SPCMDn registers are loaded with the proper values and the data is transmitted as soon as the RSPI becomes idle.

In order to view the transmission of data, it is recommended to connect an oscilloscope probe to the SCK, MOSI, MISO, and SSL-0 pins. If configuration of the RSPI is done as shown in initialization code, an output similar to that of Figure 7.53 would be observed on the oscilloscope. For our configuration D_1 was connected to serial clock, D_2 connected to Master Out Slave In, D_3 connected to Master In Slave Out and D_4 was connected Slave Select/Chip Select pins.



- | | |
|---|--|
| SPCR: RSPI control register | SSLND: RSPI slave select negate delay register |
| SPCR2: RSPI control register 2 | SPND: RSPI next-access delay register |
| SSLP: RSPI slave select polarity register | SPCMD: RSPI command registers 0 to 7 (eight registers) |
| SPPCR: RSPI pin control register | SPBR: RSPI bit rate register |
| SPSR: RSPI status register | SPTX: RSPI transmit buffer |
| SPDR: RSPI data register | SPRX: RSPI receive buffer |
| SPSCR: RSPI sequence control register | SPTI: RSPI transmit interrupt |
| SPSSR: RSPI sequence status register | SPRI: RSPI receive interrupt |
| SPDCR: RSPI data control register | SPII: SPI idle interrupt |
| SPCKD: RSPI clock delay register | SPEI: RSPI error interrupt |

Figure 7.52 Block Diagram of the Renesas Serial Peripheral Interface [4], page 1535.

The following are the codes for initialization, transmission, and the main program.

```
1. void init_RSPI(void){
2.     MSTP(RSPI0) = 0;
3.     RSPI0.SPPCR.BYTE = 0x00;
4.     RSPI0.SPBR.BYTE = 255;
5.     RSPI0.SPDCR.BYTE = 0x20;
6.     RSPI0.SPCR2.BYTE = 0x00;
7.     RSPI0.SPCMD0.WORD = 0x0400;
8.     IPR(RSPI0, SPRI0) = 3;
9.     IEN(RSPI0, SPRI0) = 0;
10.    IEN(RSPI0, SPTI0) = 0;
11.    IR (RSPI0, SPRI0) = 0;
12.    MPC.PC5PFS.BYTE = 0x0D;
13.    MPC.PC6PFS.BYTE = 0x0D;
14.    MPC.PC7PFS.BYTE = 0x0D;
15.    PORTC.PMR.BYTE = 0xE0;
16.    PORTC.PODR.BYTE = 0x17;
17.    PORTC.PDR.BYTE = 0x7F;
18.    RSPI0.SPCR.BYTE = 0xE9;
19.    RSPI0.SSLP.BYTE = 0x00;
20. }
```

Explanation of Initialization Code

- Line 2:** MSTP(RSPI0) = 0
This line of code enables the RSPIO module.
- Line 3:** RSPI0.SPPCR.BYTE = 0x00;
Initialize SPI (per flowchart in hardware manual [4], page 1539), no loopback, CMOS Output.
- Line 4:** RSPI0.SPBR.BYTE = 0x00;
Run the RSPI at Full Speed with PCLK frequency of 48 MHz.
- Line 5:** RSPI0.SPDCR.BYTE = 0x00;
16-bit data 1 frame 1 chip select.
- Line 6:** RSPI0.SPCR2.BYTE = 0x00;
Disable idle interrupt.
- Line 7:** RSPI0.SPCMD0.WORD = 0x0700;
MSB first 8-bit data, keep SSL low.
- Line 8:** IPR(RSPI0, SPRI0) = 3;
Set shared IPL for RSPIO.

- Line 9: `IEN(RSPI0, SPRI0) = 0;`
Disable receive buffer full interrupt.
- Line 10: `IEN(RSPI0, SPTI0) = 0;`
Disable transmit buffer empty interrupt.
- Line 11: `IR (RSPI0, SPRI0) = 0;`
Clear pending receive buffer full interrupts.
- Line 12: `MPC.PC5PFS.BYTE = 0x0D;`
Set PC5 to RSPCKA.
- Line 13: `MPC.PC6PFS.BYTE = 0x0D;`
Set PC6 to MOSIA
- Line 14: `MPC.PC7PFS.BYTE = 0x0D;`
Set PC7 to MISOA.
- Line 15: `PORTC.PMR.BYTE = 0xE0;`
Assign PC5-7 to SPI peripheral.
- Line 16: `PORTC.PODR.BYTE = 0x17;`
Chip selects high to start.
- Line 17: `PORTC.PDR.BYTE = 0x7F;`
All outputs except MISO.
- Line 18: `RSPI0.SPCR.BYTE = 0x6B;`
Enable RSPI function, enable generation of RSPI transmit interrupt requests, master mode, transmit only, and chock synchronous operation (3-wire method).
- Line 19: `RSPI0.SSLP.BYTE = 0x08;`
Set SSL3 to active high.

Transmission Code

```

1. void RSPI_Transmit_LWord(int16_t sLowWord, int16_t sHighWord){
2.     PORTC.PODR.BIT.B4 = 0;
3.     while(RSPI0.SPSR.BIT.IDLNF)
4.         ;
5.     RSPI0.SPDR.WORD.L = sLowWord;
6.     RSPI0.SPDR.WORD.H = sHighWord;
7.     while(RSPI0.SPSR.BIT.IDLNF)
8.         ;
9.     (void)RSPI0.SPDR.WORD.L;
10.    (void)RSPI0.SPDR.WORD.H;
11.    PORTC.PODR.BIT.B4 = 1;
12. }
```

Explanation of Transmission Code

- Line 2: `PORTC.PODR.BIT.B4 = 0;`
Here we set the bit to be pulled low so as to perform a chip select manually to begin transmission.
- Line 3: `while(RSPI0.SPSR.BIT.IDLNF)`
Wait for the RSPI to become idle. Program proceeds as soon as the IDLNF flag becomes 0.
- Line 5: `RSPI0.SPDR.WORD.L = sLowWord;`
Set the lower word of the SPDR to the value passed through the argument.
- Line 6: `RSPI0.SPDR.WORD.H = sHighWord;`
Set the higher word of the SPDR to the value passed through the argument.
- Line 7: `while(RSPI0.SPSR.BIT.IDLNF);`
Wait for the RSPI to finish transmission.
- Line 9: `(void)RSPI0.SPDR.WORD.L;`
Read the lower word of the SPDR;
- Line 10: `(void)RSPI0.SPDR.WORD.H;`
and read the higher word of the SPDR to clear interrupt flag.
- Line 11: `PORTC.PODR.BIT.B4 = 1 ;`
Set the Chip select pin to high to terminate transmission.

Main Code

```
1. void main(void) {  
2.     init_RSPI();  
3.     while(1)  
4.         RSPI_Transmit_LWord(0x0000, 0x0055);  
5. }
```

Explanation of Main Code

- Line 2: `init_RSPI();`
We initialize the Renesas SPI by calling the `Init_RSPI` function.
- Line 3: `while(1)`
Perform the next step forever.
- Line 4: `RSPI_Transmit_LWord(0x0000, 0x0055);`
Transmit `0x00000055`.

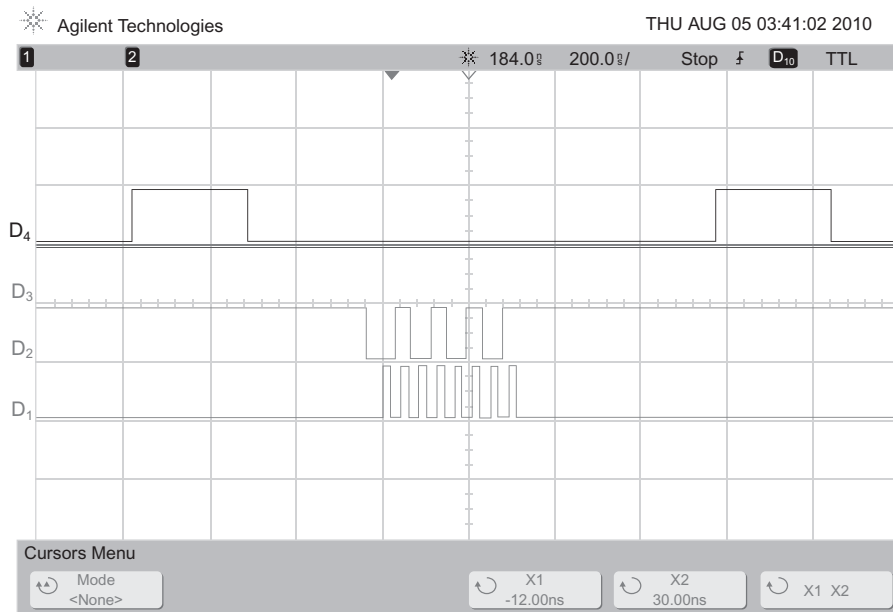


Figure 7.53 Oscilloscope capture of a functional RSPI.

7.3.3 Basic Transmission and Reception of Data Using the Renesas I²C Bus

Aim: To demonstrate the setting up of the RIIC module to transmit and receive data from a peripheral.

Details: In this example we will set up the RIIC peripheral module to transmit and receive 1 byte of data from an on board peripheral device.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit, Digital Oscilloscope, Oscilloscope probes.

Procedure: The YRDKRX63N development kit has an on board accelerometer ADXL345. This is a three axis accelerometer capable of measuring accelerations in the X, Y, and Z axis directions. The ADXL345 can communicate the measured values through the SPI and I²C buses. Depending on the mode of communication selected using the CS pin, one can use either of the two communication methods to obtain details and data from the ADXL345. The ADXL345 is composed of several registers that it constantly updates when not in the SLEEP or STAND BY mode. One particular register of interest is the 0x00 register that contains the value 0xE5 that symbolically represents “345.” Therefore when the 0x00 address location is read using the I²C mechanism, the value 0xE5 is acquired/read. The address that we are going to write to is the pointer address for the ADXL 345 which is the default register location select for the first byte of data transferred to the device after transmitting the device address 0x3A. The procedure for writing data to a peripheral device is:

1. Generate START condition.
2. Transmit address of device to communicate with and wait for the acknowledge bit to arrive.
3. Transmit the data to be communicated with the device and wait for the acknowledge bit to arrive for each byte transmitted.
4. If all bytes to be communicated have been transmitted, generate a STOP condition.

The procedure to read data from a peripheral device is in two parts that consist of writing to the register pointer and then reading the desired bytes from the peripherals. In the first half of the read cycle, the RX63N:

1. Generate a START condition.
2. Transmit address of device to communicate with and wait for acknowledge bit to arrive.
3. Transmit the value of the register pointer and wait for an acknowledge.
4. Generate a STOP condition.

Next comes the read cycle which begins with:

1. Generating a START condition.
2. Transmitting the address of the **device to communicate with +1** (note that this address is always odd) and wait for an acknowledge.
3. Generate clock cycles or generate pseudo transactions of 0xFF to which the slave device or peripheral clocks out the desired data. To each byte successfully received the RIIC has to output an ACK bit which is a 0 on the ninth bit. If the Master receiver RX63N wishes to terminate a transaction, it needs to generate a NACK, which is a 1 on the ninth bit of the last desired byte.
4. Generate a STOP condition.

To be able to do all of these activities, the microcontroller needs to be configured/initialized properly. The following code shows the procedure for initialization of the RIIC channel 0 aboard the RX63N. If RIIC channel 1 is available, then similar steps should be followed:

```
1. void RiicIni(unsigned char in_SelfAddr){
2.     SYSTEM.MSTPCRB.BIT.MSTPB21 = 0;
3.     RIIC0.ICCR1.BIT.ICE = 0;
4.     RIIC0.ICCR1.BIT.IICRST = 1;
5.     RIIC0.ICCR1.BIT.IICRST = 0;
6.     RIIC0.SARU0.BIT.FS = 0;
7.     RIIC0.SARL0.BYTE = in_SelfAddr;
```

```
8.     RIIC0.ICMR1.BIT.CKS = 7;
9.     RIIC0.ICBRH.BIT.BRH = 28;
10.    RIIC0.ICBRL.BIT.BRL = 29;
11.    RIIC0.ICMR3.BIT.ACKWP = 1;
12.    RIIC0.ICIER.BIT.RIE = 1;
13.    RIIC0.ICIER.BIT.TIE = 1;
14.    RIIC0.ICIER.BIT.TEIE = 0;
15.    RIIC0.ICIER.BIT.NAKIE = 1;
16.    RIIC0.ICIER.BIT.SPIE = 1;
17.    RIIC0.ICIER.BIT.STIE = 0;
18.    RIIC0.ICIER.BIT.ALIE = 0;
19.    RIIC0.ICIER.BIT.TMOIE = 0;
20.    PORT1.PMR.BIT.B3 = 1;
21.    PORT1.PMR.BIT.B2 = 1;
22.    RIIC0.ICCR1.BIT.ICE = 1;
23. }
```

The following is the explanation of the above code line by line:

- Line 1:** `void RiicIni(unsigned char in_SelfAddr)`
Declaring the function and the arguments.
- Line 2:** `SYSTEM.MSTPCRB.BIT.MSTPB21 = 0;`
Enable the RIIC channel zero.
- Line 3:** `RIIC0.ICCR1.BIT.ICE = 0;`
Disable the RIIC channel 0 manually just to make sure.
- Line 4:** `RIIC0.ICCR1.BIT.IICRST = 1;`
Reset the RIIC0 module.
- Line 5:** `RIIC0.ICCR1.BIT.IICRST = 0;`
Release the reset.
- Line 6:** `RIIC0.SARU0.BIT.FS = 0;`
Set the device address as a 7 bit address.
- Line 7:** `RIIC0.SARL0.BYTE = in_SelfAddr;`
Set the device address from the argument of the function.
- Line 8:** `RIIC0.ICMR1.BIT.CKS = 7;`
Select clock input to the RIIC0 module as PCLK/128.
- Line 9:** `RIIC0.ICBRH.BIT.BRH = 28;`
Set the bit counter for the high level of the serial clock cycle.
- Line 10:** `RIIC0.ICBRL.BIT.BRL = 29;`
Set the bit counter for the low level of the serial clock cycle.

- Line 11: `RIICO.ICMR3.BIT.ACKWP = 1;`
Disable write protect for the ACK bit.
- Line 12: `RIICO.ICIER.BIT.RIE = 1;`
Enable the Receive data full interrupt.
- Line 13: `RIICO.ICIER.BIT.TIE = 1;`
Enable the Transmit data full interrupt.
- Line 14: `RIICO.ICIER.BIT.TEIE = 0;`
Enable the Transmit End interrupt.
- Line 15: `RIICO.ICIER.BIT.NAKIE = 1;`
Enable the NACK received interrupt.
- Line 16: `RIICO.ICIER.BIT.SPIE = 1;`
Enable the Stop condition received interrupt.
- Line 17: `RIICO.ICIER.BIT.STIE = 0;`
Disable the Start condition received interrupt.
- Line 18: `RIICO.ICIER.BIT.ALIE = 0;`
Disable the Arbitration lost interrupt.
- Line 19: `RIICO.ICIER.BIT.TMOIE = 0;`
Timeout interrupt request is disabled.
- Line 20: `PORT1.PMR.BIT.B3 = 1;`
Enable input buffer on PORT1 pin 3.
- Line 21: `PORT1.PMR.BIT.B2 = 1;`
Enable input buffer on PORT1 pin 2.
- Line 22: `RIICO.ICCR1.BIT.ICE = 1;`
Enable the RIICO module.

The process to uninitialized the RIICO is

```
1. void RiicUnIni(void) {  
2.     SYSTEM.MSTPCRB.BIT.MSTPB21 = 1;  
3. }
```

The following is the explanation of the above code line by line:

- Line 1: `void RiicUnIni(void) {`
Declare the function name to uninitialization
- Line 2: `SYSTEM.MSTPCRB.BIT.MSTPB21 = 1;`
Disable the RIICO module

The following snippet of code demonstrates how data transfer takes place, using polling:
There are three essential parts to data transfer when using the I²C protocol:

1. Generating the START condition.
2. Performing the transfer.
3. Sending the STOP condition.

The following is the code for generating the START condition:

```

1. unsigned char RiicSendStart(void){
2.     if(RIIC0.ICCR1.BIT.ICE){
3.         while(RIIC0.ICCR2.BIT.BBSY)
4.             ;
5.         RIIC0.ICCR2.BIT.ST = 1;
6.         while(!(RIIC0.ICCR2.BIT.BBSY && RIIC0.ICSR2.BIT.START))
7.             ;
8.         RIIC0.ICSR2.BIT.START = 0;
9.         return 1;
10.    }
11.    else return 0;
12. }
```

The following is the explanation for the above code:

Line 1: `unsigned char RiicSendStart(void){`
Declare the function name and arguments.

Line 2: `if(RIIC0.ICCR1.BIT.ICE){`
Check if the RIIC0 module is enabled.

Line 3: `while(RIIC0.ICCR2.BIT.BBSY)`
Wait here until the bus becomes free.

Line 5: `RIIC0.ICCR2.BIT.ST = 1;`
When bus becomes free, request for transmitting a START condition.

Line 6: `while(!(RIIC0.ICCR2.BIT.BBSY && RIIC0.ICSR2.BIT.START))`
Wait here until START condition is detected by the RIIC0 module.

Line 8: `RIIC0.ICSR2.BIT.START = 0;`
After detecting the module, disable the interrupt bit in the status register.

Line 9: `return 1;`
Report success.

Line 11: `else return 0;`
Report failure if RIIC0 module is not enabled.

The following is the code for generating the STOP condition:

```

1. unsigned char RiicSendStop(void){
2.     if(RIIC0.ICCR1.BIT.ICE){
3.         while(RIIC0.ICCR2.BIT.BBSY){
4.             RIIC0.ICCR2.BIT.SP = 1;
5.         }
6.         return 1;
7.     }
8.     else return 0;
9. }
```

The following is the explanation for the code given above:

Line 1: unsigned char RiicSendStop(void){
Declare the function name and arguments.

Line 2: if(RIIC0.ICCR1.BIT.ICE){
If the RIIC0 module is enabled perform the following steps.

Line 3: while(RIIC0.ICCR2.BIT.BBSY){
Loop while the bus is busy.

Line 4: RIIC0.ICCR2.BIT.SP = 1;
While the bus is busy, request to generate a stop condition.

Line 6: return 1;
Report Success.

Line 8: else return 0;
If the RIIC0 module is disabled report failure.

The following is the code for writing a data byte to a peripheral device on the I²C bus:

```

1. unsigned char RiicWriteByte2(unsigned char slave_addr, unsigned
char slave_register_num, unsigned char data_byte){
2.     RIIC0.ICDRT = slave_addr & (0xFE);
3.     while(!RIIC0.ICSR2.BIT.TDRE)
4.         ;
5.     RIIC0.ICDRT = slave_register_num;
6.     while(!RIIC0.ICSR2.BIT.TEND){
7.         if(RIIC0.ICSR2.BIT.NACKF){
8.             RIIC0.ICSR2.BIT.NACKF = 0;
9.             return 0;
10.        }
11.    }
12.    while(!RIIC0.ICSR2.BIT.TDRE)
```



```
13.     ;
14.     RIIC0.ICDRT = data_byte;
15.     while(!RIIC0.ICSR2.BIT.TEND) {
16.         if(RIIC0.ICSR2.BIT.NACKF) {
17.             RIIC0.ICSR2.BIT.NACKF = 0;
18.             return 0;
19.         }
20.     }
21.     while(!RIIC0.ICSR2.BIT.TDRE)
22.         ;
23.     while(!RIIC0.ICSR2.BIT.TEND) {
24.         if(RIIC0.ICSR2.BIT.NACKF) {
25.             RIIC0.ICSR2.BIT.NACKF = 0;
26.             return 0;
27.         }
28.     }
29.     return 1;
30. }
```

The following is the explanation for the above codes:

- Line 1:** `unsigned char RiicWriteByte2(unsigned char slave_addr, unsigned char slave_register_num, unsigned char data_byte){`
Declare and define the function and its arguments.
- Line 2:** `RIIC0.ICDRT = slave_addr & (0xFE);`
Fill the transmit buffer with the slave address input as an argument to the function.
- Line 3:** `while(!RIIC0.ICSR2.BIT.TDRE)`
Wait until the Transmit data empty flag becomes high.
- Line 5:** `RIIC0.ICDRT = slave_register_num;`
Fill the transmit data buffer with the slave register number to be written to.
- Line 6:** `while(!RIIC0.ICSR2.BIT.TEND) {`
Since the RIIC has a double buffer for transmission and reception, we need to wait until the previous transmission is finished.
- Line 7:** `if(RIIC0.ICSR2.BIT.NACKF) {`
Check if a NACK is received in response to the transmit operation.
- Line 8:** `RIIC0.ICSR2.BIT.NACKF = 0;`
If a NACK is received, then Reset the NACKF flag.
- Line 9:** `return 0;`
And report failure.

Line 12: `while(!RIIC0.ICSR2.BIT.TDRE)`
Wait here until the transmit data register becomes empty again.

Line 14: `RIIC0.ICDRT = data_byte;`
Fill the transmit data register with the actual data byte that needs to be transmitted.

Line 15: `while(!RIIC0.ICSR2.BIT.TEND) {`
Since the RIIC has a double buffer for transmission and reception, we need to wait until the previous transmission is finished.

Line 16: `if(RIIC0.ICSR2.BIT.NACKF) {`
Check if a NACK is received in response to the transmit operation.

Line 17: `RIIC0.ICSR2.BIT.NACKF = 0;`
If a NACK is received, then Reset the NACKF flag.

Line 18: `return 0;`
And report failure.

Line 21: `while(!RIIC0.ICSR2.BIT.TDRE)`
Wait here until the transmit data register becomes empty again.

Line 23: `while(!RIIC0.ICSR2.BIT.TEND) {`
Since the RIIC has a double buffer for transmission and reception, we need to wait until the previous transmission is finished.

Line 24: `if(RIIC0.ICSR2.BIT.NACKF) {`
Check if a NACK is received in response to the transmit operation.

Line 25: `RIIC0.ICSR2.BIT.NACKF = 0;`
If a NACK is received, then Reset the NACKF flag.

Line 26: `return 0;`
And report failure.

Line 29: `return 1;`
If all goes well, report success.

The following is a piece of code similar to the above code, however it writes only the slave address and the register number to the I²C peripheral device. This is useful when reading data from the peripheral device in which one needs to write to the slave device the register from which the data is to be transferred and then data is read consecutively from the registers.

```
1. unsigned char RiicWriteByte(unsigned char slave_addr, unsigned
   char data_byte){
2.     RIIC0.ICDRT = slave_addr & (0xFE);
3.     while(!RIIC0.ICSR2.BIT.TDRE)
4.         ;
5.     RIIC0.ICDRT = data_byte;
```

```
6.     while(!RIIC0.ICSR2.BIT.TEND){
7.         if(RIIC0.ICSR2.BIT.NACKF){
8.             RIIC0.ICSR2.BIT.NACKF = 0;
9.             return 0;
10.        }
11.    }
12.    while(!RIIC0.ICSR2.BIT.TDRE)
13.        ;
14.    while(!RIIC0.ICSR2.BIT.TEND){
15.        if(RIIC0.ICSR2.BIT.NACKF){
16.            RIIC0.ICSR2.BIT.NACKF = 0;
17.            return 0;
18.        }
19.    }
20.    return 1;
21. }
```

The following is the code for reading a data byte from a peripheral device on the I²C bus:

```
1. unsigned char RiicReadByte(unsigned char slave_addr, unsigned char
   slave_register_num){
2.     unsigned char read_byte;
3.     RiicWriteByte(slave_addr,slave_register_num);
4.     RiicSendStop();
5.     RIIC0.ICSR2.BIT.STOP = 0;
6.     RiicSendStart();
7.     while(!RIIC0.ICSR2.BIT.TDRE)
8.         ;
9.     RIIC0.ICDRT = slave_addr | (0x01);
10.    while(!RIIC0.ICSR2.BIT.RDRF)
11.        ;
12.    if(RIIC0.ICSR2.BIT.NACKF == 0){
13.        RIIC0.ICMR3.BIT.WAIT = 1;
14.        RIIC0.ICMR3.BIT.ACKBT = 1;
15.        read_byte = RIIC0.ICDRR;
16.        while(!RIIC0.ICSR2.BIT.RDRF)
17.            ;
18.        RIIC0.ICSR2.BIT.STOP = 0;
19.        RIIC0.ICCR2.BIT.SP = 1;
20.        read_byte = RIIC0.ICDRR;
21.        while(!RIIC0.ICSR2.BIT.STOP)
```

```
22.         ;
23.         return read_byte;
24.     }
25.     else return 0xFF;
26. }
```

The following explains the above given code :

Line 1: `unsigned char RiicReadByte(unsigned char slave_addr, unsigned char slave_register_num){`
Declare and define the function and its arguments.

Line 2: `unsigned char read_byte;`
Locally declared character to hold the return value of the function.

Line 3: `RiicWriteByte(slave_addr, slave_register_num);`
Write the data register from which the data is to be read.

Line 4: `RiicSendStop();`
Send a STOP condition.

Line 5: `RIIC0.ICSR2.BIT.STOP = 0;`
Reset the STOP condition flag.

Line 6: `RiicSendStart();`
Send a START condition over the I²C Bus.

Line 7: `while(!RIIC0.ICSR2.BIT.TDRE)`
Wait here until transmit buffer gets empty.

Line 9: `RIIC0.ICDRT = slave_addr | (0x01);`
Request a read from the peripheral device by transmitting the read address as Slave device (write) address + 1.

Line 10: `while(!RIIC0.ICSR2.BIT.RDRF)`
Wait until the read buffer becomes full.

Line 12: `if(RIIC0.ICSR2.BIT.NACKF == 0){`
If a ACK is received; i.e., the device is ready, do the following actions.

Line 13: `RIIC0.ICMR3.BIT.WAIT = 1;`
Set the WAIT bit to 1, due to which the period between ninth clock cycle and first clock cycle is held low.

Line 14: `RIIC0.ICMR3.BIT.ACKBT = 1;`
Set the ACK bit transmitted as 1, which corresponds to a NACK for the peripheral device.

Line 15: `read_byte = RIIC0.ICDRR;`
Read dummy data from the I²C receive data register.

Line 16: `while(!RIIC0.ICSR2.BIT.RDRF);`
 Wait here until the ICDRR becomes full again when the shift register transfers data from itself to the ICDRR. This is due to double buffering of data.

Line 18: `RIIC0.ICSR2.BIT.STOP = 0;`
 Reset the status of the STOP bit in the ICSR2.

Line 19: `RIIC0.ICCR2.BIT.SP = 1;`
 Request for generation of STOP signal.

Line 20: `read_byte = RIIC0.ICDRR;`
 Read data from the ICDRR.

Line 21: `while(!RIIC0.ICSR2.BIT.STOP)`
 Wait here until the STOP condition is generated.

Line 23: `return read_byte;`
 Return the Data received as the return value of the function.

Line 25: `else return 0xFF;`
 If a NACK was received return 0xFF (or any desired value) as a Failure value.

The following code shows the entire process of reading 1 byte from a peripheral connected on the I²C bus:

```

1. void main(void){
2.     unsigned char i;
3.     RiicIni(0x10);
4.     RiicSendStart();
5.     RiicWriteByte2(0x3A, 0x2D, 0x00);
6.     RiicSendStop();
7.     RiicSendStart();
8.     i = RiicReadByte(0x3A, 0x00);
9.     RiicSendStop();
10.    RiicUnIni();
11.    while(1)
12.        ;
13. }
```

The following is the explanation of the above code:

Line 1: `void main(void){`
 Define the main function.

Line 2: `unsigned char i;`
 Locally declared character to hold the return value of the RiicReadByte function.

Line 3: `RiicIni(0x10);`
Initialize the I²C module RIIC0 with self address as 0x10.

Line 4: `RiicSendStart();`
Send a START condition.

Line 5: `RiicWriteByte2(0x3A, 0x2D, 0x00);`
Write a byte 0x00 to the register 0x2D of the peripheral device with address 0x3A.

Line 6: `RiicSendStop();`
Send a STOP condition.

Line 7: `RiicSendStart();`
Send a START condition again.

Line 8: `i = RiicReadByte(0x3A, 0x00);`
Read a byte from the register 0x00 of the peripheral with address 0x3A.

Line 9: `RiicSendStop();`
Send a STOP condition.

Line 10: `RiicUnIni();`
Disable the RIIC0 interface.

Line 11: `while(1)`
Wait here forever.

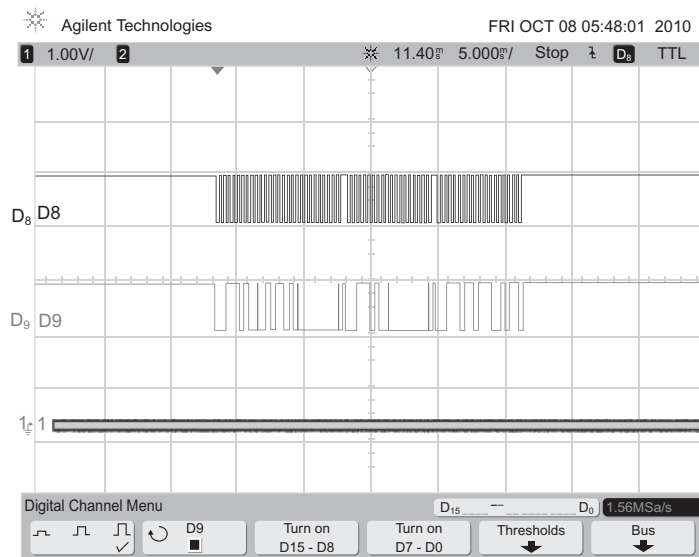


Figure 7.54 Oscilloscope Capture of the complete I²C communication for Basic Example 7.3.3.

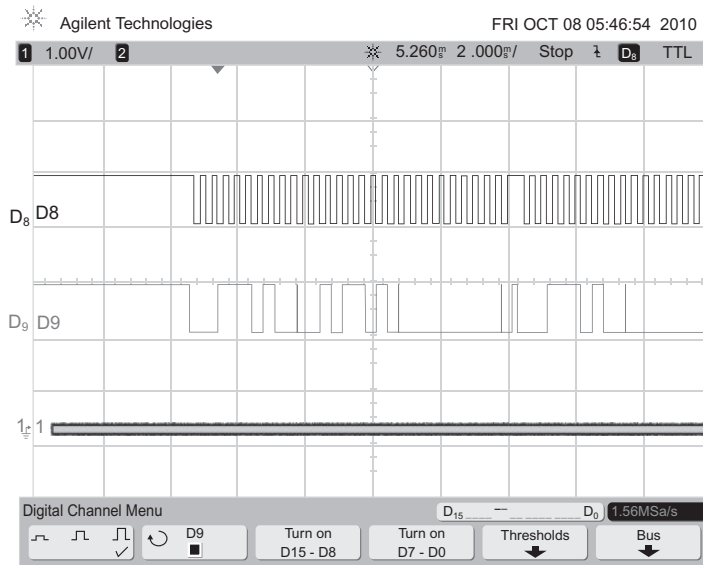


Figure 7.55 Oscilloscope Capture of the beginning of I²C communication for Basic Example 01 (scaled along x-axis). There are 3 data bytes transferred for the write cycle (first 27 clock pulses).

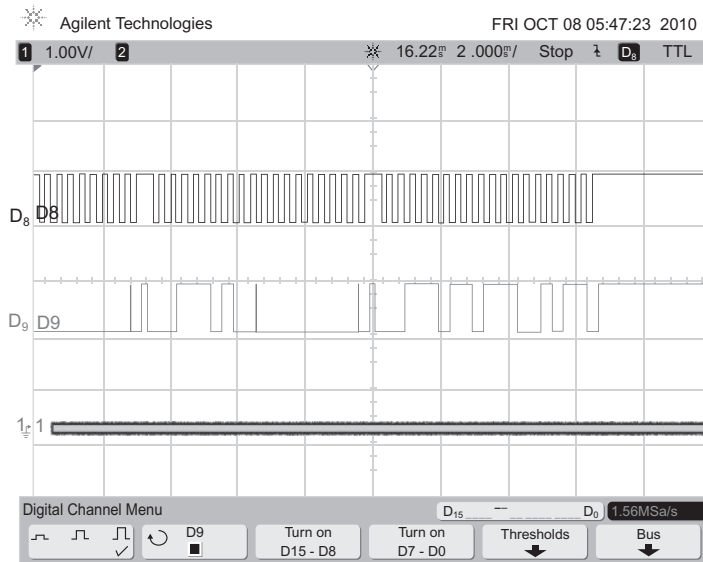


Figure 7.56 Oscilloscope Capture of the end of I²C communication for Basic Example 7.3.3 (scaled along the x-axis). There are two cycles here, each consisting of 2 data bytes. First is the 2-byte write cycle and the other is the 2-byte read cycle.

7.4 ADVANCED CONCEPTS

Now that we have learned the details of the working behind various communication techniques with polling; i.e., the UART, SPI, and I²C interfaces, in this section we will study some of the advanced features and implementations of the same. Concepts learned in these chapters will be implemented in **Section 7.5** by means of examples. Concepts learned in this section will require basic knowledge of interrupts and interrupt service routines, and additional hardware to be present. It is advisable for the reader to be aware of the additional peripherals being used while illustrating the advanced features of the communication techniques in this section.

7.4.1 Applying FIFO Data Structures for Transmission and Reception Using the UART Serial Communications Interface

As mentioned in **Section 7.2.1** the UART in essence contains a single byte buffer each for transmitting and receiving data from other peripherals connected via the UART interface. These buffers are occasionally filled with data and then the data is transmitted or received. But what if an application is required to transmit data continuously? Usually the peripherals of a Microcontroller operate slower than the actual processing unit. In short, the data output by the processing unit to be transmitted is more quickly generated than transmitted. In such a case, there are two options available: wait for the peripheral to finish transmitting the current data and then load the peripheral with new data, or maintain a First In First Out type of mechanism in which bulk data is stored in a given data structure and then transmitted as and when the peripheral becomes available. The advantage of the latter technique is that the processing unit is free to perform other tasks as data transmission is going on. Before we move on to understanding the design of a UART FIFO, let us take a quick look at a FIFO data structure.

A FIFO type data structure can be visualized as a queue of units standing in line for service. The unit that gets in line first gets service earlier than the unit that enters the queue at a later point of time. This is quite contrary to a LIFO type of data structure in which the last unit to enter the queue gets service prior to the one which entered the queue earlier. FIFOs are generally used wherever operations are to be done on all data in a sequential/consecutive manner. An example of a FIFO is shown in Figure 7.57.

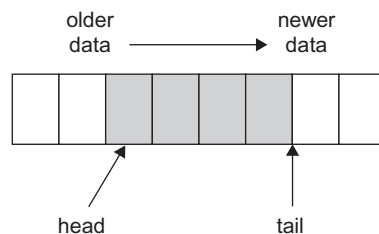


Figure 7.57 Example of a FIFO (queue).

As seen in Figure 7.57 the FIFO consists of a head and a tail where the head contains data that was added to the queue earlier, whereas the tail end contains relatively new data. The size of the queue is also maintained by monitoring variables. Essentials for regulating queues for the UART SCI are as follows:

- Need to maintain one queue for transmission and one queue for reception.
- The transmit ISR unloads data from the transmission queue.
- The receive ISR loads data to the reception queue.
- Pointers are used to maintain the head and tail of the queue.
- A variable “size” keeps track of the current size of the queue.
- Pointers are wrapped around the queue when queue is not empty but the queue reaches the end of the allotted area.
- The main program is responsible for loading the transmit queue and unloading the receive queue.

Queues are implemented with interrupt service routines and not polling, since polling requires the microcontroller to wait and do nothing until current operation is performed. Interrupt Service Routines, on the other hand, are performed intermittently when required and do not disturb the working of the main program. As we shall see in the Advanced Example 7.5.1, the queues will be loaded at a single occasion and then the main program proceeds without waiting for the transmission to complete. The ISRs continue to occur intermittently and finish the transfer of data. The following is the algorithm followed for the complex example in **Section 7.5.1**.

- Initialize the UART.
- Set up switches and define the size of the queue.
- Define a FIFO queue structure consisting of a data array, a pointer to the head of the array, a pointer to the tail of the array, and a variable for holding the current size of the queue.
- Allot memory for two queues, one for transmission and other for reception.
- Define function for checking if a queue is empty and another function to check if a queue is full.
- Initialize the queues by setting the data in the queue, head and tail to zero.
- Define a function for queuing data in a given queue. In order for the data to be queued, perform a check if the queue is full. If queue is not full, then queue data by adding to the tail of the array, update the tail and size values, and report success. Otherwise abort queuing and report failure.
- Define a function for dequeuing data. In order to dequeue data, check if the queue is empty. If the queue is not empty, copy a byte of data from the head of the queue, update the head and size of the queue, and return the copied variable. If the queue is empty, exit the function.

- Define the interrupt service routines that do the following:
 - Transmit routines: Check if the queue is empty. If the queue is not empty, dequeue a byte of data from the transmission queue and give it to the transmit buffer of the microcontroller.
 - Receive routine: Try to enqueue the data to the receive queue. If the queue is full, provide with an indication.

Setting up the interrupts: The following is the procedure for setting up the serial communication interface interrupts:

- In the vect.h file define the vector table locations of the interrupts and declare them as follows:
 - `#pragma interrupt (Excep_SCI2_RXI2(vect = 223)) void Excep_SCI2_RXI2 (void);`
 - `#pragma interrupt (Excep_SCI2_TXI2(vect = 224)) void Excep_SCI2_TXI2 (void);`
- In the file intrpg.c write the detailed interrupt service routines for transmit and receive under the function names `void Excep_SCI2_RXI2 (void)` and `void Excep_SCI2_TXI2 (void)`.

7.4.2 Multi-processor Communication Using the Renesas Serial Peripheral Interface

One of the advantages of the serial peripheral interface is the high rate of data transfer. Data is usually transferred at a rate more than 1 MHz. These speeds are much higher than most other communication protocols and makes SPI well suited for setting up communication amongst processors. As an example, we shall set up two microcontrollers, one as a master and the other as a slave, and demonstrate high speed data transfer between the two. This setup can be used for various applications such as rapid data accumulation or distributed problem solving; in which a problem is split up into various smaller sections and sent to different processors, solved simultaneously in parts, and then transferred back to the main processor. The following section will demonstrate how to set up two microcontrollers, one in master mode and the other in slave mode, such that data can be rapidly transferred between two or more processors. In essence the setup here is the Single Master Multiple Slave configuration, as shown in Figure 7.58.

Data transfer in the above mentioned configuration is done by means of interrupts and interrupt service routines. The two important interrupts for SPI transfer are the SPTIx and SPRIx interrupts, where $x = 0, 1$ and “x” is the module number of the RSPI, RSPI0/RSPIA, and RSPI1/RSPIB. Timing details of the interrupts and data transfer are described as follows.

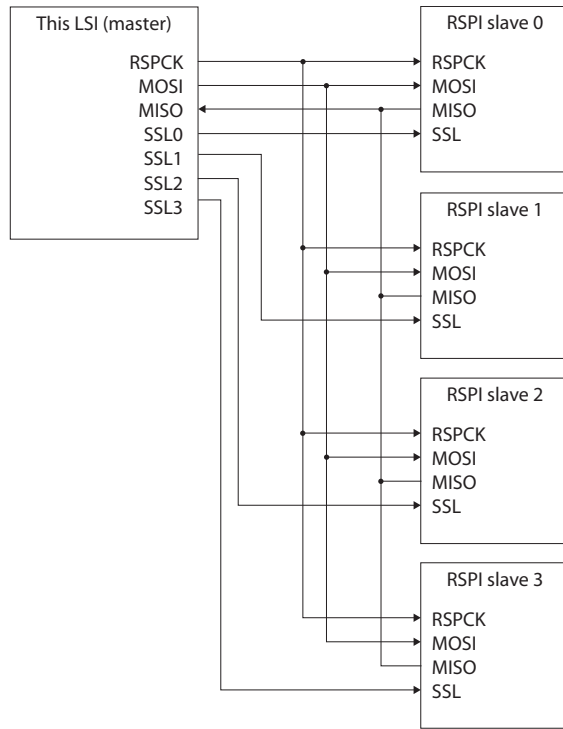


Figure 7.58 Single Master Multiple Slaves [4], page 1559.

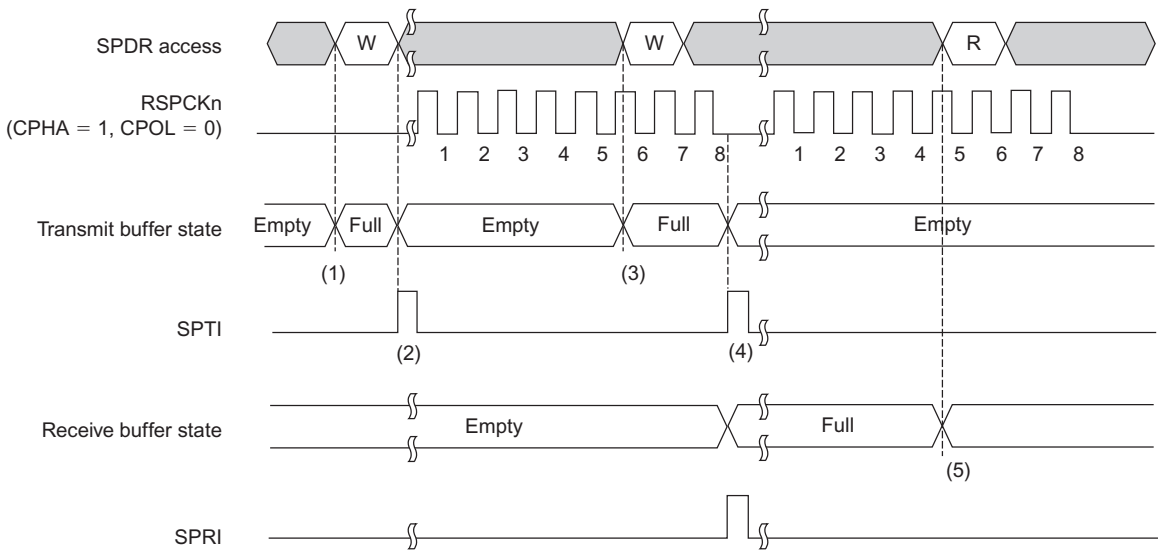


Figure 7.59 Operation and timing diagram of SPTI and SPRI interrupts [4], page 1576.

Interrupts occur at times (1) to (5) and are as follows:

1. If the interrupts are enabled and currently no data is present in the transmit buffer, an interrupt, SPTI, is generated, which writes to SPDR. Since the transmit buffer is empty, data is copied into the transmit buffer.
2. When the shift register is/becomes empty, the RSPI copies the data from the transmit buffer to the shift register, starts shifting out the data, and generates a transmit buffer empty request (SPTI).
3. When transmit data is written to SPDR by the transmit buffer empty interrupt routine, the data is transferred to the transmit buffer. Because the data being transferred serially is stored in the shift register, the RSPI does not copy the data in the transmit buffer to the shift register.
4. The serial transfer ends. Since the receive buffer is empty, the RSPI copies the received data from the shift register into the receive buffer and generates a receive buffer full interrupt SPRI. As the transmit buffer is filled from step 3, the RSPI copies the data from the transmit buffer into the shift register and resumes transmission of data.
5. When SPDR is read by the receive buffer full interrupt routine, the RSPI sends the data in the receive buffer to the bus inside the chip.

In this manner, the data transfer keeps occurring continuously when the RSPI is enabled. Next we will proceed to the setting up of the microcontrollers in required modes and then proceed to use FIFO queues as explained and demonstrated in **Section 7.4.1**. Using FIFO queues for communication simplifies the transfer of data and enables fast and continuous communication. Rules for operating the queues remain the same as in **Section 7.4.1** however one must notice that now data transfer is taking place in both directions at the same time, with much higher speeds as compared to the SCI interface. For setting up multi-processor communication, at least two microcontrollers are needed. One microcontroller will be set up in Master mode while the other will be set up in the Slave mode. The complex example in **Section 7.5.2** follows the algorithms for the two microcontrollers as mentioned in the following:

Master Algorithm

- Initialize one Renesas Microcontroller as the master device by assigning the correct values for the registers.
- Define a FIFO queue structure consisting of a data array, a pointer to the head of the array, a pointer to the tail of the array, and a variable for holding the current size of the queue.
- Allot memory for two queues, one for transmission and the other for reception.

- Define function for checking if the queue is empty, and another function to check if the queue is full.
- Initialize the queues by setting the data in the queue, head and tail to zero.
- Define a function for queuing data in a given queue. In order for the data to be queued, perform a check if the queue is full. If the queue is not full, then queue data by adding to the tail of the array, update the tail and size values, and report success. Otherwise, abort queuing and report failure.
- Define a function for dequeuing data. In order to dequeue data, check if the queue is empty. If the queue is not empty, copy a byte of data from the head of the queue, update the head and size of the queue, and return the copied variable. If the queue is empty, exit the function.
- Define the interrupt service routines that do the following:
 - Transmit routines: Check if the queue is empty. If the queue is not empty, dequeue a byte of data from the transmission queue and give it to the transmit buffer of the microcontroller.
 - Receive routine: Try to enqueue the data to the receive queue. If the queue is full, provide with an indication.

Setting up the interrupts: The following is the procedure for setting up the serial communication interface interrupts:

- In the vect.h file define the vector table locations of the interrupts and declare them as follows:
 - `#pragma interrupt (Excep_RSPIO_SPRIO(vect = 45)) void Excep_RSPIO (void);`
 - `#pragma interrupt (Excep_RSPIO_SPTIO(vect = 46)) void Excep_RSPIO_SPTIO (void);`
- In the file intprg.c write the detailed interrupt service routines for transmit and receive under the function names `void Excep_RSPIO_SPRIO (void)` and `void Excep_RSPIO_SPTIO (void)`.

Slave Algorithm

- Initialize another Renesas Microcontroller as the slave device by assigning the correct values for the registers.
- Define a FIFO queue structure consisting of a data array, a pointer to the head of the array, a pointer to the tail of the array, and a variable for holding the current size of the queue.
- Allot memory for two queues, one for transmission and the other for reception.
- Define function for checking if the queue is empty, and another function to check if the queue is full.

- Initialize the queues by setting the data in the queue, head and tail to zero.
- Define a function for queuing data in a given queue. In order for the data to be queued, perform a check if the queue is full. If the queue is not full, then queue data by adding to the tail of the array, update the tail and size values, and report success. Otherwise, abort queuing and report failure.
- Define a function for dequeuing data. In order to dequeue data, check if the queue is empty. If the queue is not empty, copy a byte of data from the head of the queue, update the head and size of the queue, and return the copied variable. If the queue is empty, exit the function.
- Define the interrupt service routines that do the following:
 - Transmit routines: Check if the queue is empty. If the queue is not empty, dequeue a byte of data from the transmission queue and give it to the transmit buffer of the microcontroller.
 - Receive routine: Try to enqueue the data to the receive queue. If the queue is full, provide with an indication.

Setting up the interrupts: The following is the procedure for setting up the serial communication interface interrupts:

- In the vect.h file define the vector table locations of the interrupts and declare them as follows:
 - `#pragma interrupt (Excep_RSPIO_SPRIO(vect = 45)) void Excep_RSPIO_SPRIO (void);`
 - `#pragma interrupt (Excep_RSPIO_SPTIO(vect = 46)) void Excep_RSPIO_SPTIO (void);`
- In the file intprg.c write the detailed interrupt service routines for transmit and receive under the function names `void Excep_RSPIO_SPRIO (void)` and `void Excep_RSPIO_SPTIO (void)`.

7.4.3 Transfer of Data Between Peripherals Connected on the I²C Bus Using FIFOs

In section 7.2.3 we explained the details of the Renesas I²C interface module and the procedure for setting it up. In section 7.3.3 we demonstrated how to transfer a single byte of data to and from a peripheral. As observed, there is a lot of overhead to transfer a single byte to a peripheral. It thus makes sense to transfer more than 1 byte at a single time to the device.

Most devices that operate using the I²C interface store and read data bytes from registers; i.e., we read and write data from registers of the device. The devices usually have a register address pointer which points to the register to write to or read from. This register is

usually auto incremented when the data is transferred. This allows us to transfer multiple bytes to and from the device. Thus we can use FIFOs to implement the transfer of data. The easiest method to operate the FIFOs is by using interrupts.

The following are the algorithms to read and write data to the device. Data provided to the transmit buffer is from the transmit FIFO and data received from the receive buffer is input into the receive FIFO:

Writing data to a peripheral device/Master transmitter operation using interrupts:

1. Set the IICRST bit in ICCR1 to 1 (internal reset) and then clear the IICRST bit to 0 (canceling reset) with the ICE bit in ICCR1 cleared to 0 (disabling the interface). This initializes the internal state and the various flags of ICSR1. After that, set registers SARLY, SARUY, ICSEY, ICMR1, ICBRH, and ICBRL ($y = 0$ to 2), and set the other registers as necessary. When the necessary register settings have been completed, set the ICE bit to 1 (to enable transfer). This step is not necessary if initialization of the RIIC has already been completed.
2. Read the BBSY flag in ICCR2 to check that the bus is open, and then set the ST bit in ICCR2 to 1 (start condition issuance request). Upon receiving the request, the RIIC issues a start condition. At the same time, the BBSY flag and the START flag in ICSR2 are automatically set to 1 and the ST bit is automatically cleared to 0. At this time, if the start condition is detected, and the internal levels for the SDA output state and the levels on the SDA_n line have matched while the ST bit is 1, the RIIC recognizes that issuing of the start condition as requested by the ST bit has been successfully completed, and the MST and TRS bits in ICCR2 are automatically set to 1, placing the RIIC in master transmitter mode. The TDRE flag in ICSR2 is also automatically set to 1 in response to the setting of the TRS bit to 1.
3. Check that the TDRE flag in ICSR2 is 1, and then write the value for transmission (the slave address and the R/W# bit) to ICDRT. Once the data for transmission are written to ICDRT, the TDRE flag is automatically cleared to 0, the data are transferred from ICDRT to ICDRS, and the TDRE flag is again set to 1. After the byte containing the slave address and R/W# bit has been transmitted, the value of the TRS bit is automatically updated to select master transmitter or master receiver mode in accord with the value of the transmitted R/W# bit. If the value of the R/W# bit was 0, the RIIC continues in master transmitter mode. Since the ICSR2.NACKF flag being 1 at this time indicates that no slave device recognized the address or that there was an error in communications, write 1 to the ICCR2.SP bit to issue a stop condition. For data transmission with an address in the 10-bit format, start by writing 1111 0b, the two higher-order bits of the slave address, and W to ICDRT as the first address transmission. Then, as the second address transmission, write the eight lower-order bits of the slave address to ICDRT.

4. After confirming that the TDRE flag in ICSR2 is 1, write the data for transmission to the ICDRT register. The RIIC automatically holds the SCL_n line low until the data for transmission are ready, or a stop condition is issued.
5. After all bytes of data for transmission have been written to the ICDRT register, wait until the value of the TEND flag in ICSR2 returns to 1, and then set the SP bit in ICCR2 to 1 (stop condition issuance request). Upon receiving a stop condition issuance request, the RIIC issues the stop condition.
6. Upon detecting the stop condition, the RIIC automatically clears the MST and TRS bits in ICCR2 to 00b and enters slave receiver mode. Furthermore, it automatically clears the TDRE and TEND flags to 0, and sets the STOP flag in ICSR2 to 1.
7. After checking that the ICSR2.STOP flag is 1, clear the ICSR2.NACKF and STOP flags to 0 for the next transfer operation.

Figures 7.60 and 7.61 show the timings of the operations.

Reading data from a peripheral device/Master receiver operation:

1. Set the IICRST bit in ICCR1 to 1 (internal reset) and then clear the IICRST bit to 0 (canceling reset) with the ICE bit in ICCR1 cleared to 0 (disabling the interface). This initializes the internal state and the various flags of ICSR1. After that, set registers SAR_L_y, SAR_U_y, ICSE_R, ICMR₁, ICBRH, and ICBRL ($n = 0$ to 2), and set the other registers as necessary. When the necessary register settings have been completed, set the ICE bit to 1 (to enable transfer). This step is not necessary if initialization of the RIIC has already been completed.
2. Read the BBSY flag in ICCR2 to check that the bus is open, and then set the ST bit in ICCR2 to 1 (start condition issuance request). Upon receiving the request, the RIIC issues a start condition. When the RIIC detects the start condition, the BBSY flag and the START flag in ICSR2 are automatically set to 1 and the ST bit is automatically cleared to 0. At this time, if the start condition is detected and the levels for the SDA output and the levels on the SDA_n line have matched while the ST bit is 1, the RIIC recognizes that issuing of the start condition as requested by the ST bit has been successfully completed. As a result the MST and TRS bits in ICCR2 are automatically set to 1, placing the RIIC in master transmitter mode. The TDRE flag in ICSR2 is also automatically set to 1 in response to setting of the TRS bit to 1.
3. Check that the TDRE flag in ICSR2 is 1, and then write the value for transmission (the first byte indicates the slave address and value of the R/W# bit) to ICDRT. Once the data for transmission are written to ICDRT, the TDRE flag is automatically cleared to 0, the data are transferred from ICDRT to ICDRS, and the TDRE flag is again set to 1. Once the byte containing the slave address and R/W# bit has been transmitted, the value of the ICCR2.TRS bit is automatically updated to

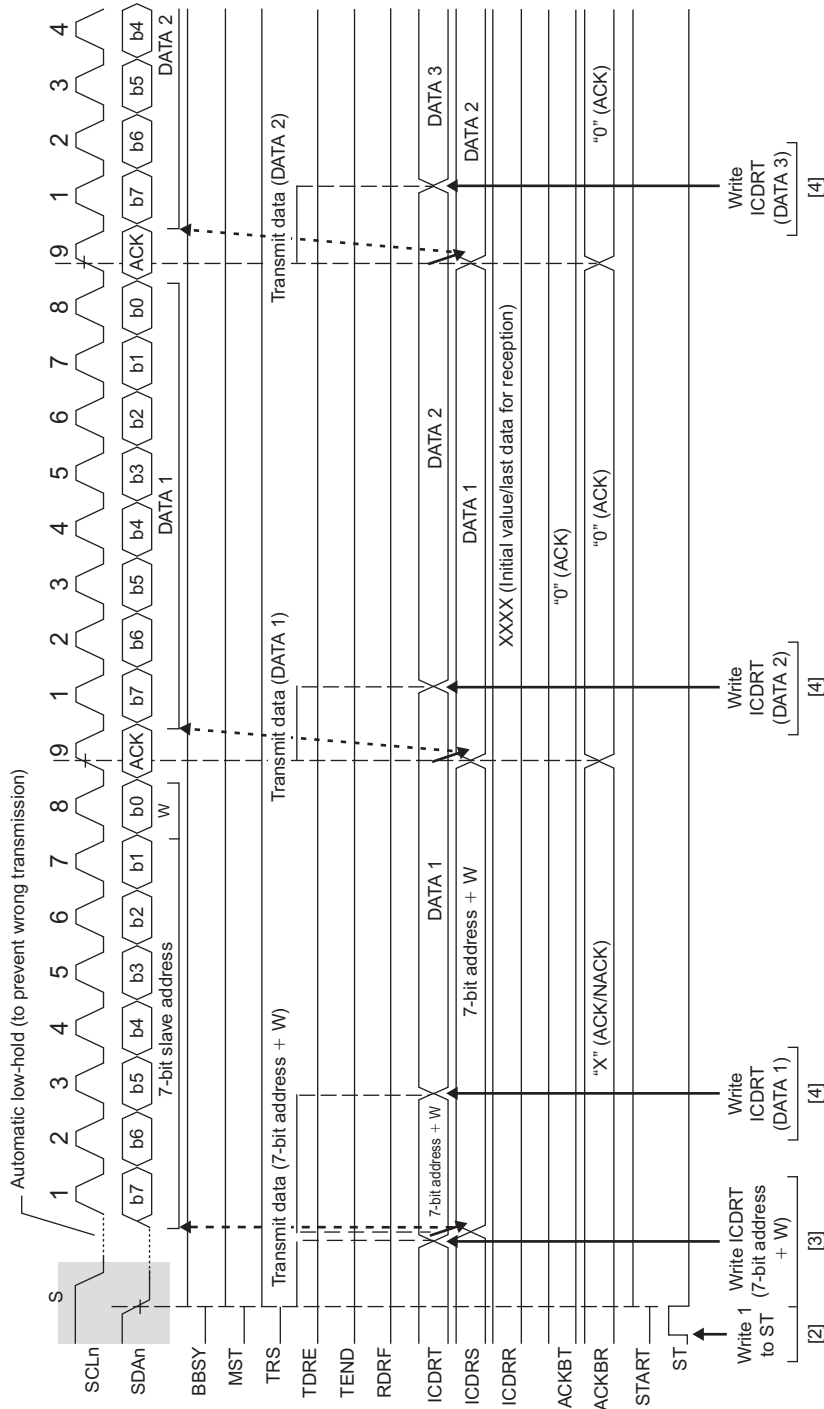


Figure 7.60 Operation of the RIIC module in master transmitter mode (7-bit address format) [4], page 1444.

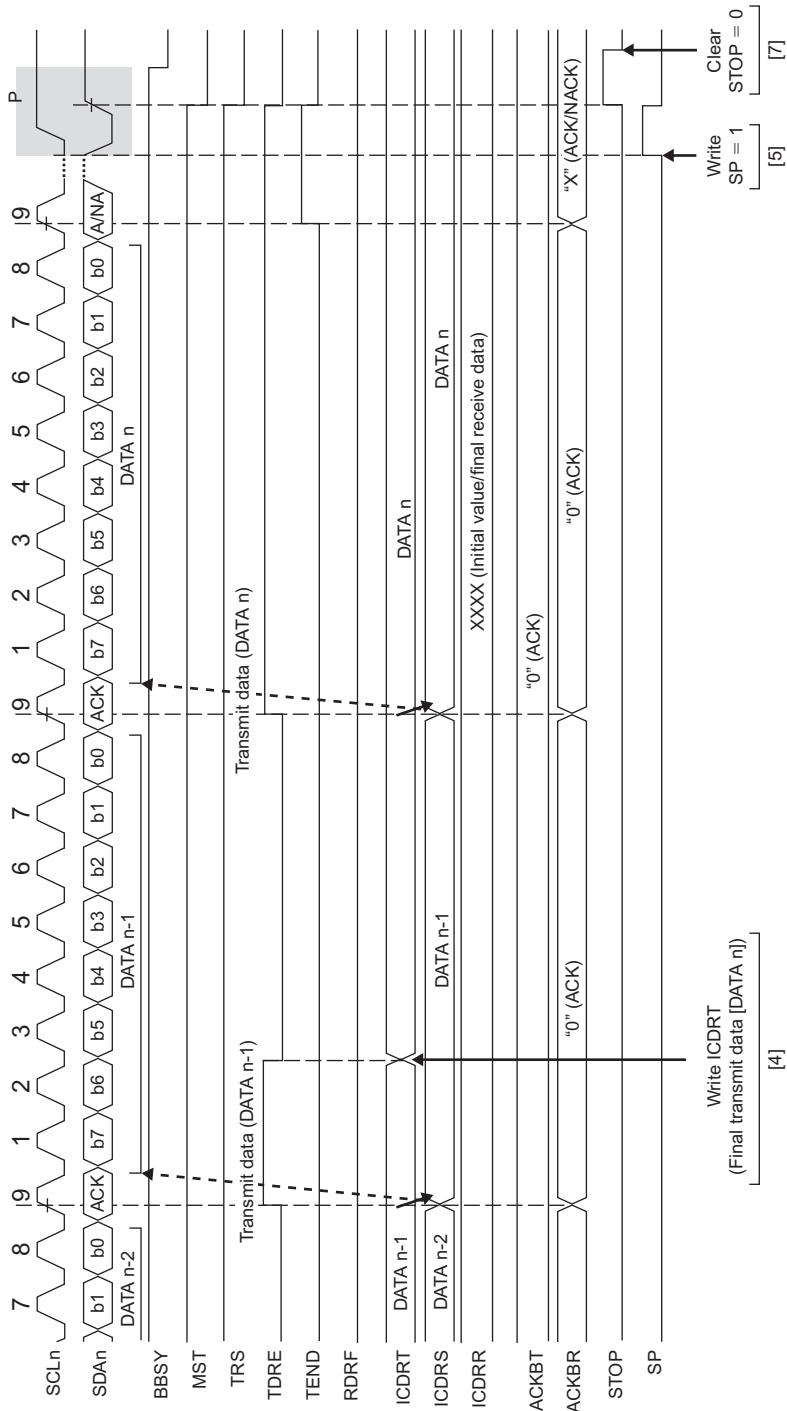


Figure 7.61 RIIC module in master transmitter mode [4], page 1445.

select master transmitter or master receiver mode in accord with the value of the transmitted R/W# bit. If the value of the R/W# bit was 1, the TRS bit is cleared to 0 on the rising edge of the ninth cycle of SCL_n (the clock signal), placing the RIIC in master receiver mode. At this time, the TDRE flag is automatically cleared to 0 and the ICSR2.RDRF flag is automatically set to 1.

Since the ICSR2.NACKF flag being 1 at this time indicates that no slave device recognized the address or there was an error in communications, write 1 to the ICCR2.SP bit to issue a stop condition. For master reception from a device with a 10-bit address, start by using the master transmission to issue the 10-bit address, and then issue a restart condition. After that, transmitting 1111 0b, the two higher-order bits of the slave address, and the R bit places the RIIC in master receiver mode.

4. Dummy read ICDRR after confirming that the RDRF flag in ICSR2 is 1. This makes the RIIC start output of the SCL (clock) signal and start data reception.
5. After 1 byte of data has been received, the RDRF flag in ICSR2 is set to 1 on the rising edge of the eighth or ninth cycle of SCL clock (the clock signal) as selected by the RDRFS bit in ICMR3. Reading out ICDRR at this time will produce the received data, and the RDRF flag is automatically cleared to 0 at the same time. Furthermore, the value of the acknowledgement field received during the ninth cycle of SCL clock is returned as the value set in the ACKBT bit of ICMR3. Save the received data into the FIFO and increment the pointer to the FIFO.
6. When the next value to be received will be the final byte, set the WAIT bit in ICMR3 to 1 (so that waiting is applied) before reading ICDRR. This causes the SCL_n line to be held low from the falling edge of the ninth clock cycle after reception of the next data (i.e., the final byte), enabling issuance of a stop condition. However, when the ICMR3.RDRFS bit is 0 and the slave device must be notified that it is to end transfer for data reception after transfer of the next (final) byte, set the ACKBT bit in ICMR3 to 1 (NACK).
7. After reading the byte before last from the ICDRR register, if the value of the ICSR2.RDRF flag is confirmed to be 1, write 1 to the SP bit in ICCR2 (stop condition issuance request) and then read the last byte from ICDRR. Save the received data bytes into the FIFO and increment the pointer to the FIFO. When ICDRR is read, the RIIC is released from the wait state and issues the stop condition after low-level output in the ninth clock cycle is completed or the SCL line is released from the low-hold state.
8. Upon detecting the stop condition, the RIIC automatically clears the MST and TRS bits in ICCR2 to “00b” and enters slave receiver mode. Furthermore, detection of the stop condition leads to setting of the STOP flag in ICSR2 to 1.
9. After checking that the ICSR2.STOP flag is 1, clear the ICSR2.NACKF and STOP flags to 0 for the next transfer operation.

Figures 7.62 and 7.63 show the timings of the operations.

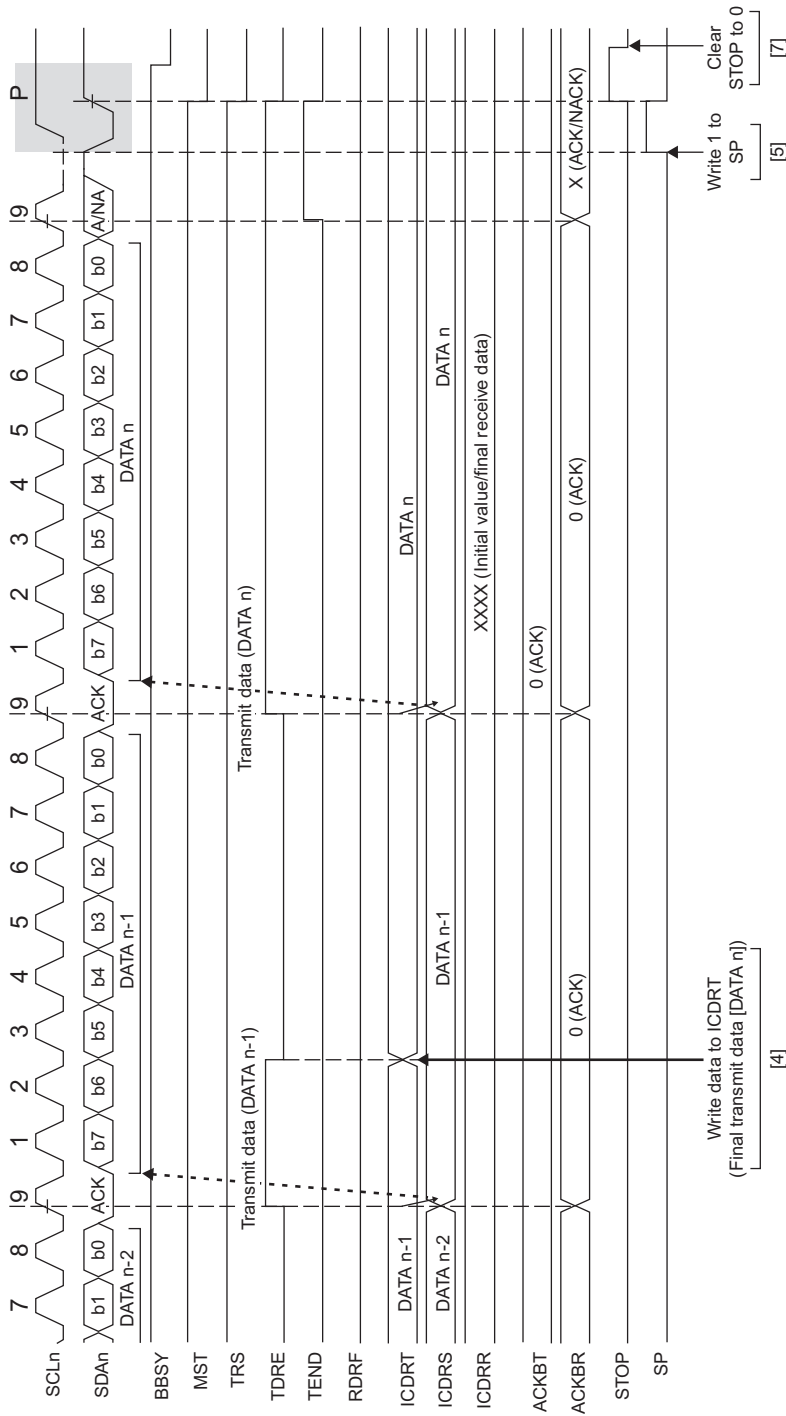


Figure 7.62 Operation of the IIC module in master receiver mode (7-bit address format) [4], page 1448.

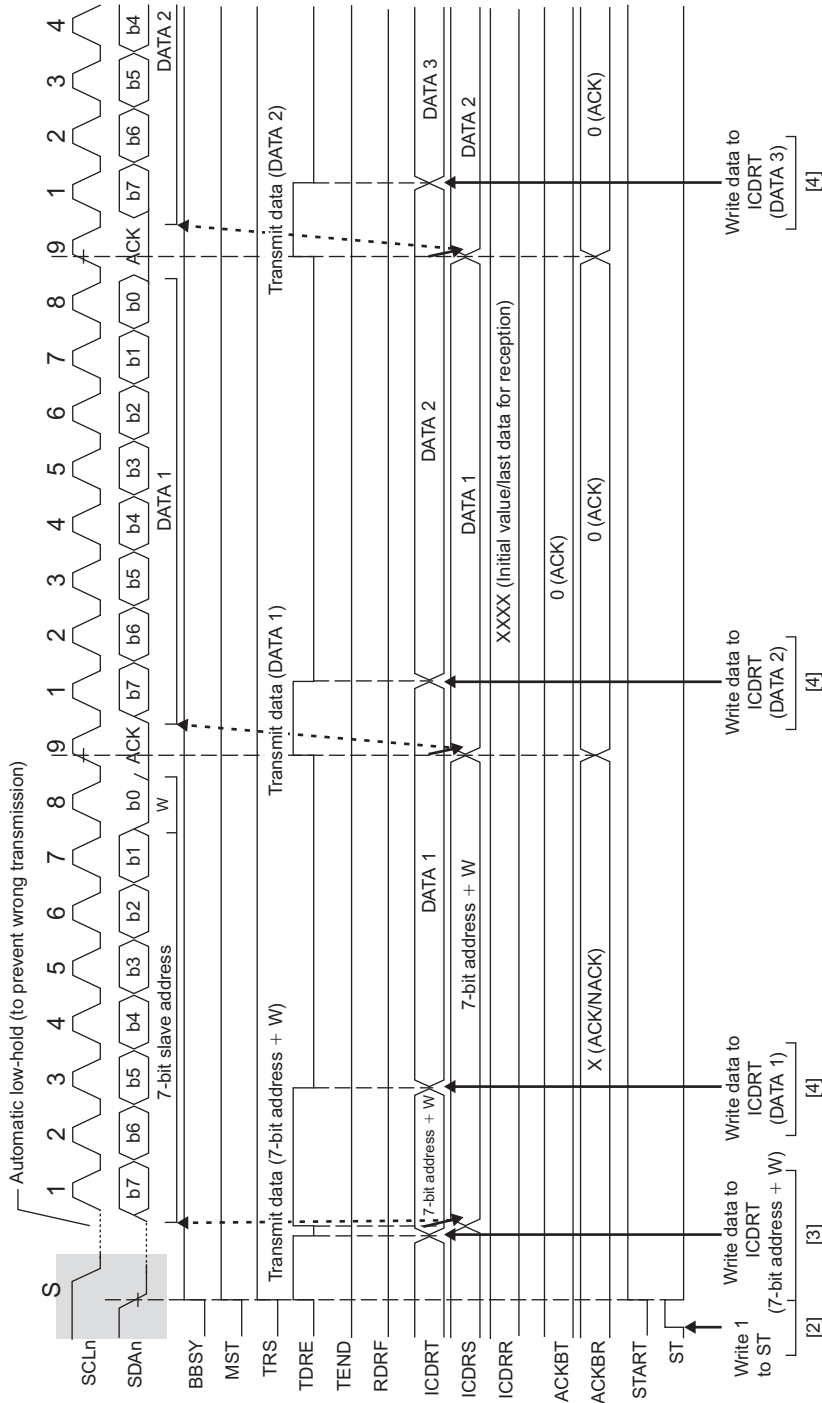


Figure 7.63 RLLC module in master receiver mode [4], page 1449.

Advanced Section 7.5.3 helps demonstrate these concepts.

7.5 ADVANCED EXAMPLES

7.5.1 FIFO Data Structures for Transmission and Reception Using the UART Serial Communications Interface

Aim: Demonstration of the use of FIFOs towards transmission and reception.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, Renesas Development Kit; PC with RS-232 serial port.

Details: In this example we demonstrate the use of FIFO data structures for transmission and reception to show how the communication interface operates using interrupts, and how the microcontroller manages to work on other tasks while communication proceeds normally. This example is based on the initialization codes of the **Basic Example 7.3.1** and is similar to the one detailed in **Section 7.4.1**.

Procedure: For this example, create a new workspace in HEW and fill the given lines of code in the corresponding files mentioned before the following code. Compile; build all files and Download to board as mentioned in Chapter 4. When downloaded, connect the RX63N development board to a standard PC with an RS-232 port configured at 115200 baud, no parity, and 1 stop bit to view the results on a HyperTerminal program or on a Serial Port Terminal.

Code: The following is the code related to the demonstration:

Setting up Interrupt Service Routines

Filename: vecttbl.c

```

1. #pragma interrupt (Excep_SCI2_RXI2(vect = 223))
2. void Excep_SCI2_RXI2(void);
3. #pragma interrupt (Excep_SCI2_TXI2(vect = 224))
4. void Excep_SCI2_TXI2(void);

```

Filename: intprg.c

```

1. #include "RX63N_SCI_UART.h"
2. #include <machine.h>
3. #include "vect.h"
4. #pragma Section IntPRG
5. void Excep_SCI2_RXI2(void){
6.     if(!Q_Enqueue(&rx_q, SCI2.RDR)){
7.         }

```

```

8. }
9. void Excep_SCI2_TXI2(void) {
10.     if(!Q_Empty(&tx_q))
11.         SCI2.TDR = Q_Dequeue(&tx_q);
12. }

```

Setting up function definitions for operating on the queues:

Filename: RX63N_SCI_UART.h

```

1. #include "iodefine.h"
2. #define Q_SIZE (32)
3. typedef struct {
4.     unsigned char Data [Q_SIZE];
5.     unsigned int Head; //points to oldest data element
6.     unsigned int Tail; //points to next free space
7.     unsigned int Size; //quantity of elements in queue
8. } Q_T;
9. int Q_Empty(Q_T * q);
10. int Q_Full(Q_T * q);
11. int Q_Enqueue(Q_T * q, unsigned char d);
12. unsigned char Q_Dequeue(Q_T * q);
13. void Q_Init(Q_T * q);
14. void delay(long unsigned int n);
15. void init_switches();
16. void init_LEDs();
17. void init_UART0();
18. void d3_send_string(far char * s);
19. void demo3(void);
20. extern Q_T tx_q, rx_q;

```

Setting up all the function details related to the functioning of the UART and FIFO queues:

Filename: RX63N_SCI_UART.c

```

1. #include "RX63N_SCI_UART.h"
2. Q_T tx_q, rx_q;
3. int Q_Empty(Q_T * q) {
4.     return (q->Size == 0);
5. }
6. int Q_Full(Q_T * q) {
7.     return (q->Size == Q_SIZE);

```

```
8. }
9. int Q_Enqueue(Q_T * q, unsigned char d){
10.     if(!Q_Full(q)){
11.         q->Data [q->Tail++] = d;
12.         q->Tail %= Q_SIZE;
13.         q->Size++;
14.         return 1;
15.     }
16.     else return 0;
17. }
18. unsigned char Q_Dequeue(Q_T * q){
19.     unsigned char t = 0;
20.     if(!Q_Empty(q)){
21.         t = q->Data [q->Head ];
22.         q->Data [q->Head++] = 0;
23.         q->Head %= Q_SIZE;
24.         q->Size--;
25.     }
26.     return t;
27. }
28. void Q_Init(Q_T * q){
29.     unsigned int i;
30.     for(i = 0; i < Q_SIZE; i++)
31.         q->Data [i] = 0;
32.     q->Head = 0;
33.     q->Tail = 0;
34.     q->Size = 0;
35. }
36. void init_UART0(){
37.     SYSTEM.MSTPCRA.BIT.ACSE = 0;
38.     MSTP(SCI2) = 0;
39.     SCI2.SCR.BYTE = 0x00;
40.     MPC.P50PFS.BYTE = 0x4A;
41.     MPC.P52PFS.BYTE = 0x4A;
42.     PORT5.PDR.BIT.B0 = 1;
43.     PORT5.PDR.BIT.B2 = 0;
44.     PORT5.PMR.BIT.B0 = 1;
45.     PORT5.PMR.BIT.B2 = 1;
46.     SCI2.SMR.BYTE = 0x00;
47.     SCI2.SCMR.BIT.SMIF = 0;
48.     SCI2.BRR = 12;
49.     SCI2.SCR.BIT.RIE = 1;
```



```

50.     SCI2.SCR.BIT.TIE  = 1;
51.     SCI2.SCR.BIT.TEIE = 1;
52.     IR(SCI2, RXI2) = 0;
53.     IR(SCI2, TXI2) = 0;
54.     SCI2.SCR.BYTE |= 0x30;
55. }
56. void d3_send_string(far char * s){
57.     while(*s){
58.         if(Q_Enqueue(&tx_q, *s))
59.             s++;
60.         else { }
61.     }
62.     if(IR(SCI2, TXI2) == 0){
63.         SCI2.TDR = Q_Dequeue(&tx_q);
64.     }
65. }
66. void demo3(void){
67.     char c;
68.     d3_send_string("Hello, interruptible world!\n\r");
69.     while(1){
70.         if(!Q_Empty(&rx_q)){
71.             c = Q_Dequeue(&rx_q);
72.             d3_send_string("Ouch!\n\r");
73.         }
74.     }
75. }

```

Main Program

Filename: Workspace_name.c

```

1. #include "RX63N_SCI_UART.h"
2. void main(){
3.     init_switches();
4.     init_LEDs();
5.     init_UART0();
6.     Q_Init(&tx_q);
7.     Q_Init(&rx_q);
8.     demo3();
9.     while(1)
10.    ;
11. }

```

7.5.2 Multi-processor Communication Using Queues and the Renesas Serial Peripheral Interface

Aim: Demonstration of multi-processor communication using queues and the RSPI for rapid communication between microcontrollers.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, Two Renesas Development Kits.

Details: In the previous example, we demonstrated how communication takes place at a continuous pace using queues. In this example we demonstrate how to perform multi-processor communication at much higher speeds than those available with the SCI interface. Baud rates can reach maximum speeds of PCLK, which is the peripheral clock generated by the RX63N processor. Since the RSPI operates much faster than the SCI, it is an ideal serial bus for multi-processor communication as compared to the SCI and I²C interface.

Procedure: For this example, create a new workspace in HEW and fill the given lines of code in the corresponding files mentioned before the following code. You now need to download two separate pieces of codes on to each board; one for the master device and one for the slave device. At the beginning of the main file for the master device, make sure that the “#define RSPI_Master_Device” is not commented out while the “#define RSPI_Slave_Device” is commented out. This will build the main example code for the master device. Once this example code has been built, download the module on to one board. For the slave device, make sure that the “#define RSPI_Slave_Device” is not commented where as the “#define RSPI_Master_Device” is commented out. This will build the main example code for the slave device. Once this example code has been built, download the module on to the other board. Make sure that you are not building both modules at the same time; i.e., “#define RSPI_Master_Device” and “#define RSPI_Slave_Device” are not defined at the same time, or else the code/device will not function.

Code: The following is the code related to the demonstration:

Setting Up Interrupt Service Routines

Filename: vect.h

```
1. #pragma interrupt (Excep_RSPIO_SPRI0 (vect = 45))
2. void Excep_RSPIO_SPRI0 (void);
3. #pragma interrupt (Excep_RSPIO_SPTI0 (vect = 46))
4. void Excep_RSPIO_SPTI0 (void);
```

Filename: intprg.c

```
1. #include "RX63N_SCI_UART.h"
2. #include <machine.h>
```

```

3. #include "vecttbl.c"
4. void Excep_RSPIO_SPRI0(void) {
5.     LED4 = LED_ON;
6.     if(!SPI_Q_Enqueue(&rx_q, (0x00FF & RSPIO.SPDR.WORD.L))){
7.         LED5 = LED_ON;
8.     }
9.     LED4 = LED_OFF;
10. }
11. void Excep_RSPIO_SPTI0(void) {
12.     LED6 = LED_ON;
13.     if(!SPI_Q_Empty(&tx_q))
14.         RSPIO.SPDR.WORD.H = (0x00FF & SPI_Q_Dequeue(&tx_q));
15.     LED6 = LED_OFF;
16. }

```

Setting Up Function Definitions for Operating on the Queues

Filename: RX63N_RSPI.h

```

1. #include "iodefine.h"
2. #define NULL (0)
3. #define Q_SIZE (32)
4. typedef struct {
5.     unsigned char Data [Q_SIZE ];
6.     unsigned int Head;
7.     unsigned int Tail;
8.     unsigned int Size;
9. } Q_T;
10. int SPI_Q_Empty(Q_T * q);
11. int SPI_Q_Full(Q_T * q);
12. int SPI_Q_Enqueue(Q_T * q, unsigned char d);
13. unsigned char Q_Dequeue(Q_T * q);
14. void SPI_Q_Init(Q_T * q);
15. void SPI_delay(long unsigned int n);
16. void SPI_init_switches();
17. void SPI_init_LEDs();
18. void SPI_init_RSPI_Master();
19. void SPI_init_RSPI_Slave();
20. void SPI_d3_send_string(far char * s);
21. void SPI_demo3(void);
22. extern Q_T tx_q, rx_q;

```

Setting Up All the Function Details Related to the Functioning of the UART and FIFO Queues

Filename: RX63N_SCI_UART.c

```
1. #include "iodefine.h"
2. #include "yrdkrx63n.h"
3. #include "RX63N_SCI_UART.h"
4. Q_T tx_q, rx_q;
5. void SPI_init_RSPI_Master(void) {
6.     MSTP(RSPI0) = 0;
7.     MPC.PC5PFS.BYTE = 0x0D;
8.     MPC.PC6PFS.BYTE = 0x0D;
9.     MPC.PC7PFS.BYTE = 0x0D;
10.    PORTC.PDR.BIT.B7 = 0;
11.    PORTC.PDR.BIT.B6 = 1;
12.    PORTC.PDR.BIT.B5 = 1;
13.    PORTC.PDR.BIT.B4 = 1;
14.    PORTC.PODR.BIT.B4 = 1;
15.    PORTC.PODR.BIT.B7 = 1;
16.    PORTC.PODR.BIT.B6 = 1;
17.    PORTC.PODR.BIT.B5 = 1;
18.    RSPI0.SPPCR.BYTE = 0x00;
19.    RSPI0.SPBR.BYTE = 0x00;
20.    RSPI0.SPDCR.BYTE = 0x00;
21.    RSPI0.SPCKD.BYTE = 0x00;
22.    RSPI0.SSLND.BYTE = 0x00;
23.    RSPI0.SPND.BYTE = 0x00;
24.    RSPI0.SPCR2.BYTE = 0x00;
25.    IPR(RSPI0, SPTI0) = 1; //Clear Transmit interrupt bit
26.    IEN(RSPI0, SPTI0) = 1; //Enable Transmit interrupt bit
27.    IPR(RSPI0, SPRI0) = 1; //Clear Transmit interrupt bit
28.    IEN(RSPI0, SPRI0) = 1; //Enable Transmit interrupt bit
29.    RSPI0.SPCMD0.WORD = 0x0701;
30.    RSPI0.SPCR.BYTE = 0xE8;
31.    RSPI0.SSLP.BYTE = 0x00;
32.    RSPI0.SPSCR.BYTE = 0x00;
33. }
34. void SPI_init_RSPI_Slave(void) {
35.     MSTP(RSPI0) = 0;
```

```
36.    MPC.PC5PFS.BYTE = 0x0D;
37.    MPC.PC6PFS.BYTE = 0x0D;
38.    MPC.PC7PFS.BYTE = 0x0D;
39.    PORTC.PDR.BIT.B7 = 1;
40.    PORTC.PDR.BIT.B6 = 0;
41.    PORTC.PDR.BIT.B5 = 0;
42.    PORTC.PDR.BIT.B4 = 0;
43.    PORTC.PODR.BIT.B4 = 0;
44.    PORTC.PODR.BIT.B7 = 1;
45.    PORTC.PODR.BIT.B6 = 0;
46.    PORTC.PODR.BIT.B5 = 0;
47.    RSPI0.SPPCR.BYTE = 0x04;
48.    RSPI0.SPBR.BYTE = 0x00;
49.    RSPI0.SPDCR.BYTE = 0x00;
50.    RSPI0.SPCKD.BYTE = 0x00;
51.    RSPI0.SSLND.BYTE = 0x00;
52.    RSPI0.SPND.BYTE = 0x00;
53.    RSPI0.SPCR2.BYTE = 0x00;
54.    RSPI0.SPCMD0.WORD = 0x0701;
55.    RSPI0.SPDR.WORD.L = 0xAA55;
56.    RSPI0.SPDR.WORD.H = 0x55AA;
57.    IEN(RSPI0, SPRI0) = 1; //Enable Receive interrupt
58.    IEN(RSPI0, SPTI0) = 1; //Enable Transmit interrupt
59.    IPR(RSPI0, SPRI0) = 1;
60.    IPR(RSPI0, SPTI0) = 1;
61.    RSPI0.SSLP.BYTE = 0x00;
62.    RSPI0.SPCR.BYTE = 0xA0;
63.    RSPI0.SPSCR.BYTE = 0x00;
64.    RSPI0.SPCR.BIT.SPE = 1;
65. }
66. int SPI_Q_Empty(Q_T * q){
67.     return (q->Size == 0);
68. }
69. int SPI_Q_Full(Q_T * q){
70.     return (q->Size == Q_SIZE);
71. }
72. int SPI_Q_Enqueue(Q_T * q, unsigned char d){
73.     if(!SPI_Q_Full(q)){
74.         q->Data [q->Tail++] = d;
```

```
75.     q->Tail %= Q_SIZE;
76.     q->Size++;
77.     return 1;
78. }
79. else return 0;
80. }
81. unsigned char SPI_Q_Dequeue(Q_T * q){
82.     unsigned char t = 0;
83.     if(!SPI_Q_Empty(q)){
84.         t = q->Data [q->Head ];
85.         q->Data [q->Head++] = 0;
86.         q->Head %= Q_SIZE;
87.         q->Size--;
88.     }
89.     return t;
90. }
91. void SPI_Q_Init(Q_T * q){
92.     unsigned int i;
93.     for(i = 0; i < Q_SIZE; i++)
94.         q->Data [i] = 0;
95.     q->Head = 0;
96.     q->Tail = 0;
97.     q->Size = 0;
98. }
99. void SPI_delay(long unsigned int n){
100.     while (n-)
101.         ;
102. }
103. void SPI_init_switches(){
104.     SW1 = SW2 = SW3 = 0; //inputs
105. }
106. void SPI_init_LEDs(){
107.     PORTD.PODR.BYTE = 0x00;
108.     PORTE.PODR.BYTE = 0x00;
109. }
110. void SPI_d3_send_string(far char * s){
111.     while(*s){
112.         if(SPI_Q_Enqueue(&tx_q, *s))
113.             s++;
114.         if(IR(RSPI0, SPTI0) == 0){
```

```
115.         SCI2.TDR = SPI_Q_Dequeue(&tx_q);
116.     }
117. }
118. }
119. void SPI_demo3(void) {
120.     char c;
121.     SPI_d3_send_string("Hello, interruptible world!\n\r");
122.     while(1) {
123.         if(!SPI_Q_Empty(&rx_q)) {
124.             c = SPI_Q_Dequeue(&rx_q);
125.             (void)c;
126.             SPI_d3_send_string("Ouch!\n\r");
127.         }
128.     }
129. }
```

Main Program

Filename: Workspace_name.c

```
1. #include "iodefine.h"
2. #include "yrdkrx63n.h"
3. #include "RX63N_SCI_UART.h"
4. #define RSPI_SLAVE
5. #define RSPI_MASTER
6. void main() {
7.     SPI_init_switches();
8.     SPI_init_LEDs();
9.     #ifdef RSPI_MASTER
10.    SPI_init_RSPI_Master();
11.    #endif
12.    #ifdef RSPI_MASTER
13.    SPI_init_RSPI_Slave();
14.    #endif
15.    SPI_Q_Init(&tx_q);
16.    SPI_Q_Init(&rx_q);
17.    SPI_demo3();
18.    while(1)
19.        ;
20. }
```

7.5.3 Transfer of data between peripherals connected on the I²C bus using FIFOs

Aim: To demonstrate mass transfer of data between peripherals connected on the I²C bus.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, Renesas Development Kits (YRDKRX63N) with on board I²C peripherals.

Details: In this example we will demonstrate how to use the I²C bus to transfer large amounts of data to the desired peripheral with minimum overhead. The device we will use is the ADXL345 and will be writing the default values to the ADXL345, specified in the device datasheet and reading the acceleration values for the X, Y, and Z values. The code also provides for a standard framework that can be used to access other devices using the RX63N microcontroller.

Procedure: For this example, create a new workspace in HEW and fill the given lines of code in the corresponding files mentioned before the code below. To use the following code for other peripherals make sure to specify the correct address and number of data bytes to read and write. The given following code is for the Analog Devices Accelerometer ADXL345 [6].

Filename: riic.h

This file contains the most declarations and #define variables used by the RIIC module.

```

1. #ifndef _RIIC_SETTING_DEF
2. #define _RIIC_SETTING_DEF
3. #define RIIC_CH0 //When use channel0, define "RIIC_CH0"
4. #define RIIC_CH1 //When use channel1, define "RIIC_CH1"
5. #ifdef RIIC_CH0
6. #define RIIC RIIC0 //Replace I/O define
7. #else
8. #define RIIC RIIC1 //Replace I/O define
9. #endif
10. #define RIIC_OK 0 //Return value for function "RiicMst"
11. #define RIIC_NG 1 //Return value for function "RiicMst"
12. #define RIIC_BUS_BUSY 2 //Return value for function "RiicMst"
13. void RiicIni(unsigned char, unsigned char);
14. unsigned char RiicStart(unsigned char, unsigned char*, unsigned
    long);
15. #endif // _RIIC_SETTING_DEF

```

Filename: riic.c

This file contains definitions of functions that perform actions in response to calls from either the user or the interrupts.

```

1. void RiicIni(unsigned char in_SelfAddr, unsigned char in_Enable)
2. {
3.     #ifdef RIIC_CH0
4.         SYSTEM.MSTPCRB.BIT.MSTPB21 = 0; //RIIC0(MSTPB21)
5.     #else
6.         SYSTEM.MSTPCRB.BIT.MSTPB20 = 0; //RIIC1(MSTPB20)
7.     #endif
8.     RIIC0.ICCR1.BIT.ICE = 0; //RIIC disable
9.     RIIC0.ICCR1.BIT.IICRST = 1; //RIIC all reset
10.    RIIC0.ICCR1.BIT.IICRST = 0;
11.    RiicMstCnt = 0;
12.    RiicMstNum = 0;
13.    if(in_Enable != 0){ //Initialise RIIC
14.        /* Self address setting */
15.        RIIC0.SARU0.BIT.FS = 0; //7bit address format
16.        RIIC0.SARL0.BYTE = in_SelfAddr; //Set self address
17.        RIIC0.ICMR1.BIT.CKS = 7; //IIC phi = PCLK/128 clock
18.        RIIC0.ICBRH.BIT.BRH = 28; //100kbps (PCLK = 50 MHz)
19.        RIIC0.ICBRL.BIT.BRL = 29;
20.        RIIC0.ICMR3.BIT.ACKWP = 1; //Disable ACKBT protect
21.        RIIC0.ICIER.BIT.RIE = 1; //Edge interrupt
22.        RIIC0.ICIER.BIT.TIE = 1; //Edge interrupt
23.        RIIC0.ICIER.BIT.TEIE = 0; //Level interrupt
24.        RIIC0.ICIER.BIT.NAKIE = 1; //Level interrupt
25.        RIIC0.ICIER.BIT.SPIE = 1; //Level interrupt
26.        RIIC0.ICIER.BIT.STIE = 0; //Level interrupt
27.        RIIC0.ICIER.BIT.ALIE = 0; //Level interrupt
28.        RIIC0.ICIER.BIT.TMOIE = 0; //Level interrupt
29.        #ifdef RIIC_CH0 //RIIC channel0
30.        ICU.IPR [0x88].BYTE = 0x04; //EEIO interrupt level
31.        ICU.IPR [0x89].BYTE = 0x04; //RXIO interrupt level
32.        ICU.IPR [0x8A].BYTE = 0x04; //TXIO interrupt level
33.        ICU.IPR [0x8B].BYTE = 0x04; //TEIO interrupt level
34.        ICU.IER [0x1E].BIT.IEN6 = 1; //EEIO interrupt enable
35.        ICU.IER [0x1E].BIT.IEN7 = 1; //RXIO interrupt enable
36.        ICU.IER [0x1F].BIT.IEN0 = 1; //TXIO interrupt enable

```

```
37.         ICU.IER [0x1F].BIT.IEN1 = 1; //TEI0 interrupt enable
38.         ICU.IR [246].BIT.IR = 0; //EEI0 clear interrupt flag
39.         ICU.IR [247].BIT.IR = 0; //RXI0 clear interrupt flag
40.         ICU.IR [248].BIT.IR = 0; //TXI0 clear interrupt flag
41.         ICU.IR [249].BIT.IR = 0; //TEI0 clear interrupt flag
42.         PORT1.ICR.BIT.B3 = 1; //SDA0 setting
43.         PORT1.ICR.BIT.B2 = 1; //SCL0 setting
44.         #else //RIIC channel1
45.         ICU.IPR [0x8C].BYTE = 0x04; //EEI1 interrupt level
46.         ICU.IPR [0x8D].BYTE = 0x04; //RXI1 interrupt level
47.         ICU.IPR [0x8E].BYTE = 0x04; //TXI1 interrupt level
48.         ICU.IPR [0x8F].BYTE = 0x04; //TEI1 interrupt level
49.         ICU.IER [0x1F].BIT.IEN2 = 1; //EEI1 interrupt enable
50.         ICU.IER [0x1F].BIT.IEN3 = 1; //RXI1 interrupt enable
51.         ICU.IER [0x1F].BIT.IEN4 = 1; //TXI1 interrupt enable
52.         ICU.IER [0x1F].BIT.IEN5 = 1; //TEI1 interrupt enable
53.         ICU.IR [250].BIT.IR = 0; //EEI1 clear interrupt flag
54.         ICU.IR [251].BIT.IR = 0; //RXI1 clear interrupt flag
55.         ICU.IR [252].BIT.IR = 0; //TXI1 clear interrupt flag
56.         ICU.IR [253].BIT.IR = 0; //TEI1 clear interrupt flag
57.         PORT1.PMR.BIT.B3 = 1; //SDA1 setting
58.         PORT1.PMR.BIT.B2 = 1; //SCL1 setting
59.         #endif //RIIC_CH0
60.         RIIC0.ICCR1.BIT.ICE = 1; //RIIC enable
61.     }
62.     else { //Stop RIIC
63.         #ifdef RIIC_CH0
64.             SYSTEM.MSTPCRB.BIT.MSTPB21 = 1; //RIIC0 (MSTPB21)
65.         #else
66.             SYSTEM.MSTPCRB.BIT.MSTPB20 = 1; //RIIC1 (MSTPB20)
67.         #endif
68.     }
69. }
70. unsigned char RiicStart(unsigned char in_addr, unsigned char
    *in_buff, unsigned long in_num)
71. {
72.     if(in_num < 2){ //Check data number (include first
        byte(address))
73.         return RIIC_NG;
74.     }
```

```
75.     if((RIIC0.ICCR2.BYTE & 0xE0) != 0x00){
76.         return RIIC_BUS_BUSY; //Bus busy
77.     }
78.     RIIC0.ICCR2.BIT.ST = 1; //Generate start condition
79.     RiicTrmAddr = in_addr; //Set transmission address
80.     RiicMstBuff = in_buff; //Set transmission buffer
81.     RiicMstCnt = 0;
82.     RiicMstNum = in_num;
83.     return RIIC_OK;
84. }
85. void RiicRDRF(void){
86.     volatile unsigned long cnt;
87.     if(RIIC0.ICSR2.BIT.NACKF != 0){ //When receive NACK
88.         if(RIIC0.ICCR1.BIT.SCLI == 0){
89.             for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
90.         }
91.         RIIC0.ICCR2.BIT.SP = 1; //Generate stop condition
92.         *RiicMstBuff = RIIC0.ICDRR; //Dummy read
93.         return;
94.     }
95.     if(RiicMstCnt >= RiicMstNum){ //After receive all data
96.         if(RIIC0.ICCR1.BIT.SCLI == 0){
97.             for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
98.         }
99.         RIIC0.ICCR2.BIT.SP = 1; //Generate stop condition
100.        RIIC0.ICMR3.BIT.ACKBT = 0; //Set ACK
101.        *RiicMstBuff = RIIC0.ICDRR; //Read data
102.        RiicMstBuff++; //Add pointer
103.    }
104.    else if(RiicMstCnt == RiicMstNum -1){ //Next is last data
105.        RIIC0.ICMR3.BIT.WAIT = 1;
106.        RIIC0.ICMR3.BIT.ACKBT = 1; //Set NACK
107.        *RiicMstBuff = RIIC0.ICDRR; //Read data
108.        RiicMstBuff++; //Add pointer
109.    }
110.    else { //Transfer next data
111.        *RiicMstBuff = RIIC0.ICDRR; //Read data
112.        RiicMstBuff++; //Add pointer
113.    }
114.    RiicMstCnt++; //Add internal counter
```

```
115. }
116. void RiicTDRE(void)
117. {
118.     volatile unsigned long cnt;
119.     if(RiicMstCnt >= RiicMstNum){ //After transfer all data
120.         #ifdef RIIC_CHO
121.             ICU.IER [0x1F].BIT.IEN0 = 0; //TXIO
122.         #else
123.             ICU.IER [0x1F].BIT.IEN4 = 0; //TXI1
124.         #endif
125.         RIIC0.ICIER.BIT.TEIE = 1; //TEND
126.     }
127.     else if(RiicMstCnt == 0){ //First byte
128.         #ifdef RIIC_CHO
129.             ICU.IER [0x1F].BIT.IEN0 = 0; //TXIO
130.         #else
131.             ICU.IER [0x1F].BIT.IEN4 = 0; //TXI1
132.         #endif
133.         RIIC0.ICIER.BIT.TEIE = 1; //TEND
134.         RIIC0.ICDRT = RiicTrmAddr; //Write slave address
135.     }
136.     else { //Transfer next data
137.         if((RIIC0.ICSR2.BIT.TEND == 1) &&
138.            (RIIC0.ICCR1.BIT.SCLI == 0)){
139.             for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
140.         }
141.         RIIC0.ICDRT = *RiicMstBuff; //Write next data
142.         RiicMstBuff++; //Add pointer
143.     }
144.     RiicMstCnt++; //Add internal counter
145. }
146. void RiicTEND(void)
147. {
148.     volatile unsigned long cnt;
149.     if(RiicMstCnt >= RiicMstNum){ //After transfer all data
150.         if(RIIC0.ICCR1.BIT.SCLI == 0){ //
151.             for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
152.         }
153.         RIIC0.ICCR2.BIT.SP = 1; //Generate stop condition
154.         return;
155.     }
```

```
155.     #ifdef RIIC_CH0
156.     ICU.IER [0x1F].BIT.IEN0 = 1; //TXI0
157.     #else
158.     ICU.IER [0x1F].BIT.IEN4 = 1; //TXI1
159.     #endif
160.     RIIC0.ICIER.BIT.TEIE = 0; //TEND
161.     if(RIIC0.ICCR1.BIT.SCLI == 0){
162.         for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
163.     }
164.     RIIC0.ICDRT = *RiicMstBuff; //Write first data
165.     RiicMstBuff++; //Add pointer
166.     RiicMstCnt++; //Add internal counter
167. }
168. void RiicSTOP(void){
169.     RIIC0.ICSR2.BIT.STOP = 0;
170.     RIIC0.ICSR2.BIT.NACKF = 0;
171.     #ifdef RIIC_CH0
172.     ICU.IER [0x1F].BIT.IEN0 = 1; //TXI0
173.     #else
174.     ICU.IER [0x1F].BIT.IEN4 = 1; //TXI1
175.     #endif
176.     RIIC0.ICIER.BIT.TEIE = 0; //TEND
177. }
178. void RiicNACK(void)
179. {
180.     volatile unsigned long cnt;
181.     #ifdef RIIC_CH0
182.     ICU.IER [0x1F].BIT.IEN0 = 0; //TXI0
183.     #else
184.     ICU.IER [0x1F].BIT.IEN4 = 0; //TXI1
185.     #endif
186.     RIIC0.ICIER.BIT.TEIE = 0; //TEND
187.     if(RIIC0.ICCR1.BIT.SCLI == 0){
188.         for(cnt = RIIC_WAIT_VALUE; cnt != 0; cnt--);
189.     }
190.     RIIC0.ICCR2.BIT.SP = 1; //Generate stop condition
191. }
192. void RiicSTART(void){}
193. void RiicAL(void){}
194. void RiicTMO(void){}
```

Filename: vect.h

Add the following definition to vect.h to enable the working of the EEI0, RXI0, and TXI0 interrupts.

```
1. #pragma interrupt (Excep_RIIC0_EEI0 (vect = 246))
2. void Excep_RIIC0_EEI0 (void);
3. #pragma interrupt (Excep_RIIC0_RXI0 (vect = 247))
4. void Excep_RIIC0_RXI0 (void);
5. #pragma interrupt (Excep_RIIC0_TXI0 (vect = 248))
6. void Excep_RIIC0_TXI0 (void);
```

Filename: riic_int.c:

This file contains the definitions of the interrupts and what they should do whenever they occur.

```
1. #include "iodefine.h"
2. #include "vecttbl.h"
3. #include "riic.h"
4. void RiicSTART(void);
5. void RiicAL(void);
6. void RiicNACK(void);
7. void RiicTMO(void);
8. void RiicSTOP(void);
9. void RiicRDRF(void);
10. void RiicTDRE(void);
11. void RiicTEND(void);
12. void Excep_RIIC0_EEI0(void){
13.     if((RIIC0.ICIER.BIT.STIE != 0) &&
14.        (RIIC0.ICSR2.BIT.START != 0)){
15.         RiicSTART();
16.     }
17.     if((RIIC0.ICIER.BIT.NAKIE != 0) &&
18.        (RIIC0.ICSR2.BIT.NACKF != 0)){
19.         RiicNACK();
20.     }
21.     if((RIIC0.ICIER.BIT.ALIE != 0) && (RIIC0.ICSR2.BIT.AL != 0)){
22.         RiicAL();
23.     }
```

```

23.     if((RIIC0.ICIER.BIT.TMOIE != 0) &&
        (RIIC0.ICSR2.BIT.TMOF != 0)){
24.         RiicTMO();
25.     }
26.     if((RIIC0.ICIER.BIT.SPIE != 0) && (RIIC0.ICSR2.BIT.STOP != 0)){
27.         RiicSTOP();
28.     }
29. }
30. void Excep_RIIC0_RXI0(void){
31.     RiicRDRF();
32. }
33. void Excep_RIIC0_TXI0(void){
34.     RiicTDRE();
35. }
36. void Excep_RIIC0_TEI0(void){
37.     RiicTEND();
38. }
39. void Excep_RIIC1_EEI1(void){
40.     if((RIIC0.ICIER.BIT.STIE != 0) &&
        (RIIC0.ICSR2.BIT.START != 0)){
41.         RiicSTART();
42.     }
43.     if((RIIC0.ICIER.BIT.NAKIE != 0) &&
        (RIIC0.ICSR2.BIT.NACKF != 0)){
44.         RiicNACK();
45.     }
46.     if((RIIC0.ICIER.BIT.ALIE != 0) &&
        (RIIC0.ICSR2.BIT.AL != 0)){
47.         RiicAL();
48.     }
49.     if((RIIC0.ICIER.BIT.TMOIE != 0) &&
        (RIIC0.ICSR2.BIT.TMOF != 0)){
50.         RiicTMO();
51.     }
52.     if((RIIC0.ICIER.BIT.SPIE != 0) &&
        (RIIC0.ICSR2.BIT.STOP != 0)){
53.         RiicSTOP();
54.     }
55. }
56. void Excep_RIIC1_RXI1(void){

```

```

57.   RiicRDRF();
58. }
59. void Excep_RIIC1_TXI1(void){
60.   RiicTDRE();
61. }
62. void Excep_RIIC1_TEI1(void){
63.   RiicTEND();
64. }

```

Filename: main.c

This is the main file responsible for setting up the RIIC module correctly.

```

1. #include "iodefine.h"
2. #include "iic\riic.h"
3. #define SELF_ADDRESS 0x10 //Self address (bit0 = 0. (R/W bit))
4. #define SLV_ADDRESS 0x3A //Slave address (bit0 = 0. (R/W bit))
5. #define DATA_NUM (1 + 1) //Date number ("+1" means first
                               byte(slave address))
6. #define T_BUFF_SIZE (2)
7. #define R_BUFF_SIZE (7)
8. #define POWER_CTL_ADDR (0x2D)
9. #define POWER_CTL_VAL0 (0)
10. #define POWER_CTL_VAL1 (16)
11. #define POWER_CTL_VAL2 (8)
12. #define DATA_ADDRESS (0x32)
13. #define MST_WRITE 0x00 //Write bit (Don't change)
14. #define MST_READ 0x01 //Read bit (Don't change)
15. unsigned char MstTrmBuff [T_BUFF_SIZE]; //Buffer for
                                             transmission data
16. unsigned char MstRcvBuff [R_BUFF_SIZE] = {255}; //Buffer for
                                             reception data
17. void main(void)
18. {
19.   unsigned long cnt,i;
20.   unsigned char rtn;
21.   SYSTEM.SCKCR.LONG = 0x00020100; //ICLK = 100 MHz, BCLK =
                                       25 MHz, PCLK = 50 MHz
                                       (EXTAL = 12.5 MHz)
22.   for(cnt = 0; cnt < T_BUFF_SIZE; cnt++){
23.     MstTrmBuff [cnt] = 0xFF;

```



```
24.     MstRcvBuff [cnt] = 0xFF;
25.     }
26.     MstTrmBuff [0] = POWER_CTL_ADDR;
27.     MstTrmBuff [1] = POWER_CTL_VAL0;
28.     RiicIni(SELF_ADDRESS, 1); //Initialise RIIC (Enable)
29.     rtn = RiicStart(SLV_ADDRESS | MST_WRITE, MstTrmBuff,
30.     DATA_NUM + 1);
31.     switch (rtn){ //Return value check
32.         case RIIC_OK: //OK
33.             break;
34.         case RIIC_BUS_BUSY: //Bus busy
35.             break;
36.         case RIIC_NG: //Data number error
37.             break;
38.         default: //Internal error
39.             while(1)
40.                 ;
41.     }
42.     while(RIIC0.ICCR2.BIT.BBSY != 1) //Check Bus busy
43.         ;
44.     while(RIIC0.ICCR2.BIT.BBSY != 0) //Check Bus free
45.         ;
46.     MstTrmBuff [1] = POWER_CTL_VAL1;
47.     rtn = RiicStart(SLV_ADDRESS | MST_WRITE, MstTrmBuff,
48.     DATA_NUM+1);
49.     switch (rtn){ //Return value check
50.         case RIIC_OK: //OK
51.             break;
52.         case RIIC_BUS_BUSY: //Bus busy
53.             break;
54.         case RIIC_NG: //Data number error
55.             break;
56.         default: //Internal error
57.             while(1)
58.                 ;
59.     }
60.     MstTrmBuff [1] = POWER_CTL_VAL2;
61.     while(RIIC0.ICCR2.BIT.BBSY != 1) //Check Bus busy
62.         ;
63.     while(RIIC0.ICCR2.BIT.BBSY != 0) //Check Bus free
64.         ;
```

```
63.     MstTrmBuff [0] = DATA_ADDRESS;
64.     rtn = RiicStart(SLV_ADDRESS | MST_WRITE, MstTrmBuff,
65.                   DATA_NUM);
66.     switch (rtn){ //Return value check
67.         case RIIC_OK: //OK
68.             break;
69.         case RIIC_BUS_BUSY: //Bus busy
70.             break;
71.         case RIIC_NG: //Data number error
72.             break;
73.         default: //Internal error
74.             while(1)
75.                 ;
76.     }
77.     while(RIIC0.ICCR2.BIT.BBSY != 1) //Check Bus busy
78.         ;
79.     while(RIIC0.ICCR2.BIT.BBSY != 0) //Check Bus free
80.         ;
81.     rtn = RiicStart(SLV_ADDRESS | MST_WRITE, MstTrmBuff,
82.                   DATA_NUM);
83.     switch (rtn){ //Return value check
84.         case RIIC_OK: //OK
85.             break;
86.         case RIIC_BUS_BUSY: //Bus busy
87.             break;
88.         case RIIC_NG: //Data number error
89.             break;
90.         default: //Internal error
91.             while(1)
92.                 ;
93.     }
94.     while(RIIC0.ICCR2.BIT.BBSY != 1) //Check Bus busy
95.         ;
96.     while(RIIC0.ICCR2.BIT.BBSY != 0) //Check Bus free
97.         ;
98.     rtn = RiicStart(SLV_ADDRESS | MST_READ, MstRcvBuff,
99.                   DATA_NUM+6);
100.    switch (rtn){ //Return value check
101.        case RIIC_OK: //OK
102.            break;
```

```

100.     case RIIC_BUS_BUSY:    //Bus busy
101.         break;
102.     case RIIC_NG:         //Data number error
103.         break;
104.     default:             //Internal error
105.         while(1)
106.             ;
107. }
108. while(RIIC0.ICCR2.BIT.BBSY != 1)    //Check Bus busy
109.     ;
110. while(RIIC0.ICCR2.BIT.BBSY != 0)    //Check Bus free
111.     ;
112. RiicIni(0, 0);    //Stop RIIC
113. while(1)
114.     ;
115. }

```

7.6 RECAP

- The Serial Communications Interface can act as a Smart Card Interface and as a Universal Synchronous/Asynchronous Receiver and Transmitter.
- The UART is one of the oldest, simplest, and most frequently used techniques for half duplex serial communication that uses three wires at the most for data transfer.
- The SCI2 interface is available on the YRDKRX63N development board via an RS-232 level shifter.
- The Serial Peripheral Interface bus is a full duplex bus similar to the Universal Synchronous Receiver/Transmitter and is capable of data transfer at very high speeds.
- Each SPI device can act as either a master or a slave device. The master device is responsible for generating the clock cycles for synchronizing the data transfer.
- Slave Selection is always required prior to transfer of data on the SPI bus, otherwise data on the bus is void.
- Slave devices available aboard the YRDKRX63N on the SPI bus are the Graphical LCD module, Micro SD card interface, and the Micron/Numonyx Omneo P5Q Serial Flash Chip.
- I²C is a two wire interface capable of talking to up to 128 devices connected on the same bus.

- The I²C cycle consists of generation of a start condition, selecting a slave device, performing a data transfer, and sending a stop condition.
- Devices available with the YRDKRX63N board that are connected on the I2C bus are accelerometer: ADXL345 (slave address: 0x3A) and the temperature sensor ADT7410 (slave address: 0x90).
- Table 7.1 summarizes the differences between the three protocols.

7.7 REFERENCES

- [1] Becke, G., Borgert, C., Corrigan, S., Dehmelt, F., Feulner, M., Gonzalez, C., Groenebaum, M., Kabir, F., Kacprzak, A., Kinnaird, C., and Zipperer, J. *Comparing Bus Solutions; High- Performance Linear/Interface: An Application Report*. Texas Instruments. Revised February 2004. Electronic publication. Accessed at <http://www.lammertbies.nl/download/ti-appl-slla067a.pdf>
- [2] Hwang, Enoch. *Digital Logic and Microprocessor Design with VHDL*. Thomson. ISBN 0-534-46593-5. 2006. Electronic Publication. Accessed at <http://faculty.lasierra.edu/~ehwang/digitaldesign/>
- [3] Electronic Industries Association, “*EIA Standard RS- 232-C Interface Between Data Terminal Equipment and Data Communication Equipment Employing Serial Data Interchange*,” August 1969. Reprinted in Telebyte Technology Data Communication Library, Greenlawn, NY, 1985. Print.
- [4] Hardware Manual, *Renesas 32-Bit Microcomputer, RX Family/RX600 Series*. Renesas Electronics America, Inc., 2013. Print.
- [5] Soltero, M., Zhang, J. and Cockril, C. Revised by Kevin Zhang, Clark Kinnaird, and Thomas Kugelstadt, 2010. *RS- 422 and RS- 485 Standards Overview and System Configurations, Application Report, SLLA070D*. Texas Instruments, Revised May 2010. Electronic publication. Accessed at <http://focus.ti.com/lit/an/slla070d/slla070d.pdf>
- [6] Analog Devices, Inc. *ADXL345 datasheet: 3-Axis, 2 g/4 g/8 g/16 g Digital Accelerometer, ADXL345*. Norwood, MA: Analog Devices, Inc. 2009–2011. Electronic publication. Accessed at http://www.analog.com/static/importedfiles/data_sheets/ADXL345.pdf

7.8 EXERCISES

1. Write a program to setup the Renesas serial communication interface to operate in the UART mode functioning at 9600 baud, odd parity, 2 Stop bits to transmit 8 bits of data with the LSB first.
2. Write a program to set up the Renesas Serial Peripheral Interface to transfer and receive 32 bit and 16 bit long data alternately as a single unit at 5 Mbps, with parity enabled in clock synchronous mode. The RSPI should function only as a master.
3. Write a program to maintain queues for multi-processor communication using the Renesas Serial Peripheral Interface so as to perform data transfer between

one master device and two slave devices. Mention algorithms for both. (Hint: Maintain six queues; two for each microcontroller).

4. Write a program to communicate with and to continuously obtain the values of the X , Y , and Z axis of the onboard ADXL345 accelerometer at 100 kbps.
5. Write a program to interface two microcontrollers that are monitoring temperatures and exchanging the observed temperature as strings with each other. Each board should display the observed temperature of itself and the other board on the graphical/character LCD. (Hint: Use FIFO type data structures).

Event Counters, Timers, and the Real Time Clock

8.1 LEARNING OBJECTIVES

In this chapter we show how timers work as event counters, as well as go into more advanced features. It is possible to cascade timers together when one timer does not provide the range needed. Using timers it is also possible to output a square wave with a controllable frequency and duty cycle. Additionally, the RX63N includes a real time clock peripheral that can keep track of the current date and time. In this chapter we will cover the concepts behind these features and how to use them.

8.2 BASIC CONCEPTS

8.2.1 Timer and Event Counter

Timer

A timer in a microcontroller is a counter whose value can be read and written as a special function register. When the timer is started, the value in the register increases or decreases each time it is clocked, and the rate at which the value changes is based upon the clock source provided to it. If the clock source for the timer is 10 MHz, then one count (increment or decrement) of the register would be equal to $0.1 \mu\text{s}$. The timers may have a bit length of 8-bit (0 to 255), 16-bit (0 to 65535), and 32-bit (0 to 4294967295). For an 8-bit timer with a clock source of 10 MHz, the maximum time a timer can count depends on the maximum value a timer count register can hold; i.e., the maximum value in an 8-bit register is 255 (FFh). Therefore the maximum time for an 8-bit timer count is:

$$\frac{255}{10 \text{ MHz}} = 255 * 0.1 \mu\text{sec} = 25.5 \mu\text{sec}$$

Therefore, with an 8-bit timer you can measure a maximum of $25.5 \mu\text{sec}$, but what if you want to measure $100 \mu\text{sec}$ with an 8-bit register? Should we count four times through an 8-bit timer? The answer is no. For this purpose the microcontroller has a prescaler, which

is used to divide the external or internal clock source by a fixed integer. This increases the amount of time a timer can count without adding much hardware. The general division factor for the prescaler would be multiples of two. For example, if we have a division factor of 32, then the maximum amount of time a timer can count with a 10 MHz clock source is:

$$\frac{255}{\frac{10 \text{ MHz}}{32}} = \left(255 \times \frac{32}{10} \right) \mu\text{sec} = 816 \mu\text{sec}$$

As a result, the maximum amount of time a timer can count increases as the prescaler division factor increases.

A timer can also be used as an event counter. The function of the event counter is the same as the counter, but the event counter counts external events (indicated by signal transitions on an input pin or on overflows of another timer). For example, an event counter can be set up in a place where you need to automatically keep track of the number of people entering a building using a particular entrance. A person passing the entrance is tracked using an infrared sensor. The sensor is set up such that a person entering the building breaks an infrared light beam directed at the sensor, which changes its output from high to low as long as the beam is broken. The event counter can be set up to increment on the high to low transition of the sensor output, and in the end the count would give us the amount of people who entered the building using a selected entrance. We can also use the event counter to calculate the time intervals between two events.

Event Counter

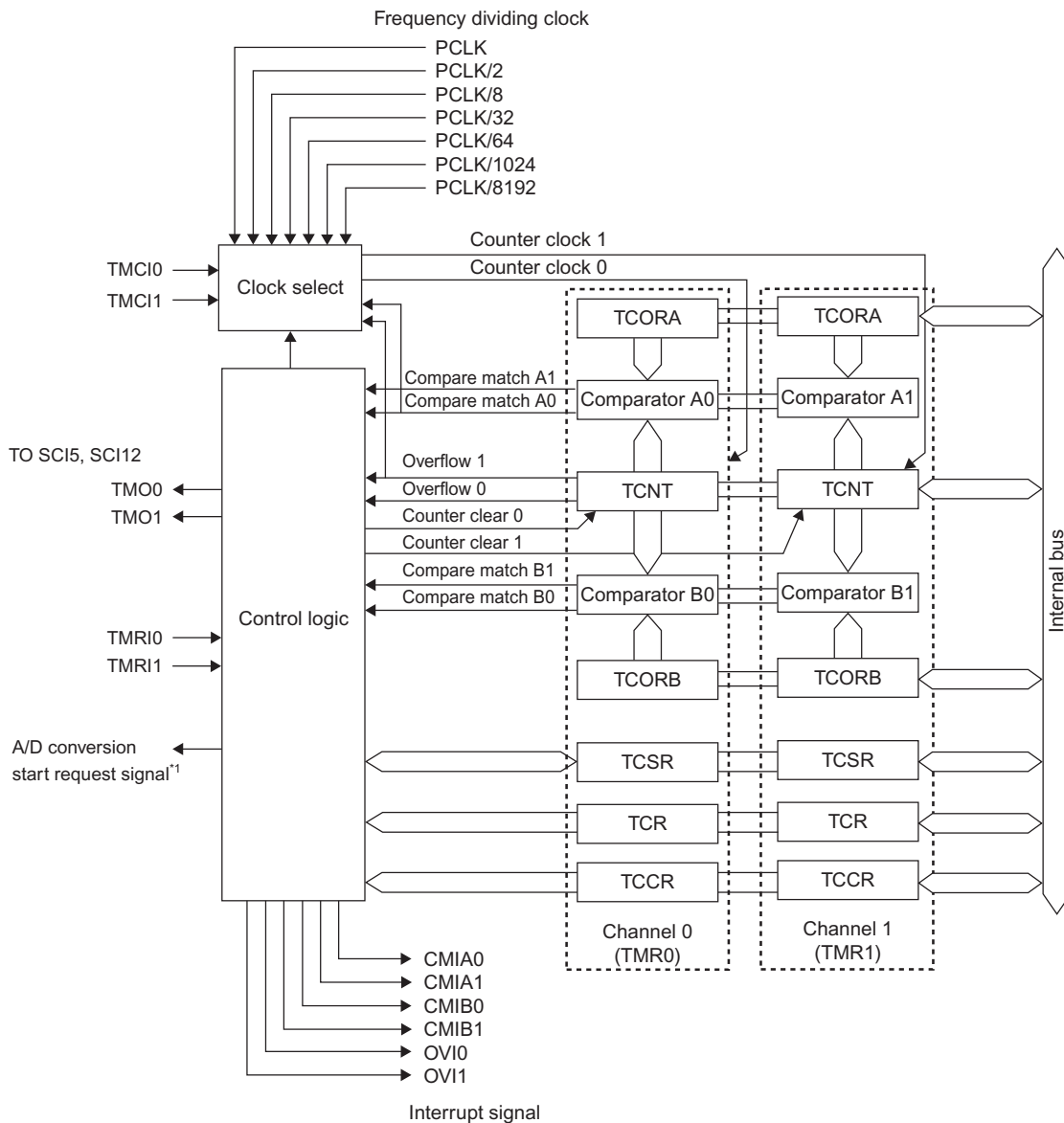
The RX63N/RX631 Group has two units (unit 0, unit 1) of 8-bit timers/counters. Each unit has 2 channels. So there are a total of 4 channels of an 8-bit timer. The 8-bit timer can be used in different operating modes: timer mode, event counter mode, and pulse output mode. The timer mode can also be used to generate interrupts at particular intervals, and two timers can be cascaded to use a 16-bit timer. In this chapter we cover the basic concepts of an event counter mode. The timer units can also generate a baud rate clock, which can be used for serial communication. Table 8.1 shows the functionality available from the timers.

The event counter of RX63N microcontroller is used detect the overflow of the timer. After detecting the overflow, another timer can be made to start counting. For example, TMR0 (TMR2) can be made to start counting once TMR1 overflows (TMR3). This feature is mainly used to cascade two timers. The overflow function can be used by setting the TCCR.CSS[1:0] bits to a value of 3.

TABLE 8.1 Specifications of TMR [1], Table 27.1, page 1012.

ITEM	DESCRIPTION
Count clock	<ul style="list-style-type: none"> ■ Frequency dividing clock: PCLK/1, PCLK/2, PCLK/8, PCLK/32, PCLK/64, PCLK/1024, PCLK/8192 ■ External clock
Number of channels	(8 bits × 2 channels) × 2 units
Compare match	<ul style="list-style-type: none"> ■ 8-bit mode (compare match A, compare match B) ■ 16-bit mode (compare match A, compare match B)
Counter clear	Selected by compare match A or B, or an external reset signal.
Timer output	Output pulses with a desired duty cycle or PWM output
Cascading of two channels	<ul style="list-style-type: none"> ■ 16-bit count mode 16-bit timer using TMR0 for the upper 8 bits and TMR1 for the lower 8 bits (TMR2 for the upper 8 bits and TMR3 for the lower 8 bits) ■ Compare match count mode TMR1 can be used to count TMR0 compare matches (TMR3 can be used to count TMR2 compare matches).
Interrupt sources	Compare match A, compare match B, and overflow
DTC activation	DTC can be activated by compare match A interrupts or compare match B interrupts.
Generation of trigger to start A/D converter conversion	Compare match A of TMR0 and TMR2* ¹
Capable of generating baud rate clock for SCI	Generates baud rate clock for SCI.* ²
Low power consumption facilities	Each unit can be placed in a module-stop state.
Note 1. For details, see section 41, 12-Bit A/D Converter (S12ADa), and section 42, 10-Bit A/D Converter (ADb).	
Note 2. For details, see section 35, Serial Communications Interface (SCIc, SCId).	

The RX63N has a timer peripheral which provides two 8-bit timer units (units 1 and 0), each comprised of two counter channels. Each timer can be used as an independent timer, to count an external event, or as a pulse output device. The timer works by incrementing a register each time there is a 'count' within the device. The count is either triggered by a pulse from the internal peripheral clock, a scaled version of the clock, or an external source. When this count overflows from its maximum value to zero and/or there is



TCORA: Time constant register A TCSR: Timer control/status register
 TCNT: Timer counter TCR: Timer control register
 TCORB: Time constant register B TCCR: Timer counter control register

Note: * For the corresponding A/D converter channels, see section 40, 12-Bit A/D Converter (S12ADa), and section 41, 10-Bit A/D Converter (ADb).

Figure 8.1 Block Diagram of TMR (Unit 0) [1], Figure 27.1, page 1014.

a compare match with one of the timer constant registers; an action is performed, such as toggling an output signal, triggering an interrupt. Before covering how the timer works more specifically we will briefly describe the 8-bit timer device’s registers and how they work.

Figure 8.1 is a block diagram of timer unit 0; unit 1 is identical except for naming differences (e.g., timer2 in place of timer0, and timer3 in place of timer1). We will start by first covering the registers that are used when setting up a timer channel.

The legend in the bottom left of Figure 8.1 lists the registers you need to consider when setting up the 8-bit timer unit. For some registers we have an illustration included of the registers contents taken from the RX63N User’s Manual: Hardware. Make note of the register parts, as we will use these later when setting them up for specific features. Further details are available in the hardware manual if needed.

Registers

The TCNT (Timer Counter) register holds the current timer value at any time after the timer has been configured. Whenever you want to know the value of the timer or counter you will read the value in this register. Also, when not currently operating the timer, you can load a value into this register and the timer will begin counting from that value when restarted. Note in Figure 8.2 that in the 16-bit mode TMR0.TCNT and TMR1.TCNT (TMR2.TCNT and TMR3.TCNT as well) cascade into one 16-bit register. This holds true for the timer constant registers as well.

Address: TMR0.TCNT 0008 8208h, TMR1.TCNT 0008 8209h
 TMR2.TCNT 0008 8218h, TMR3.TCNT 0008 8219h

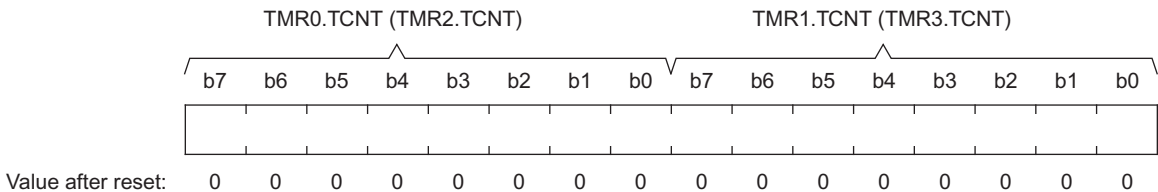


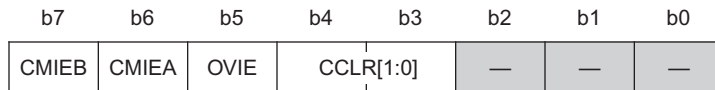
Figure 8.2 TCNT (Timer Counter) register [1], page 1017.

The TCNT register is where the count is held. After the timer is started this register will increment every time a count is detected. If you want to know the current count, you can read this register. If the timer is stopped you can write a value to this register and it will begin counting from the written value when re-started.

The Timer Control Register (TCR) is used to enable interrupt requests and counter clearing. It is an 8-bit register whose lower 3 bits are reserved and upper 5 bits are used as follows:

Timer Control Register (TCR)

Address(es): TMR0.TCR 0008 8200h, TMR1.TCR 0008 8201h
 TMR2.TCR 0008 8210h, TMR3.TCR 0008 8211h



Value after reset: 0 0 0 0 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b2 to b0	—	Reserved	These bits are always read as 0. The write value should always be 0.	R/W
b4, b3	CCLR[1:0]	Counter Clear*	b4 b3	R/W
			0 0: Clearing is disabled	
			0 1: Cleared by compare match A	
			1 0: Cleared by compare match B	
			1 1: Cleared by the external reset input (Select edge or level by the TMRIS bit in TCCR.)	
b5	OVIE	Timer Overflow Interrupt	0: Overflow interrupt requests (OVIn) are disabled	R/W
		Enable	1: Overflow interrupt requests (OVIn) are enabled	
b6	CMIEA	Compare Match Interrupt	0: Compare match A interrupt requests (CMIA _n) are disabled	R/W
		Enable A	1: Compare match A interrupt requests (CMIA _n) are enabled	
b7	CMIEB	Compare Match Interrupt	0: Compare match B interrupt requests (CMIB _n) are disabled	R/W
		Enable B	1: Compare match B interrupt requests (CMIB _n) are enabled	

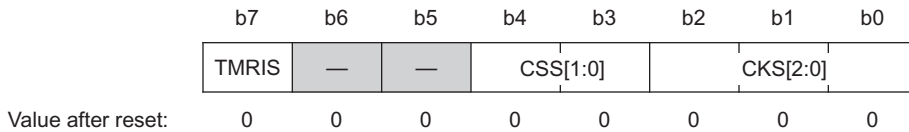
Note: * To use an external reset, set the Pn.DDR.Bi bit for the corresponding pin to "0" and the Pn.ICR.Bi bit to "1".

Figure 8.3 TCR (Timer Control Register) description [1], page 1018.

The TCCR controls where the timers count source comes from. Depending what value is set here will determine if the count comes from the internal peripheral clock, a pre-scaled peripheral clock, an external count source, or from another timer overflowing. This register also enables the timer’s interrupts on the peripheral level. Keep in mind you must also enable to interrupts in the ICU (Interrupt Controls Unit) in order for an interrupt routine to be called.

Timer Counter Control Register (TCCR)

Address(es): TMR0.TCCR 0008 820Ah, TMR1.TCCR 0008 820Bh
 TMR2.TCCR 0008 821Ah, TMR3.TCCR 0008 821Bh



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b2 to b0	CKS[2:0]	Clock Select*	See table below.	R/W
b4, b3	CSS[1:0]	Clock Source Select	See table below.	R/W
b6, b5	—	Reserved	These bits are always read as 0. The write value should always be 0.	R/W
b7	TMRIS	Timer Reset Detection Condition Select	0: Cleared at rising edge of the external reset	R/W
			1: Cleared when the external reset is high	

Note: * To use an external clock, set the Pn.PDR.Bi bit for the corresponding pin to “0” and the PORTn.PMR.Bi bit to “1”. For details, see [1] section 21, I/O Ports.

Figure 8.4 TCCR (Timer Counter Control Register) description [1], page 1019.

The TCORA (Time Constant Register A) and TCORB (Time Constant Register B) are used to store constants to compare against the TCNT register. Every time the TCNT increments it is constantly being compared against either of these registers. When TCNT matches either of these registers, a compare match event occurs. Compare match events have many uses depending on what mode we are using the timer in.

The TCSR (Timer Control/Status Register) register controls compare match output. Each timer has an output port assigned to it which is controlled via compare match events. This is one of many uses of the compare match events. When a compare match event occurs this register can set the output of the timer’s port to 1 or 0, or toggle it. This register is used when we want the timer to control a pulse output.

CHANNEL	TCR REGISTER					DESCRIPTION		
	CSS[1:0]		CKS[2:0]					
	b4	b3	b2	b1	b0			
TMR0 (TMR2)	0	0	—	0	0	Clock input prohibited		
					1	Uses external clock. Counts at rising edge* ¹ .		
					1	0	Uses external clock. Counts at falling edge* ¹ .	
					1	1	Uses external clock. Counts at both rising and falling edges* ¹ .	
	0	1	0	0	0	0	Uses frequency dividing clock. Counts at PCLK.	
					1	0	Uses frequency dividing clock. Counts at PCLK/2.	
					1	0	Uses frequency dividing clock. Counts at PCLK/8.	
					1	1	Uses frequency dividing clock. Counts at PCLK/32.	
					1	0	0	Uses frequency dividing clock. Counts at PCLK/64.
					1	1	0	Uses frequency dividing clock. Counts at PCLK/1024.
					1	0	0	Uses frequency dividing clock. Counts at PCLK/8192.
					1	1	1	Clock input prohibited
	1	0	—	—	—	Setting prohibited		
	1	1	—	—	—	Counts at TMR1.TCNT (TMR3.TCNT) overflow signal* ²		
TMR1 (TMR3)	0	0	—	0	0	Clock input prohibited		
					1	Uses external clock. Counts at rising edge* ¹ .		
					1	0	Uses external clock. Counts at falling edge* ¹ .	
					1	1	Uses external clock. Counts at both rising and falling edges* ¹ .	
	0	1	0	0	0	0	Uses frequency dividing clock. Counts at PCLK.	
					1	0	Uses frequency dividing clock. Counts at PCLK/2.	
					1	0	Uses frequency dividing clock. Counts at PCLK/8.	
					1	1	Uses frequency dividing clock. Counts at PCLK/32.	
					1	0	0	Uses frequency dividing clock. Counts at PCLK/64.
					1	1	0	Uses frequency dividing clock. Counts at PCLK/1024.
					1	0	0	Uses frequency dividing clock. Counts at PCLK/8192.
					1	1	1	Clock input prohibited
	1	0	—	—	—	Setting prohibited		
	1	1	—	—	—	Counts at TMR0.TCNT (TMR2.TCNT) compare match A* ²		

Notes: 1. To use an external reset, set the PORTn.PDR.Bi bit for the corresponding pin to "0" and the PORTn.PMR.Bi bit to "1". For details, see [1] section 21, I/O Ports.
2. If the clock input of TMR0 (TMR2) is the overflow signal of the TMR1.TCNT (TMR3.TCNT) counter and that of TMR1 (TMR3) is the compare match signal of the TMR0.TCNT (TMR2.TCNT) counter, no incrementing clock is generated. Do not use this setting.

Figure 8.5 Clock input to TCNT and count condition [1], Table 27.5, page 1020.

Timer Control/Status Register (TCSR)

Address: TMR0.TCSR 0008 8202h, TMR2.TCSR 0008 8212h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	—	ADTE	OSB[1:0]		OSA[1:0]	

Value after reset: x x x 0 0 0 0 0

Address: TMR1.TCSR 0008 8203h, TMR3.TCSR 0008 8213h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	—	—	OSB[1:0]		OSA[1:0]	

Value after reset: x x x 1 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b1, b0	OSA[1:0]	Output Select A* ¹	b1 b0	R/W
			0 0: No change when compare match A occurs	
			0 1: 0 is output when compare match A occurs	
			1 0: 1 is output when compare match A occurs	
b3, b2	OSB[1:0]	Output Select B* ¹	b3 b2	R/W
			0 0: No change when compare match B occurs	
			0 1: 0 is output when compare match B occurs	
			1 0: 1 is output when compare match B occurs	
b4	ADTE	A/D Trigger Enable* ²	0: A/D converter start requests by compare match A are disabled	R/W
			1: A/D converter start requests by compare match A are enabled	
b7 to b5	—	Reserved	These bits are always read as an indefinite value. The write value should always be 1.	R/W

Notes: 1. Timer output is disabled when the OSB[1:0] and OSA[1:0] bits are all 0. Timer output is 0 until the first compare match occurs after a reset.

2. For the corresponding A/D converter channels, see [1] section 41, 12-Bit A/D Converter (S12ADa), and section 42, 10-Bit A/D Converter (ADb).

Figure 8.6 TCSR (Timer Control/Status Register) description [1], page 1021.

That is a basic overview of the registers and what they do. Now that we know a bit about how the timer works we can start going into how we modify these registers to get the timer to go into its different modes of operation.

8.2.2 Cascading Timers

Sometimes when using a timer for an application you need a delay longer than is allowed when only using 8-bits. The RX63N allows both timer channels in either time unit to be cascaded into one 16-bit channel. Essentially every time the first timer overflows, the next timer will count. This multiplies the total time able to be counted by a factor of 2^8 (256). Originally we could only count from 0 to 255, now we can count to 65535.

So how do we calculate how long it will take for the timer to count to 0xFFFF (our max value)? First we consider the RX63N's main clock which is 24 MHz. This means every clock tick takes approximately 41.57 nanoseconds. We multiply by what division of the peripheral clock we are using, say 64, because the period for that clock is 64 times as long. Then we multiply by the number of ticks which is 0xFFFF or 65535. So when using PCLK/64 and a 16-bit counter, there will be approximately 174.76 ms between each overflow interrupt.

$$\frac{1}{24 \text{ MHz (peripheral clock)}} * \frac{64 \text{ (clock division)}}{1} * \frac{65535 \text{ (counts per interrupt)}}{1} = 174.76 \text{ ms.}$$

Table 8.2 lists the approximate time between interrupts for each clock division.

TABLE 8.2 Clock Division and Interrupt Times.

CLOCK DIVISION	TIMER PER COUNT	TIME BETWEEN OVERFLOW INTERRUPTS IN 16-BIT MODE
PCLK	41.67 ns	2.73 ms
PCLK/2	83.33 ns	5.41 ms
PCLK/8	333.33 ns	21.84 ms
PCLK/32	1.33 μ s	87.38 ms
PCLK/64	2.67 μ s	174.76 ms
PCLK/1024	42.67 μ s	2.79 s
PCLK/8192	341.333 μ s	22.37 s

NOTE:

It is possible in hardware setup to alter the speed of the PCLK, make sure to take note of this and alter your calculations accordingly. A basic HEW setup with no alterations will still have a PCLK of 24 MHz.

To set up a timer unit in 16-bit cascaded timer mode, set in TMR0.TCCR.CSS[1:0] bits to 11b. This effectively sets the count source for timer 0 as timer 1. Whenever TCNT in timer 1 overflows, timer 0 will count once. In effect, this makes TMR0.TCNT and TMR1.TCNT combine into a single 16-bit register. The speed at which timer 1 can count is still determined in TMR1.TCCR.CSS and TMR1.TCCR.CKS. The settings for clearing the counter and interrupts are now controlled by the TMR0.TCR register; any settings in TMR1.TCR are ignored.

We have just covered how to cascade two 8-bit timer units to make one 16-bit timer. In the examples section we will give an example of how to set up a cascaded timer and an example of its usage.

8.2.3 Pulse Output Operation

Before covering how the RX63N's 8-bit timer peripheral handles pulse outputs, we'll do a brief overview of pulse-width modulation concepts. There are three aspects of a wave we will concern ourselves with when dealing with pulse output operation: the period, frequency, and duty cycle. Any wave is basically a repeating pattern in output over time, such as a sine wave, square wave, or sawtooth wave. The period of the wave is defined as the time between repeats in the simplest form of the wave's pattern. In the case of a square wave, the period is the time between the rising edges of the positive output portion. The frequency is determined by how many periods there are of a wave in a second. We can determine frequency by the formula $f = \frac{\text{Number of Periods}}{\text{Length of Time}}$, yielding a value in Hertz (Hz, periods/second). If we want to determine the period using the frequency we use the

formula $T(\text{period}) = \frac{1}{f(\text{Hz})}$. Duty cycle is defined as the percentage of the period during

which the waveform is high. Duty cycle can be determined by the formula $\frac{\text{Time High}}{T(\text{period})} \times 100\%$.

Using the 8-bit timer peripheral we can output a square wave where the frequency and duty cycle are controlled by changing values in the registers we have already covered.

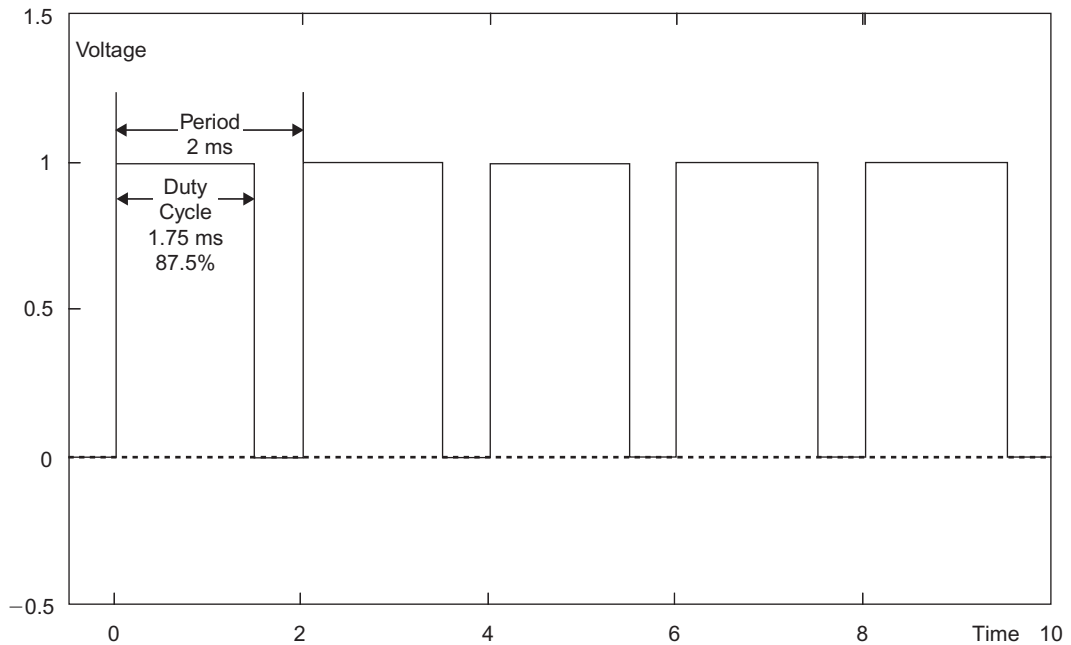


Figure 8.7 Pulse-width modulation signal attributes.

Pulse output mode is handy in applications such as interfacing the microcontroller to several types of motors. A servo motor usually uses a square wave input to determine the position or speed of the motor. Varying the duty cycle will vary the speed or position. When interfacing to a DC motor, the microcontroller almost always lacks the power output to drive the motor. A power amplifier must be used, most often an H-bridge. The H-bridge will take a square wave signal from the microcontroller and amplify it to whatever voltage and current levels are needed for the application. By varying the duty cycle of the wave we vary the average power that is delivered to the motor, making an efficient means of digitally controlling an analog device.

Now we will go over how to set up the RX63N in pulse output mode. First in pulse output mode, `TCR.CCLR[1:0]` bits are set to `01b`. This will make `TCNT` clear to `0x00` every time a compare match A occurs. Now we set `TCSR.OSA[1:0]` to `10b` and `TCSR.OSB[1:0]` to `01b`. This will make the output from the timer channel change to 1 at the occurrence of compare match A and change back to 0 at the occurrence of compare match B.

Here is a brief overview of what happens on a single timer channel when set up in pulse output mode. `TCNT` begins to count up. Once it reaches the value of time constant register A the first time, the pulse output becomes 1 and `TCNT` resets to `00h`. `TCNT` restarts counting and upon reaching the value of time constant register B, the output goes

to 0. TCNT continues to count until it reaches the value of timer constant register A again. TCNT now resets to 00h again and the output goes back to 0. This process repeats, producing a square wave on the TCO_n port (n being the number of the timer used). This is illustrated in Figure 8.8, TMO_n being the waveform of the output pulse.

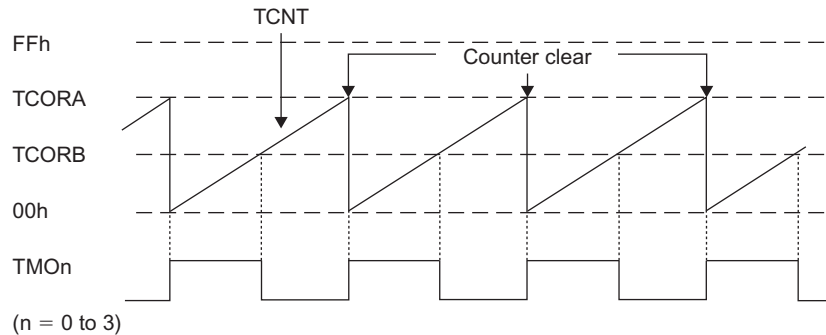


Figure 8.8 An example of pulse output [1], Figure 27.3, page 1023.

By altering the value of TCORA we change the frequency of the pulse output, and by altering TCORB without altering TCORA we alter the duty cycle of the wave. Take note that by altering TCORA without altering TCORB the duty cycle does not remain the same because the output is going low at the same amount of time after TCNT resets, but the time between when the pulse goes low and a compare match A occurrence has become longer.

We have just covered a basic overview of concepts to do with pulse output and how to control it on the RX63N. In the examples section we will show and explain a basic example of how to set up pulse output from one of the timer units.

8.3 REAL TIME CLOCK

The Real Time Clock is a separate unit unto itself. Without an independent Real Time Clock unit it would be necessary to cascade timers, set up variables, and use interrupt routines to track the time. Another advantage to a separate unit is that it takes less energy to keep running in low power modes. This unit makes keeping track of time much easier by keeping a separate binary coded decimal register for the years, months, date, day of the week, hours, minutes, and seconds. The unit also automatically tracks leap years. Using the Real Time Clock is as simple as setting the values for the date then setting it to start counting. The clock keeps count via a dedicated 32.768 kHz count source connected between XCIN and XCOUT and outputs a 1 Hz clock on the RTCOUT pin.

8.3.1 RTC Registers

We will now cover all of the registers in the RTC and their functions.

64-Hz Counter (R64CNT)

Address: 0008 C400h

b7	b6	b5	b4	b3	b2	b1	b0
—	F1HZ	F2HZ	F4HZ	F8HZ	F16HZ	F32HZ	F64HZ

Value after reset: 0 x x x x x x x

[Legend] x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	F64HZ	64 Hz	Indicate the state between 1 Hz and 64 Hz	R
b1	F32HZ	32 Hz		R
b2	F16HZ	16 Hz		R
b3	F8HZ	8 Hz		R
b4	F4HZ	4 Hz		R
b5	F2HZ	2 Hz		R
b6	F1HZ	1 Hz		R
b7	—	Reserved	This bit is always read as 0 and cannot be modified.	R

Figure 8.9 R64CNT (64 Hz Counter) [1], page 1044.

The second counter uses the 64 Hz counter (R64CNT) as its count source. This register can be read to determine time in the sub-seconds range.

RSECCNT is where the current count in seconds is read/written. Once the value is above fifty-nine it will reset to zero and the minute counter will increment.

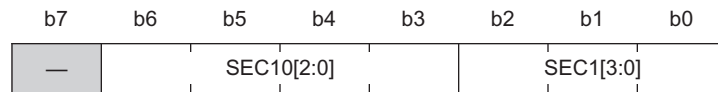
The RMINCNT register is where the current value of the minutes is read/written. This counter behaves just like the second counter in that the hour counter will increment once it counts past fifty-nine and the minute counter will reset.

The RHRCNT register is where the current value in hours is read/written. The register counts from zero to twenty-three, then resets. When it resets, the day counter and day of the week counter are incremented.

RWKCNT holds the value of the current day of the week. It counts from zero to six, then resets.

Second Counter (RSECCNT)

Address: 0008 C402h



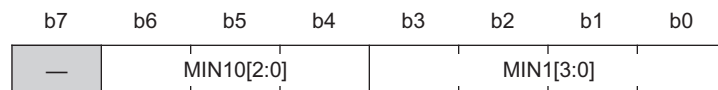
Value after reset: 0 x x x x x x x

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	SEC1[3:0]	Ones Place of Seconds	Counts from 0 to 9 once per second. When a carry is generated, 1 is added to the tens place.	R/W
b6 to b4	SEC10[2:0]	Tens Place of Seconds	Counts from 0 to 5 for 60-second counting.	R/W
b7	—	Reserved	This bit is always read as 0. The write value should always be 0.	R/W

Figure 8.10 RSECCNT (Second Counter) [1], page 1045.

Minute Counter (RMINCNT)

Address: 0008 C404h



Value after reset: 0 x x x x x x x

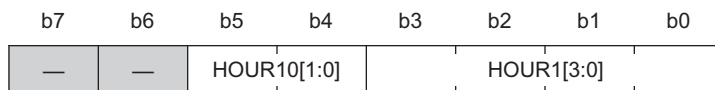
[Legend] x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	MIN1[3:0]	Tens Place of Minutes	Counts from 0 to 9 once per minute. When a carry is generated, 1 is added to the tens place.	R/W
b6 to b4	MIN10[2:0]	Ones Place of Minutes	Counts from 0 to 5 for 60-minute counting.	R/W
b7	—	Reserved	This bit is always read as 0. The write value should always be 0.	R/W

Figure 8.11 RMINCNT (Minute Counter) [1], page 1045.

Hour Counter (RHRCNT)

Address: 0008 C406h



Value after reset: 0 0 x x x x x x

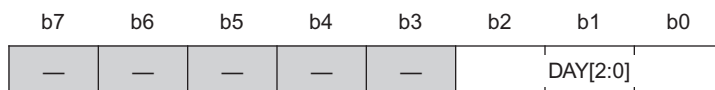
[Legend] x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	HOUR1[3:0]	Ones Place of Hours	Counts from 0 to 9 once per hour. When a carry is generated, 1 is added to the tens place.	R/W
b5, b4	HOUR10[1:0]	Tens Place of Hours	Counts from 0 to 2 once per carry from the ones place.	R/W
b7, b6	—	Reserved	These bits are always read as 0. The write value should always be 0.	R/W

Figure 8.12 RHRCNT (Hour Counter) [1], page 1046.

Day-of-Week Counter (RWKCNT)

Address: 0008 C408h



Value after reset: 0 0 0 0 0 x x x

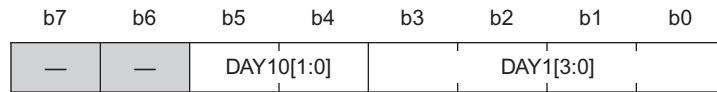
[Legend] x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b2 to b0	DAY[2:0]	Day-of-Week Counting	000: Sunday	R/W
			001: Monday	
			010: Tuesday	
			011: Wednesday	
			100: Thursday	
			101: Friday	
			110: Saturday	
b7 to b3	—	Reserved	111: (Setting Prohibited)	R/W
			These bits are always read as 0. The write value should always be 0.	

Figure 8.13 RWKCNT (Day-of-Week Counter) [1], page 1047.

Date Counter (RDAYCNT)

Address: 0008 C40Ah



Value after reset: 0 0 x x x x x x

[Legend] x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	DAY1[3:0]	Ones Place of Days	Counts from 0 to 9 once per day. When a carry is generated, 1 is added to the tens place.	R/W
b5, b4	DAY10[1:0]	Tens Place of Days	Counts from 0 to 3 once per carry from the ones place.	R/W
b7, b6	—	Reserved	These bits are always read as 0. The write value should always be 0.	R/W

Figure 8.14 RDAYCNT (Date Counter) [1], page 1048.

RDAYCNT holds the current value of the day of the month. The counter automatically accounts for the number of specifiable days in a month and leap years. When the count goes above the days of the current month it resets to zero and the month counter is incremented.

RMONCNT holds the value for the current month. It counts from one to twelve, and then resets. When it resets to zero, the year counter is incremented.

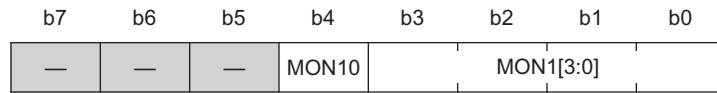
The RYRCNT register holds the current count of the years from 0 to 99.

For each counter register besides the 64 Hz Counter (R64CNT), there is a corresponding alarm register. Each of these is written to the same as the corresponding count register, other than the unused bit 7 which is now an enable bit; except in the case of the year alarm register which uses an entire word (it has a separate enable register named RYAREN). Whenever the values in each of the counters match the alarm registers with the enable bits set, the Real Time Clock alarm interrupt is triggered.

Take note that writing the decimal value of the number you want to input to these registers will not be input as the value you want. This is because the registers are not read as an 8-bit decimal value, but are instead split so that each 4-bit span is a binary encoded decimal digit. As a review of basic concepts of base 2 (binary) and base 16 (hexadecimal) numbers you will remember that a hexadecimal number can be used as shorthand for 4 bits of a binary number. As an example the hexadecimal 0x45 is equivalent to the binary number 0b01000101. So if we were to write 0x45 to the seconds counter register, then 4 would be written to the tens span and 5 would be written to the ones span. The new count for the seconds register would be read as 45.

Month Counter (RMONCNT)

Address: 0008 C40Ch



Value after reset:

[Legend] x: Undefined

0 0 0 x x x x x

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	MON1[3:0]	Ones Place of Months	Counts from 0 to 9 once per month. When a carry is generated, 1 is added to the tens place.	R/W
b4	MON10	Tens Place of Months	Counts from 0 to 1 once per carry from the ones place.	R/W
b7 to b5	—	Reserved	These bits are always read as 0. The write value should always be 0.	R/W

Figure 8.15 RMONCNT (Month Counter) [1], page 1048.

Year Counter (RYRCNT)

Address: 0008 C40Eh



Value after reset:

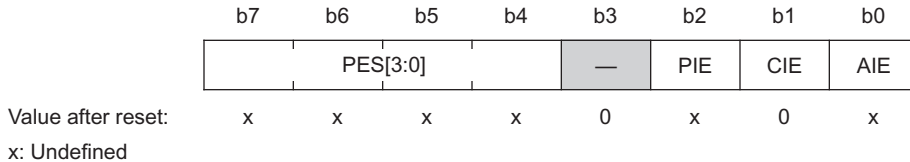
x: Undefined

0 0 0 0 0 0 0 0 x x x x x x x x

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	YR1[3:0]	Ones Place of Years	Counts from 0 to 9 once per year. When a carry is generated, 1 is added to the tens place.	R/W
b7 to b4	YR10[3:0]	Tens Place of Years	Counts from 0 to 9 once per carry from ones place. When a carry is generated in the tens place, 1 is added to the hundreds place.	R/W
b15 to b8	—	Reserved	These bits are read as 0. The write value should be 0.	R/W

Figure 8.16 Year Counter (RYRCNT) [1], page 1049.

We can set alarm using the RTC. The date and time of alarm is set in the alarm registers of the RTC module in the BCD format, the same way as the time registers. The alarm registers are constantly compared with the current time registers. When the corresponding values match, the IR92.IR flag of the ICU is set to 1. All the alarm registers are reset to zero by a software reset of the RTC.



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	AIE	Alarm Interrupt Enable	0: An alarm interrupt request is disabled.	R/W
			1: An alarm interrupt request is enabled.	
b1	CIE	Carry Interrupt Enable	0: A carry interrupt request is disabled.	R/W
			1: A carry interrupt request is enabled.	
b2	PIE	Periodic Interrupt Enable	0: A periodic interrupt request is disabled.	R/W
			1: A periodic interrupt request is enabled.	
b3	—	Reserved	This bit is read as 0. The write value should be 0.	R/W
b7 to b4	PES[3:0]	Periodic Interrupt Select	b7 b4	
			0 1 1 0: A periodic interrupt is generated every $\frac{1}{256}$ second. (However, when the main clock is selected (RCR4.RCKSEL = 1) while PES[3:0] = 0110b, a periodic interrupt is generated every $\frac{1}{128}$ second.)	R/W
			0 1 1 1: A periodic interrupt is generated every $\frac{1}{128}$ second	
			1 0 0 0: A periodic interrupt is generated every $\frac{1}{64}$ second	
			1 0 0 1: A periodic interrupt is generated every $\frac{1}{32}$ second	
			1 0 1 0: A periodic interrupt is generated every $\frac{1}{16}$ second	
			1 0 1 1: A periodic interrupt is generated every $\frac{1}{8}$ second	
			1 1 0 0: A periodic interrupt is generated every $\frac{1}{4}$ second	
			1 1 0 1: A periodic interrupt is generated every $\frac{1}{2}$ second	
			1 1 1 0: A periodic interrupt is generated every 1 second	
			1 1 1 1: A periodic interrupt is generated every 2 seconds	
			Other than above, no periodic interrupts are generated.	

Figure 8.17 RTC Control Register 1 (RCR1) [1], page 1056.

Address(es): 0008 C424h

b7	b6	b5	b4	b3	b2	b1	b0
—	HR24	AADJP	AADJE	RTCOE	ADJ30	RESET	START

Value after reset:
x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	START	Start	0: Year, month, day-of-week, date, hour, minute, second, and 64-Hz counters, and prescaler are stopped.	R/W
			1: Year, month, day-of-week, date, hour, minute, second, and 64-Hz counters, and prescaler operate normally.	
b1	RESET	RTC Software Reset	In writing	R/W
			0: Writing is invalid.	
			1: The prescaler and target registers (R64CNT, RSECAR, RMINAR, RHRAR, RWKAR, RDAYAR, RMONAR, RYRAR, RYRAREN, RADJ, RTCCRy, RSECCPy, RMINCPy, RHRCPy, RDAYCPy, RMONCPy, RCR2.ADJ30, RCR2.AADJE, and RCR2.RTCOE) are reset by RTC software reset.	
			In reading	
			0: In normal clock operation, or RTC software reset has completed.	
			1: During a RTC software reset.	
b2	ADJ30	30-Second Adjustment	In writing	R/W
			0: Writing is invalid.	
			1: 30-second adjustment is executed.	
			In reading	
			0: In normal clock operation, or 30-second adjustment has completed.	
			1: During 30-second adjustment.	
b3	RTCOE	RTCOUT Output Enable	0: RTCOUT output disabled.	R/W
			1: RTCOUT output enabled.	
b4	AADJE	Automatic Adjustment Enable* ¹	0: Automatic adjustment is disabled. 1: Automatic adjustment is enabled.	R/W
b5	AADJP	Automatic Adjustment Period Select* ¹	0: The RADJ.ADJ[5:0] setting value is adjusted from the count value of the prescaler every one minute.	R/W
			1: The RADJ.ADJ[5:0] setting value is adjusted from the count value of the prescaler every ten seconds.	
b6	HR24	Hours Mode	0: The RTC operates in 12-hour mode.	R/W
			1: The RTC operates in 24-hour mode.	
b7	—	Reserved	Set this bit to 0. It is read as 0.	R/W

Note 1. When the main clock is selected, the AADJE and AADJP settings are invalid.

Figure 8.18 RTC Control Register 2 (RCR2) [1], page 1057.

Address(es): 0008 C426h



Value after reset:

x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	RTCEN	Sub-clock Control	0: Sub-clock oscillator is stopped. 1: Sub-clock oscillator is running.	R/W
b3 to b1	RTCDV[2:0]	Sub-clock Oscillation Driving Ability Control	b3 b1 0 0 1: Low driving ability for the clock. 1 1 0: Standard driving ability for the clock ^{*1} Settings other than the above are prohibited.	R/W
b7 to b4	—	Reserved	These bits are read as 0. The write value should be 0.	R/W

Note 1: For the product in a 64-pin package, set these bits to 110b.

Figure 8.19 RTC Control Register 3 (RCR3) [1], page 1059.

Address(es): 0008 C428h



Value after reset:

x: Undefined

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	RCKSEL	Count Source Select	0: The sub-clock is selected. 1: The main clock is selected.	R/W
b7 to b1	—	Reserved	These bits are read as 0. The write value should be 0.	R/W

Figure 8.20 RTC Control Register 4 (RCR4) [1], page 1060.

The RTC control registers are named RCR n ($n = 1$ to 4). All are 8-bit registers. RCR1 enables or disables all RTC interrupt requests and periodic interrupts. The PES[3:0] bits allow for interrupt after every $1/256$ second to every 2 seconds.

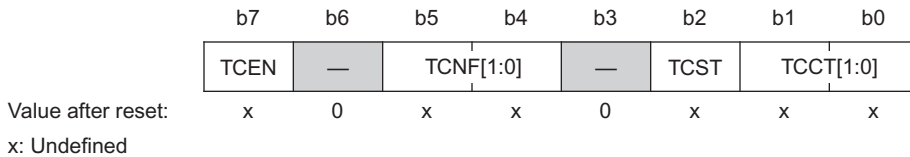
RCR2 handles setting to start the RTC, reset the RTC, RTCOUT enable, 12-hour or 24-hour mode. Writing 1 to the RESTART bit will reset the 64 Hz counter, prescalers, and alarm registers to 0.

RCR3 controls the sub-clock oscillator in the clock generation circuit and its driving ability.

Only the lowest bit of the RCR4 is used. It is used to select the count source from the sub-clock and the main clock.

Time Capture Control Register y (RTCCR y) ($y = 0$ to 2) is used to control the settings of the capture mode of the RTC. The TCCT[1:0] bits decide which edge to detect on the RTCIC y ($y = 0$ to 2) pin. Setting the TCEN bit to '1' enables the capture mode. The register also has a status bit TCST which is set to '1' when the vent is detected.

Address(es): RTCCR0 0008 C440h RTCCR1 0008 C442h RTCCR2 0008 C444h



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b1, b0	TCCT[1:0]	Time Capture Control	b1 b0	R/W
			0 0: No event is detected.	
			0 1: Rising edge is detected.	
			1 0: Falling edge is detected.	
		1 1: Both edges are detected.		
b2	TCST	Time Capture Status	Indicates that an event has been detected.	R/W
			Writing 0 clears this bit.	
			0: No event is detected.	
			1: An event is detected.* ¹	
b3	—	Reserved	This bit is read as 0. The write value should be 0.	R/W
b5, b4	TCNF[1:0]	Time Capture Noise Filter Control	b5 b4	R/W
			0 0: The noise filter is off.	
			0 1: Setting prohibited.	
			1 0: The noise filter is on (count source).	
		1 1: The noise filter is on (count source of 32-division).		
b6	—	Reserved	This bit is read as 0. The write value should be 0.	
b7	TCEN	Time Capture Event Input Pin Enable	0: The RTCIC n pin is invalid as the time capture event input.	R/W
			1: The RTCIC n pin is valid as the time capture event input.	
			($n = 0$ to 2)	

Note 1. Writing 1 to this bit has no effect.

Figure 8.21 Time Capture Control Register y (RTCCR y) ($y = 0$ to 2) [1], page 1063.

When the event is detected the current second count, minute count, hour count, date count and month count are stored in the RSECCP y , RMINCP y , RHRCP y , RDAYCP y and RMONCP y ($y = 0$ to 2) registers respectively in the BCD format.

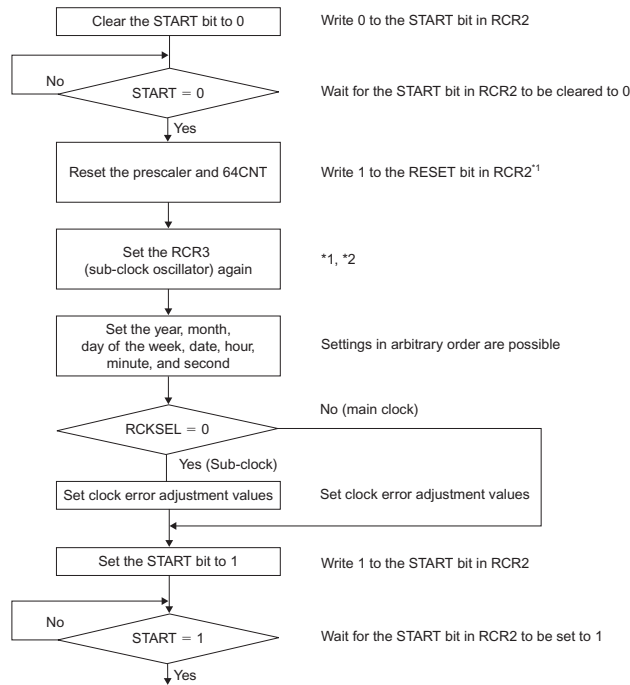
Keep in mind it is not a good idea to write to each span of the register individually as the counters update on each 128 Hz count. If your code writes a new value to the register during the same 128 Hz count it may not be acknowledged, even if is to different bits.

RCR1 enables and disables the three available RTC interrupts and the period of the periodic interrupt request. We will go over these interrupts in further detail in the advanced concepts section, for now we are most concerned with just understanding and initially setting up the Real Time Clock.

RCR2 controls the start and reset of the Real Time Clock. By writing a 1 or 0 to the START bit you start or stop the clock. By writing a 1 to the RESTART bit you will reset the 64 Hz counter, prescalers, and alarm registers to 0. Take note that these bits are updated in sync with the count source, so if you write to either of these bits it won't take effect until the next count of the RTC's 128 Hz clock. More details are available in the hardware manual. We will cover how to account for this in code examples.

8.3.2 Setting the RTC

Setting the Real Time Clock is relatively simple, as illustrated in Figure 8.22. After setting and waiting for the START bit in RCR2 to clear to 0, you set a 1 to the RESET bit. After this you can set the counter registers in any order. Then you set the START bit in RCR2 to get the counter started again. Be sure to wait for the bit to set to 1 before you continue with any other operations on the RTC.



Note 1: This step is not necessary for the time-setting procedure because a software reset is executed in the clock setting procedure of the initial settings for the power supply.

Note 2: When setting RCR3 again, repeat the same settings as are made for the RCR3 register in section 28.3.2, Clock Setting Procedure.

Figure 8.22 Setting the RTC [1], Figure 19.4, page 1069.

8.3.3 Reading the RTC

Reading the values in the RTC is a little tricky. If a carry request is performed from the 64 kHz clock to the second counter while a reading occurs, then the correct time won't be read. There are two ways to read the time that avoids this.

This flowchart from the RX63N manual¹ illustrates the operation to take when reading the counter values using interrupts or not using interrupts. In the non-interrupt method you disable the carry interrupt in the ICU, but enable it in the RTC. Then you check the interrupt flag for the carry operation after reading the registers. If a carry has occurred, you clear the carry flag and start reading over again because the time has changed since reading started. When using the interrupt method you start the same, but instead of checking the carry flag use the carry interrupt to indicate that a carry has occurred between the 64 Hz counter and the second count. The non-interrupt method is preferred as it requires less code.

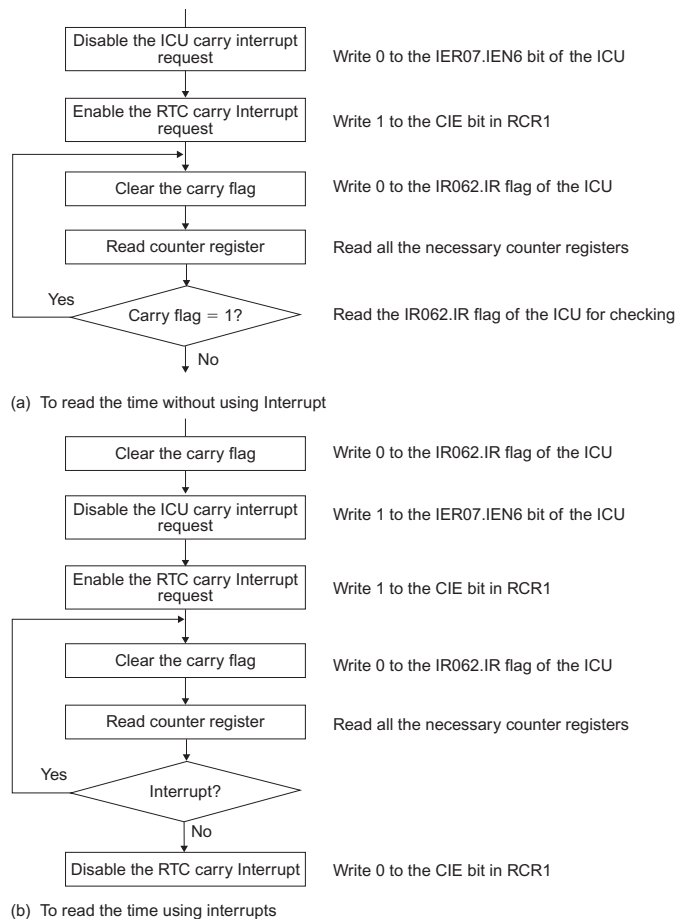


Figure 8.23 Reading 64 Hz Counter and Time [1], Figure 29.6, page 1071.

16-bit Timer Pulse Unit (TPU)

RX63N microcontroller has 16-bit timer units called TPUa (Timer Pulse Unit) ($a = 0$ to 11). The TPUs are divided into 2 units. Each unit contains 6 channels. Buffer operation and phase counting mode can be set on some of the channels of the TPU. There are 52 interrupt sources for 16-bit TPU. The figure below shows the block diagram of unit 0.

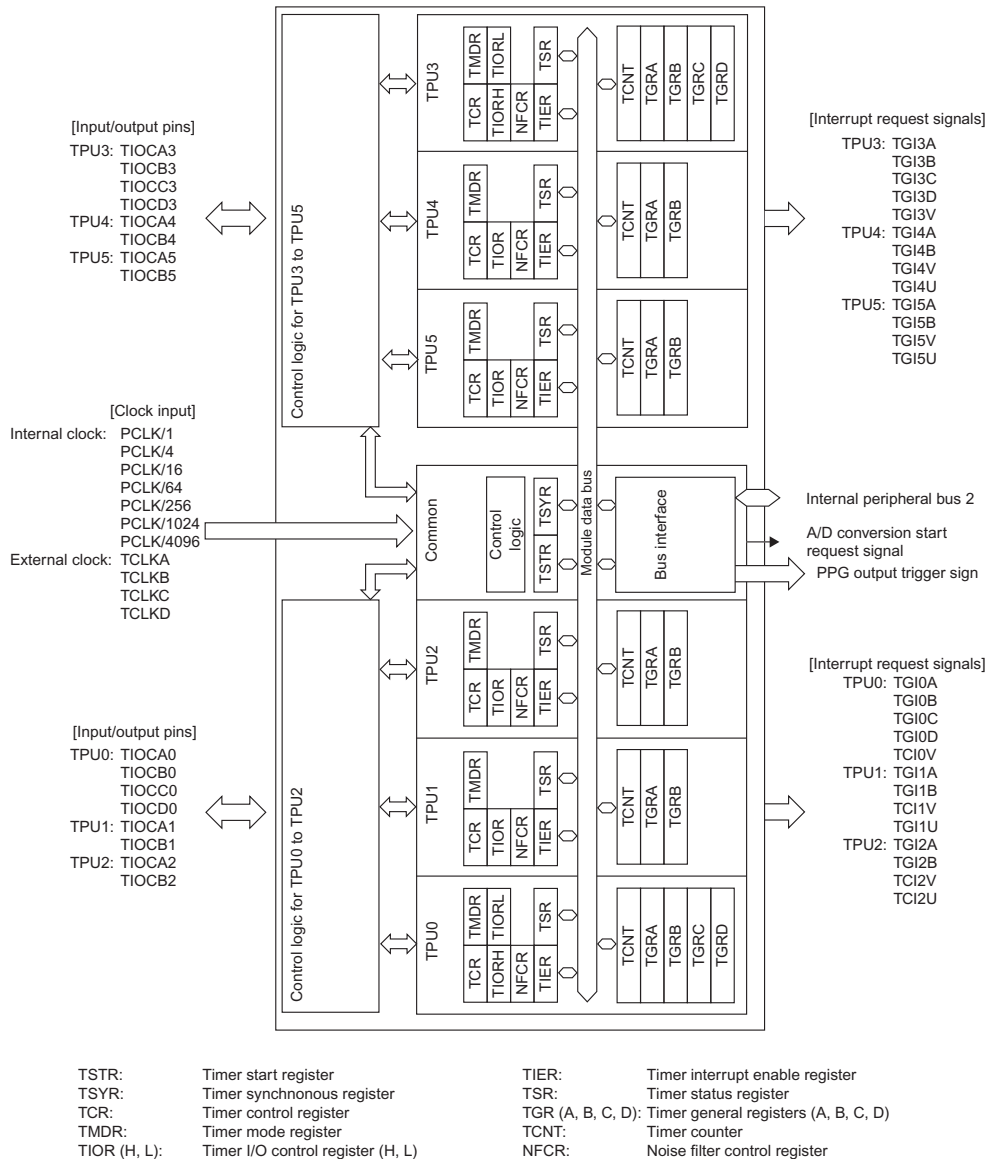


Figure 8.24 Block Diagram of TPU (Unit 0) [1], Table 25.1, page 914.

TPU Registers

The timer operation must be stopped before setting the TPU configuration registers.

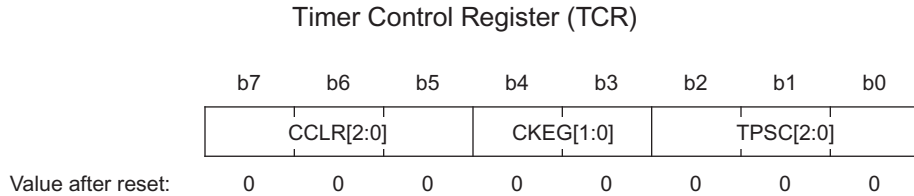


Figure 8.25 Timer Control Register (TCR) [1], page 917.

The TPSC[2:0] bits set the timer preselect for clock source. Different TPUs have different clock source frequency scaling down options. The CKEG[1:0] bits selects whether the count should be incremented on rising, falling or both edges of the clock. The CCLR[2:0] bits give counter clearing options. There are various sources for clearing the counter like compare match, input capture or clearing of other timer channel.

Timer Mode Register (TMDR)

Timer Mode Register (TMDR) selects the mode in which the timer should operate. It also selects the hardware pin source for input capture. Bit 3 is reserved.

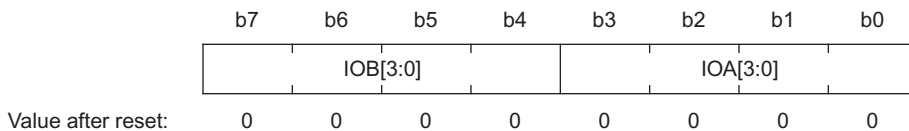
BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	MD[3:0]	Mode Select	b3 ^{*1} b0 0 0 0 0: Normal Operation 0 0 0 1: Setting prohibited 0 0 1 0: PWM mode 1 0 0 1 1: PWM mode 2 0 1 0 0: Phase counting mode 1 ^{*2} 0 1 0 1: Phase counting mode 2 ^{*2} 0 1 1 0: Phase counting mode 3 ^{*2} 0 1 1 1: Phase counting mode 4 ^{*2} Setting other than above are prohibited.	R/W

Figure 8.26 Timer Mode Register (TMDR) [1], page 922.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b4	BFA ^{*3}	Buffer Operation A	0: TPUm.TGRA operates normally	R/W
			1: TPUm.TGRA and TPUm.TGRC used together for buffer operation	
			($m = 0, 3, 6, 9$)	
b5	BFB ^{*4}	Buffer Operation B	0: TPUm.TGRB operates normally	R/W
			1: TPUm.TGRB and TPUm.TGRD used together for buffer operation	
			($m = 0, 3, 6, 9$)	
b6	ICSELB	TGRB Input Capture Input Select	0: Input capture input source is TIOCBn pin	R/W
			1: Input capture input source is TIOCA _n pin	
			($n = 0$ to 11)	
b7	ICSELD ^{*4}	GRD Input Capture Input Select	0: Input capture input source is TIOCD _n pin	R/W
			1: Input capture input source is TIOCC _n pin	
			($n = 0, 3, 6, 9$)	

Figure 8.26 Continued.

Timer I/O Control Register (TIORH, TIORL, TIOR)

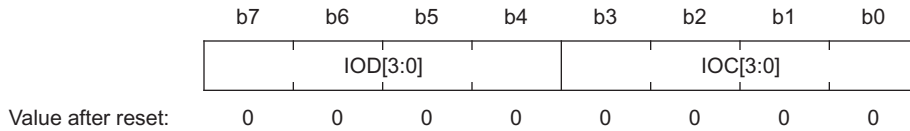


BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	IOA[3:0]	TGRA Control	See table 25.14 to Table 25.19 ^{*1}	R/W
b7 to b4	IOB[3:0]	TGRB Control	See table 25.14 to Table 25.19 ^{*1}	R/W

Note 1. If the IO_n[3:0] bit ($n = A$ or B) values are changed to output disabled (0000b or 0100b) during low/high/toggle output on compare match, the TIOCA_n/TIOCB_n pin ($n = 0$ to 11) is placed in high-impedance state.

Figure 8.27 TIORH/TIOR [1], page 923.

The register is named TIORH for TPU x ($x = 0,3,6,9$) and TIOR for TPU y ($y = 1,2,4,5,7,8,10,11$).



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	IOC[3:0]	TGRC Control	See table 25.20 to Table 25.21 ^{*1}	R/W
b7 to b4	IOD[3:0]	TGRD Control	See table 25.20 to Table 25.21 ^{*1}	R/W

Note 1. If the IOn[3:0] bit ($n = C$ or D) values are changed to output disabled (0000b or 0100b) during low/high/toggle output on compare match, the TIOCCn/TIOCDn pin ($n = 0, 3, 6, \text{ or } 9$) is placed in high-impedance state.

Figure 8.28 TIORL [1], page 924.

The TIORL register is defined for TPU x ($x = 0, 3, 6, 9$). The Timer I/O Control Register describes setting for initial output state (low or high) at compare match, disabling output and detecting edges for input capture.

Timer Counter (TCNT)

Timer Counter (TCNT) is a 16-bit register which holds the current timer count. The register is initialized to 0000h by reset.

Timer General Register (TGR x) ($x = A$ to D)

TPU has 32 TGR registers in total, four each for TPU0, TPU3, TPU6, and TPU9 and two each for TPU1, TPU2, TPU4, TPU5, TPU7, TPU8, TPU10, and TPU11. PUm.TGRA ($m = 0$ to 11), PUm.TGRB ($m = 0$ to 11), PUm.TGRC ($m = 0, 3, 6, 9$), and PUm.TGRD ($m = 0, 3, 6, 9$) are 16-bit registers with a dual function as output compare and input capture registers. These registers can be read/written in 16-bit units. PUm.TGRC and PUm.TGRD can also be specified for operation as buffer registers. Register combinations during buffer operations are PUm.TGRA—TPUm.TGRC and PUm.TGRB—TPUm.TGRD.

Timer Interrupt Enable Register (TIER)

b7	b6	b5	b4	b3	b2	b1	b0
TTGE	—	TCIEU	TCIEV	TGIED	TGIEC	TGIEB	TGIEA
Value after reset:	0	1	0	0	0	0	0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	TGIEA	TGRA Interrupt Enable	0: Interrupt requests (TGImA) disabled	R/W
			1: Interrupt requests (TGImA) enabled	
			($m = 0$ to 11)	
b1	TGIEB	TGRB Interrupt Enable	0: Interrupt requests (TGImB) disabled	R/W
			1: Interrupt requests (TGImB) enabled	
			($m = 0$ to 11)	
b2	TGIEC ^{*1}	TGRC Interrupt Enable	0: Interrupt requests (TGImC) disabled	R/W
			1: Interrupt requests (TGImC) enabled	
			($m = 0, 3, 6, 9$)	
b3	TGIED ^{*1}	TGRD Interrupt Enable	0: Interrupt requests (TGImD) disabled	R/W
			1: Interrupt requests (TGImD) enabled	
			($m = 0, 3, 6, 9$)	
b4	TCIEV	Overflow Interrupt Enable	0: Interrupt requests (TGImV) disabled	R/W
			1: Interrupt requests (TGImV) enabled	
			($m = 0$ to 11)	
b5	TCIEU ^{*2}	Underflow Interrupt Enable	0: Interrupt requests (TCImU) disabled	R/W
			1: Interrupt requests (TCImU) enabled	
			($m = 1, 2, 4, 5, 7, 8, 10, 11$)	
b6	—	Reserved	This bit is read as 1. The write value should be 1.	R/W
b7	TTGE ^{*3}	A/D Conversion Start Request Enable	0: A/D conversion start request generation disabled	R/W
			1: A/D conversion start request generation enabled	

Figure 8.29 Timer Interrupt Enable Register (TIER) [1], page 933.

Timer Status Register (TSR)

	b7	b6	b5	b4	b3	b2	b1	b0
	TCFD	—	TCFU	TCFV	TGFD	TGFC	TGFB	TGFA
Value after reset:	1	1	0	0	0	0	0	0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	TGFA	Input Capture/Output Compare Flag A	0: Input capture to TPUM.TGRA or compare match with TPUM.TGRA has not occurred.	R/W* ²
			1: Input capture to TPUM.TGRA or compare match with TPUM.TGRA has occurred.	
			($m = 0$ to 11)	
b1	TGFB	Input Capture/Output Compare Flag B	0: Input capture to TPUM.TGRB or compare match with TPUM.TGRB has not occurred.	R/W* ²
			1: Input capture to TPUM.TGRB or compare match with TPUM.TGRB has occurred.	
			($m = 0$ to 11)	
b2	TGFC* ⁴	Input Capture/Output Compare Flag C	0: Input capture to TPUM.TGRC or compare match with TPUM.TGRC has not occurred.	R/W* ²
			1: Input capture to TPUM.TGRC or compare match with TPUM.TGRC has occurred.	
			($m = 0, 3, 6, 9$)	
b3	TGFD* ⁴	Input Capture/Output Compare Flag D	0: Input capture to TPUM.TGRD or compare match with TPUM.TGRD has not occurred.	R/W* ²
			1: Input capture to TPUM.TGRD or compare match with TPUM.TGRD has occurred.	
			($m = 0, 3, 6, 9$)	
b4	TCFV	Overflow Flag	0: TPUM.TCNT has not overflowed.	R/W* ²
			1: TPUM.TCNT has overflowed.	
			($m = 0$ to 11)	
b5	TCFU* ³	Underflow Flag	0: TPUM.TCNT has not overflowed.	R/W* ²
			1: TPUM.TCNT has overflowed.	
			($m = 1, 2, 4, 5, 7, 8, 10, 11$)	
b6	—	Reserved	This bit is read as 1. The write value should be 1.	R
b7	TCFD* ¹	Counting Direction Flag	0: Counter (TCUM.TCNT) counts down.	R
			1: Counter (TCUM.TCNT) counts up.	
			($m = 1, 2, 4, 5, 7, 8, 10, 11$)	

Figure 8.30 Timer Status Register (TSR) [1], page 934.

Timer Start Register (TSTR) Unit 0 (TPUA.TSTR)

Address(es): TPUA.TSTR 0008 6100h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	CST5	CST4	CST3	CST2	CST1	CST0

Value after reset: 0 0 0 0 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	CST0	Counter Start 0	0: TCNT count operation is stopped 1: TCNT performs count operation	R/W
b1	CST1	Counter Start 1		R/W
b2	CST2	Counter Start 2		R/W
b3	CST3	Counter Start 3		R/W
b4	CST4	Counter Start 4		R/W
b5	CST5	Counter Start 5		R/W
b7,b6	—	Reserved		These bits are read as 0. The write value should be 0.

Unit 1 (TPUB.TSTR)

Address(es): TPUB.TSTR 0008 6170h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	CST11	CST10	CST9	CST8	CST7	CST6

Value after reset: 0 0 0 0 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	CST6	Counter Start 6	0: TCNT count operation is stopped 1: TCNT performs count operation	R/W
b1	CST7	Counter Start 7		R/W
b2	CST8	Counter Start 8		R/W
b3	CST9	Counter Start 9		R/W
b4	CST10	Counter Start 10		R/W
b5	CST11	Counter Start 11		R/W
b7,b6	—	Reserved		These bits are read as 0. The write value should be 0.

Figure 8.31 Timer Start Register (TSTR) [1], page 938.

The timer operation can be started by setting the CSTx bit. The timer is stopped by writing '0' to the corresponding CST bit.

Timer Synchronous Register (TSYR) Unit 0 (TPUA.TSYR)

Address(es): TPUA.TSYR 0008 8101h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	SYNC5	SYNC4	SYNC3	SYNC2	SYNC1	SYNC0

Value after reset: 0 0 0 0 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	SYNC0	Timer Synchronization 0	0: TCNT operates independently (TCNT presetting/clearing is unrelated to other channels) 1: TCNT performs synchronous operation* ¹ (TCNT synchronous presetting/synchronous clearing is possible)	R/W
b1	SYNC1	Timer Synchronization 1		R/W
b2	SYNC2	Timer Synchronization 2		R/W
b3	SYNC3	Timer Synchronization 3		R/W
b4	SYNC4	Timer Synchronization 4		R/W
b5	SYNC5	Timer Synchronization 5		R/W
b7, b6	—	Reserved	These bits are read as 0. The write value should be 0.	R/W

Notes 1. To set synchronous operation, the SYNCn bit ($n = 0$ to 5) for at least two channels must be set to 1. To set synchronous clearing, the TCNT clearing source must also be set by the CCLR[2:0] bits in TCR in addition to the SYNCn bit.

Unit 1 (TPUB.TSYR)

Address(es): TPUB.TSYR 0008 8171h

b7	b6	b5	b4	b3	b2	b1	b0
—	—	SYNC11	SYNC10	SYNC9	SYNC8	SYNC7	SYNC6

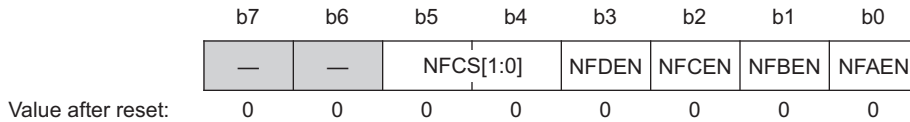
Value after reset: 0 0 0 0 0 0 0 0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	SYNC6	Timer Synchronization 6	0: TCNT operates independently (TCNT presetting/clearing is unrelated to other channels) 1: TCNT performs synchronous operation* ¹ (TCNT synchronous presetting/synchronous clearing is possible)	R/W
b1	SYNC7	Timer Synchronization 7		R/W
b2	SYNC8	Timer Synchronization 8		R/W
b3	SYNC9	Timer Synchronization 9		R/W
b4	SYNC10	Timer Synchronization 10		R/W
b5	SYNC11	Timer Synchronization 11		R/W
b7, b6	—	Reserved	These bits are read as 0. The write value should be 0.	R/W

Notes: 1. To set synchronous operation, the SYNCn bit ($n = 6$ to 11) for at least two channels must be set to 1. To set synchronous clearing, the TCNT clearing source must also be set by the CCLR[2:0] bits in TCR in addition to the SYNCn bit.

Figure 8.32 Timer Synchronous Register (TSYR) [1], page 939.

Noise Filter Control Register (NFCR)



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	NFAEN	Noise Filter Enable A	0: The noise filter for TIOCA _m is disabled.	R/W
			1: The noise filter for TIOCA _m is enabled.	
			(<i>m</i> = 0 to 11)	
b1	NFBEN	Noise Filter Enable B	0: The noise filter for TIOCB _m is disabled.	R/W
			1: The noise filter for TIOCB _m is enabled.	
			(<i>m</i> = 0 to 11)	
b2	NFCEN* ¹	Noise Filter Enable C	0: The noise filter for TIOCC _m is disabled.	R/W
			1: The noise filter for TIOCC _m is enabled.	
			(<i>m</i> = 0, 3, 6, 9)	
b3	NFDEN* ¹	Noise Filter Enable D	0: The noise filter for TIOCD _m is disabled.	R/W
			1: The noise filter for TIOCD _m is enabled.	
			(<i>m</i> = 0, 3, 6, 9)	
b5, b4	NFC S[1:0]	Noise Filter Clock Select	00: PCLK/1	R/W
			01: PCLK/8	
			10: PCLK/32	
			11: Clock source that drives counting	
b7, b6	—	Reserved	These bits are read as 0. Writing to these bits is not possible.	R

Notes: 1. Bits 2 and 3 of TPU1.NFCR, TPU2.NFCR, TPU4.NFCR, TPU5.NFCR, TPU7.NFCR, TPU8.NFCR, TPU10.NFCR, and TPU11.NFCR are reserved. The bits are read as 0. Writing to these bits is not possible.

Figure 8.33 Noise Filter Control Register (NFCR) [1], page 940.

8.4 BASIC EXAMPLES

Now that we have covered the basic concepts needed to understand how the timer works in these different modes, we will cover a few examples. For now we will demonstrate the initial setup of the clock and how to read from it.

8.4.1 Setting Up Cascaded Timers

For this demo we will be setting up 8-bit unit 0 in cascaded timer mode by cascading timer 0 and timer 1 together. We will call an interrupt service routine every time this cascaded counter overflows from 0xFFFF to 0x0000. In the service routine we will put a call to a function that rotates the LEDs on the board. The resulting program will make the LEDs on the board blink in a rotating sequence at a speed determined by how we set up our timer.

We will start with a base HEW project that includes the `iodef.h` file and other support headers for the RX63N. In this example we will use macros to control the LEDs, we will continue assuming you have defined a similar substitute for performing the action described by the macro.

The first thing to do in our main program is to declare our only global variable.

```
1. int Current_LED = 1;
```

We will use this variable to keep track of which LED is currently lit. We will cover how when we discuss the function that uses it.

Then we need to include our function prototypes. As you can see we will only use two function calls, one to set up the timer and another to blink the LEDs.

```
1. void InitTimer(void);
2. void Rotate_LED(void);
```

After our `main()` loop begins we will only need to include the macro for initializing the LEDs and our timer initialization function call. Our `while(1)` loop will be empty, as all operations will be handled in the timer interrupt. Note that this is generally bad programming practice and very uncommon; however, in some cases this is the correct solution.

```
1. void main(void){
2.     ENABLE_LEDS;
3.     InitTimer();
4.     while(1){}
5. }
```

Now comes the part we are most concerned with, the timer initialization. In this function we will set the timer registers for 16-bit cascaded mode.

```
1. void InitTimer(void){
2.     IEN(TMR0,OVI0) = 1;    //Enable TMR0 Overflow interrupt in ICR
3.     IPR(TMR0,OVI0) = 2;    //Set priority level of interrupt
4.     MSTP(TMR0) = 0;    //Activate TMR0 unit
```



```

5.     MSTP(TMR1) = 0;    //Activate TMR1 unit
6.     TMR1.TCCR.BIT.CSS = 1;
7.     TMR1.TCCR.BIT.CKS = 4;    //Count source is PCLK/64 for TMR1
8.     TMR0.TCCR.BIT.CSS = 3;
9.     TMR0.TCR.BIT.CCLR = 1;    //Count source is TMR1 for TMR0
10.    TMR0.TCR.BIT.OVIE = 1;    //Overflow interrupt enabled
11. }

```

We start on lines 2 to 3 by enabling the timer 0 overflow interrupt in the ICU and setting its priority level. Then on lines 4 to 5 we activate the timer 0 and 1 units in the Module Stop Control Register (they are off by default). On lines 6 to 7 we set the count source for timer 1 as the PCLK/64. On lines 9 to 10 we set the count source for timer 0 as timer 1. With the count source set, this will make timer 0 count every time timer 1 overflows. The timers TMR0 and TMR1 are now cascaded. On line 14 we finish by setting the interrupt in the timer unit itself.

As we calculated earlier in our concepts, this setup will take the main clock of 24 MHz and divide it by 64. Then every 65535 counts the timer 0 interrupt will occur and the interrupt routine will be called, thus rotating the current LED that is lit. This is calculated to be approximately every 174.76 ms.

$$\frac{1}{24 \text{ MHz (main clock)}} * \frac{64 \text{ (clock division)}}{1} * \frac{65535 \text{ (counts per interrupt)}}{1} = 174.76 \text{ ms}$$

The next function is used to light the LEDs on the board one at a time in a circular sequence. It uses the Current_LED variable to hold which Led is currently lit. Each time it is called, it increments the value, and as soon as it passes 12 it restarts at 1.

```

1. void LED_Rotate(void) {
2.     switch(Current_LED) {
3.         case 1:
4.             ALL_LEDS_ON;
5.             LED6 = LED_OFF;
6.             break;
7.         case 2:
8.             ALL_LEDS_ON;
9.             LED12 = LED_OFF;
10.            break;
11.        case 3:
12.            ALL_LEDS_ON;
13.            LED3 = LED_OFF;
14.            break;

```

```
15.         case 4:
16.             ALL_LEDS_ON;
17.             LED9 = LED_OFF;
18.             break;
19.         case 5:
20.             ALL_LEDS_ON;
21.             LED5 = LED_OFF;
22.             break;
23.         case 6:
24.             ALL_LEDS_ON;
25.             LED11 = LED_OFF;
26.             break;
27.         case 7:
28.             ALL_LEDS_ON;
29.             LED2 = LED_OFF;
30.             break;
31.         case 8:
32.             ALL_LEDS_ON;
33.             LED8 = LED_OFF;
34.             break;
35.         case 9:
36.             ALL_LEDS_ON;
37.             LED4 = LED_OFF;
38.             break;
39.         case 10:
40.             ALL_LEDS_ON;
41.             LED10 = LED_OFF;
42.             break;
43.         case 11:
44.             ALL_LEDS_ON;
45.             LED1 = LED_OFF;
46.             break;
47.         case 12:
48.             ALL_LEDS_ON;
49.             LED7 = LED_OFF;
50.             break;
51.         default:
52.             ALL_LEDS_OFF;
53.             break;
54.     }
55.     Current_LED++;
```

```
56.     if(Current_LED == 13){
57.         Current_LED = 1;
58.     }
59. }
```

That is all of the code we need in the main program file. Now we need to define our interrupt and put a call to our `LED_Rotate()` function.

```
1. #pragma interrupt (Excep_TMR0_OV0I(vect = VECT_TMR0_OVI0))
2. void Excep_TMR0_OV0I(void);
3. //TMR0_OV0I
4. void Excep_TMR0_OV0I(void){LED_Rotate();}
```

The first line of this code snippet defines an interrupt at the vector for timer 0 overflow. Next it gives a function definition and the function itself. Inside the function is a call to the `LED_Rotate()` function. Make note that it is bad practice to include function calls inside of an ISR for many reasons. We will go over reasons why and workarounds for this later.

We have now successfully set up a 16-bit cascaded timer on the RX63N and used it to trigger an interrupt that rotates the board's LEDs. By modifying the count source of timer 1 we can change the speed of this rotation. Later, in a more advanced example, we will cover how to take greater control of the timer and interrupt timing using the time constant registers and compare match events.

8.4.2 Setting Up a Timer for Pulse Output

Now we will cover an example of setting up a timer for pulse output. This requires very little code to execute. Once we have set up the timer it will begin to output our desired pulse without any further intervention.

```
1. void main(void);
2. void InitTimer(void);
3. void main(void){
4.     InitTimer();
5.     while(1){}
6. }
7. void InitTimer(void){
8.     MSTP(TMR0) = 0;    //Activate TMR0 unit
9.     TMR0.TCCR.BIT.CSS = 1;    //Count source is PCLK/8
10.    TMR0.TCCR.BIT.CKS = 2;
11.    TMR0.TCR.BIT.CCLR = 1;    //Timer resets at compare match A
```

```

12.     TMR0.TCSR.BIT.OSA = 2;    //1-output at compare match A
13.     TMR0.TCSR.BIT.OSB = 1;    //0-output at compare match B
14.     TMR0.TCORA = 0x55;    //Frequency
15.     TMR0.TCORB = 0x20;    //Duty cycle
16.     //Pulse outputs to TMo0, which is also P22/USB_DRPD
17.     //Can be monitored by touching a scope probe to the top
18.     //of resistor R46, near bottom right corner of ethernet
19.     //port. Port JN2 provides a ground.
20. }

```

As can be seen here, we have no global variables to initialize and the only function we need is the function to set up the timer. In the timer initialization we first enable the 8-bit timer unit on line 8. We set the count source for timer 0 as PCLK/8 on lines 9 and 10.

On line 11 we set timer 0 to clear every time a compare match A occurs. This allows us to alter how fast the timer resets with more control than just changing the count source.

On lines 12 and 13 we set the timer output to go high every time there is a compare match A and to go low when there is a compare match B. This allows us to control the frequency using time constant register A (TCORA), and the duty cycle using time constant register B (TCORB).

On lines 14 and 15 we set the frequency and duty cycle by assigning a value to timer constant registers A and B. These are randomly chosen; we will worry about getting an exact frequency and duty cycle in the advanced concept section.

When running this code the pulse will be output on pin TMO0. By referencing the hardware manual and schematic we find that this is output to pin number 26 (Port2.2) on the board. You can get a ground reference by connecting to one of the GND terminals on the board.

In this example we have set up a pulse output from timer 0 and observed the output wave. In a more advanced example later we will cover how to calculate and control the exact frequency of the wave and discuss how this relates to controlling external devices.

8.4.3 Setting and Reading from the Real Time Clock

In this example we will demonstrate how to set the time in the Real Time Clock. We will then continuously read the value in the RTC and display it on the LCD.

To start we will use a base project that has all of the included support files for the graphic LCD. Also included is the `iodef.h` file.

The first step in this example is to define our global variables.

```

1. char Year1000, Year100, Year10, Year1, Mon10, Mon1, Day10, Day1,
    Day, Hour10, Hour1, Min10, Min1, Sec10, Sec1;

```

These will all hold the value for each of the decimal places of the date values.

Next we insert the function prototypes for the functions we will write:

```
1. void InitTimer(void);
2. void DisplayTime(void);
3. void GetTime(void);
```

Now that all of that is defined we go into our main() program.

```
1. void main(void){
2.     int i;
3.     lcd_initialize();
4.     InitTimer();
5.     while(1){
6.         DisplayTime();
7.         for (i = 0; i < 100000; i++){
8.     }
```

First we define the variable ‘i’ in line 2. This is used to create a delay loop between writes to the LCD. The LCD is initialized by calling the built-in function `lcd_initialize` (line 3) defined in `lcd.c`. Next we call our function initializing the RTC in Line 4. Inside the while loop we call the function `DisplayTime` (line 6) to display the current time on the LCD.

The next section of code we will consider is the `InitTime()` function.

```
1. void InitTimer(void){
2.     //Set date and time on RTC
3.
4.     RTC.RCR2.BIT.START = 0;    //Write 0 to start bit in RCR2
5.     while(RTC.RCR2.BIT.START == 1){}    //Wait for start bit to
                                           clear to 0
6.     RTC.RCR2.BIT.HR24 = 0;    //RTC operates in 12 hour mode
7.     RTC.RCR2.BIT.RESET = 1;   //Write 1 to Reset bit in RCR2
8.
9.     RTC.RYRCNT.WORD = 0x0015;  //Set year, month, day of
10.    RTC.RMONCNT.BYTE = 0x10;   //week, date, hour, minute,
11.    RTC.RDAYCNT.BYTE = 0x21;   //second to 2015 Oct 21st
12.    RTC.RWKCNT.BYTE = 0x02;   //Tue 12:00:00
13.    RTC.RHRCNT.BYTE = 0x12;
14.    RTC.RMINCNT.BYTE = 0x00;
```

```

15.     RTC.RSECCNT.BYTE = 0x00;
16.
17.     RTC.RCR2.BIT.START = 1;    //Set start bit to 1 in RCR2
18.     while(RTC.RCR2.BIT.START == 0){}    //Wait for start bit to set
                                           to 1
19.
20.     //Set carry interrupt for use later when reading time from RTC
21.     IEN(RTC,COUNTUP) = 0;    //Disable carry interrupt in ICU
22.     RTC.RCR1.BIT.CIE = 1;    //Enable carry interrupt in the RTC
23. }

```

Here we set up the Real Time Clock and initialize all of the count registers to the date we want. This follows the flowchart in Figure 8.19. Lines 4 and 5 clear and wait for the RCR2.START bit to become 0. The wait is necessary because the bits in this register only update on every count of the 128 kHz clock in the RTC, and the program is executing at a much faster 24 MHz. Next the RCR2.RESET bit is set to 1 on line 7. This resets the RTC's prescaler clocks, 64 Hz counter, and alarm registers to 0. After this is done, from line 9 through 15 the clock's count registers are set to the starting date and time desired. In this example the start time and date is 12:00 PM Tue, Oct 21, 2015. The next step is to start the clock. In line 17 we write a 1 to the RCR2.START bit and then wait for it to be set in line 18. The code on lines 21 and 22 disable the carry interrupt in the ICU, but enable it in the Real Time Clock peripheral. This allows us to monitor if there has been a carry from the 64 Hz counter to the second counter later on when we are reading the time. We will demonstrate this later in the example.

The next function is the DisplayTime() function. This function calls the GetTime function to update the value of the time in our global variables. It then writes them to the LCD using the printf() and lcd_display() functions.

```

1. void DisplayTime(void){
2.     char buffer [30];
3.     const char DayNames [7] = {"Sun", "Mon", "Tue", "Wed", "Thu",
    "Fri", "Sat"};
4.     GetTime();
5.     lcd_display(LCD_LINE1, "RTC Example");
6.     sprintf((char *)buffer, "20%d%d %d%d / %d%d",
7.     Year10,
8.     Year1,
9.     Mon10,
10.    Mon1,
11.    Day10,
12.    Day1);

```

```
13.     lcd_display(LCD_LINE2, buffer);
14.     lcd_display(LCD_LINE3, DayNames [Day]);
15.     sprintf((char *)buffer, "%d%d:%d%d:%d%d",
16.     Hour10,
17.     Hour1,
18.     Min10,
19.     Min1,
20.     Sec10,
21.     Sec1);
22.     lcd_display(LCD_LINE4, buffer);
23. }
```

In this function we first define two character arrays on lines 2 and 3. The `GetTime()` function is called on line 4; this copies the values of the time and date into our global variables. On line 6 we write text to the first line of the display. On line 14 we write the day. On line 15 we use `sprintf()` once again to write the time to an array of ASCII characters. On line 22 we write this to line 4 of the display.

The last function we use is the `GetTime()` function.

```
1. void GetTime(void)
2. {
3.     do {
4.         IR(RTC,COUNTUP) = 0; //Clear the Carry Flag
5.         Year10 = RTC.RYRCNT.BIT.YR10;
6.         Year1 = RTC.RYRCNT.BIT.YR1;
7.         Mon10 = RTC.RMONCNT.BIT.MON10;
8.         Mon1 = RTC.RMONCNT.BIT.MON1;
9.         Day10 = RTC.RDAYCNT.BIT.DATE10;
10.        Day1 = RTC.RDAYCNT.BIT.DATE1;
11.        Day = RTC.RWKCNT.BYTE;
12.        Hour10 = RTC.RHRCNT.BIT.HR10;
13.        Hour1 = RTC.RHRCNT.BIT.HR1;
14.        Min10 = RTC.RMINCNT.BIT.MIN10;
15.        Min1 = RTC.RMINCNT.BIT.MIN1;
16.        Sec10 = RTC.RSECCNT.BIT.SEC10;
17.        Sec1 = RTC.RSECCNT.BIT.SEC1;
18.    } while(IR(RTC,COUNTUP) == 1);
19. }
```

We start this function by clearing the interrupt request flag for the carry interrupt (line 4). We then read all of the digits the RTC counter registers into separate variables from

lines 5 through 17. After we read the time we check and make sure the interrupt request flag for the carry interrupt has not been set. If it has, that means the seconds counter has incremented, the time held in our variables is no longer correct, and we will need to get the time again. The `GetTime()` function will repeat itself until it successfully reads a time without the carry interrupt being requested.

Once all of this code is in our program we can compile it and load it onto our board. Once run, within a second the following text should appear on the graphical LCD screen.

```
RTC           Example
2015         10/21
Tue
12:00:00
```

The time will now be displayed as a clock until the program is paused in the debugger and/or power is removed from the board.

This example covered the basics of setting up and reading from the Real Time Clock by setting the time and then reading and displaying it on the boards graphical LCD as it counts. In the advanced concepts section we will cover how to use the RTC interrupts such as the periodic and alarm interrupts.

8.5 ADVANCED CONCEPTS

By now we should have a basic grasp of how to set up and use the more advanced features of the 8-bit timers along with how to set up and read the real time clock. We have covered the basics in setting up a cascaded timer, the bare minimum set up of a pulse output signal, and how to set up and read the real time clock. Now we will cover how to take more control of our timer count duration by using the timer counter registers. We will go into more detail on the pulse output operation by covering how to calculate and control our output frequency and duty cycle. Also, we will cover usage of the real time clocks alarm and periodic interrupts.

8.5.1 Using a Cascaded Timer with 16-Bit Time Constant Registers

We have covered the basics of using a cascaded 16-bit timer and have given examples of a basic set up. However, this set up lacks a bit of control that an embedded designer would want. Currently, with what we know, we can only count in increments of `0xFFFF` (65535). The only control we have over how fast the timer overflows is by altering the count source. This only leaves us with the capability to count to the lengths of time in Table 8. With the time constant registers we can extend that functionality. We have taken note of this while setting up the timer in pulse output mode, and now will cover it in more depth.

Each timer channel offers three interrupts: the overflow interrupt, and two timer constant interrupts. If we set a value in either of the time constant registers and enable these interrupts, the respective interrupt will be triggered when a compare match event occurs for that register. A compare match event will occur when the TCNT register matches the value in that time constant register; i.e., compare match A when TCNT matches time constant register A, and compare match B when TCNT matches time constant register B. So now that gives us the ability to trigger interrupts at even more precise times. But we still have to wait for the timer to finish counting to 0xFFFF and overflow and then count back to the timer constant value before the interrupt is triggered again. This is imprecise and not practical in many situations. So, by setting in the TCR for the timer channel to reset on compare match A or B, we can control to a much higher degree the time the counter will count to.

This describes how the compare match counters work in 8-bit mode, but what about 16-bit mode? There is only a minor difference. When we place the timer channel into 16-bit mode, the TCNT, TCORA, and TCORB registers from the two timer channels in the unit span into one register. So now they each are practically one 16-bit register. We can still only write to them as their 8-bit entities; so when we calculate the values we want to enter into them, we just convert to hex and write the upper byte to the register of the channel with a higher number and the lower byte to the other. If we wanted a value of 0x1234 in TCORA of timer unit 1, we would enter 0x12 in TCORA of timer 0, and 0x34 in TCORA of timer 1. For timer unit 2 we write the upper bytes to timer 2's registers and the lower bytes to timer 3's registers.

As an example we have a timer set up in 16-bit cascaded timer mode with a count source of 1/1028. If we wait for an overflow, that gives us an interrupt every 2.8 s. But what if we want to generate an interrupt every 1 second? First we calculate what fraction of 2.8 that 1 is, and then multiple that by 65535: $\frac{1}{2.8} * 65535 = 23405$ (approximately). We enter this value into time constant register A and enable the compare match A interrupt. Of course, this is a 16-bit value, so we can't enter it all at one time. So we convert it to hex and enter the upper byte into TMR0.TCORA and the lower byte into TMR1.TCORA. Now we still have the interrupt occurring every 2.8 s, but that's because the timer is still counting to 65535 before resetting. So we set the TCR.CCL bit so the timer is cleared by compare match A, thus giving us an interrupt every 1 second on compare match A.

8.5.2 Calculating and Programming Pulse Frequency and Duty Cycle in Pulse Output Mode, and Controlling a Servo Motor

We have covered the concept of how a pulse output works and demonstrated the basic register set up needed to get a pulse output. We did not go into much detail about calculating the frequency and duty cycle of our output wave. This is not too complex but has been

saved for this section just to give time to get used to the concept of pulse output operation first. If you understand the concepts of pulse output operation and calculating timer speeds from the basic concepts section, this should be no problem.

For this example we will assume we are using the pulse output to control a servo motor. Common servo motors use a pulse input to determine how or where it moves to. Specifications vary by motor, as per frequency and duty cycle required. We will use specifications from an anonymously chosen motor for this example. In the case of this motor we need a 1 ms pulse to turn full left and a pulse of 2 ms to turn full right. Usually a frequency is not specified, however you want to have adequate space between your pulses for smooth operation; and also not have them too spaced apart, so that when the duty cycle is updated the servo reacts in a timely manner. 50 Hz (20 ms period) is a safe frequency for smooth operation.

For this example we will be using the timer in 16-bit cascaded mode as well as in pulse output mode. This gives us more precise control over the duty cycle while still allowing for a wide period between pulses (low frequency). This is not much more complicated than 8-bit pulse output.

Our first step is to choose a speed for our prescaler. If we look at Table 8.2: Clock Division and Interrupt Times we see that PCLK/8 (3 MHz) offers almost a 21.84 ms period between TCNT overflows. We will choose this prescaler, as choosing PCLK/32 (87.38 μ s) will provide us with a much smaller resolution between a 1 ms pulse and a 2 ms pulse. Now we must calculate the values for the timer counter registers. First, we will calculate the values to place in time constant register B to obtain a pulse of 1 ms and 2 ms. Then we must calculate the value to place in time constant register A to obtain a 20 ms low signal after the pulse. Note that when we change the value of TCORB, the frequency of the wave still stays the same, so the time our wave is low is affected. However, since 1–2 ms is small compared to 20 ms, this is negligible and we don't have to worry about recalculating for TCORA.

To calculate the value for TCORB we divide 1 ms and 2 ms by the length of time between timer counts; $\frac{1 \text{ ms}}{333.33 \text{ ns}} = 3000$ and $\frac{2 \text{ ms}}{333.33 \text{ ns}} = 6000$. For the value in TCORA we add 20 ms to our maximum high period (2 ms) to get 22 ms, then divide this by the time for a clock tick, $\frac{22 \text{ ms}}{333.33 \text{ ns}} = 66000$. In this case it gives us a value greater than our range, which is 65535. Luckily we only max out 155 ns shorter than our desired time, which is acceptable because, once again, having a precise low period is not crucial with servo motors, only having a fair amount of low time for the control circuitry to acknowledge our high pulse. So in the case of this application it is fine to leave the value of TCORA at 0xFFFF.

So, in all practicality, when setting up a pulse output signal we are just calculating a timer length for the period of our wave and for each high duty cycle we desire, and then

programming it into the time constant registers. Also, keep in mind that with this example 1 ms and 2 ms are the maximum value pulses for our motor. If this were a 180 degree servo, 1 ms would put it at 0 degrees, and 2 ms at 180 degrees. If we wanted any position in between we would have to output a signal proportionally between 1 and 2 ms. 1.5 ms would place the servo at 90 degrees, 1.75 ms at 135 degrees and so on. In the case of a continuous rotation servo, 1 and 2 ms would be full forward and backward, and any pulse length in between would speed up or slow down the rotation; 1.5 ms would be a full stop.

8.5.3 Using the Real Time Clock's Alarm and Periodic Interrupts

The RX63N's real time clock peripheral includes three interrupts: the carry interrupt, periodic interrupt, and alarm interrupt. The carry interrupt we have used in a previous example, and is triggered every time there is a carry from the 64 kHz counter to the second counter. The periodic interrupt is an interrupt that can be set to occur on a regular interval determined by what we set in the RCR1 register. We can alter this interval by editing 3 bits in the register, allowing us seven options for interrupt intervals. The alarm interrupt gives us the ability to choose an exact time for an interrupt to occur. For each count register there is an alarm register. When enabled, once the values in all of the enabled registers match the real time clocks counter registers, an interrupt will be triggered. Besides triggering an interrupt routine the alarm interrupt also has the ability to wake the processor from low power modes.

Setting the periodic interrupt is simple in comparison to calculating and setting an 8-bit timer to do the same task. First we must make sure that the interrupt is disabled in the ICU. Then we set the periodic interrupt enable bit in RCR1 and set the periodic interrupt select bits to whichever interrupt period we desire. The options are 2 seconds, 1 second, $\frac{1}{2}$ second, $\frac{1}{4}$ second, $\frac{1}{8}$ second, $\frac{1}{16}$ second, $\frac{1}{32}$ second, $\frac{1}{64}$ second, $\frac{1}{128}$ second. After clearing the request flag we enable the interrupt in the ICU and the ISR will begin triggering on the chosen interval.

Setting the alarm interrupt is a bit more complicated, but is illustrated in a flowchart in the RX63N User's Manual: Hardware. We can set all of the alarm registers and have the interrupt only trigger at a specific date and time, or we can only enable certain registers so the interrupt triggers each time the counters match those particular alarm registers. Say we want an interrupt to trigger at thirty minutes of every hour; we will set the minute alarm register to thirty minutes, and then set the enable bit in the same register. After enabling and setting a priority level for the alarm interrupt, every time the value in the minute count register matches 30 the interrupt will occur.

First we make sure that the real time clock is running. Then we make sure the interrupt is not enabled in the ICU, so that it doesn't trigger accidentally while we are setting it. Now we are able to set all of the alarm registers to the time we desire the interrupt to be triggered at. Once done, we write a 1 to the alarm interrupt bit in the ICU. Using the periodic interrupt we will wait for the $\frac{1}{64}$ second interrupt, this is to allow time for the alarm interrupt

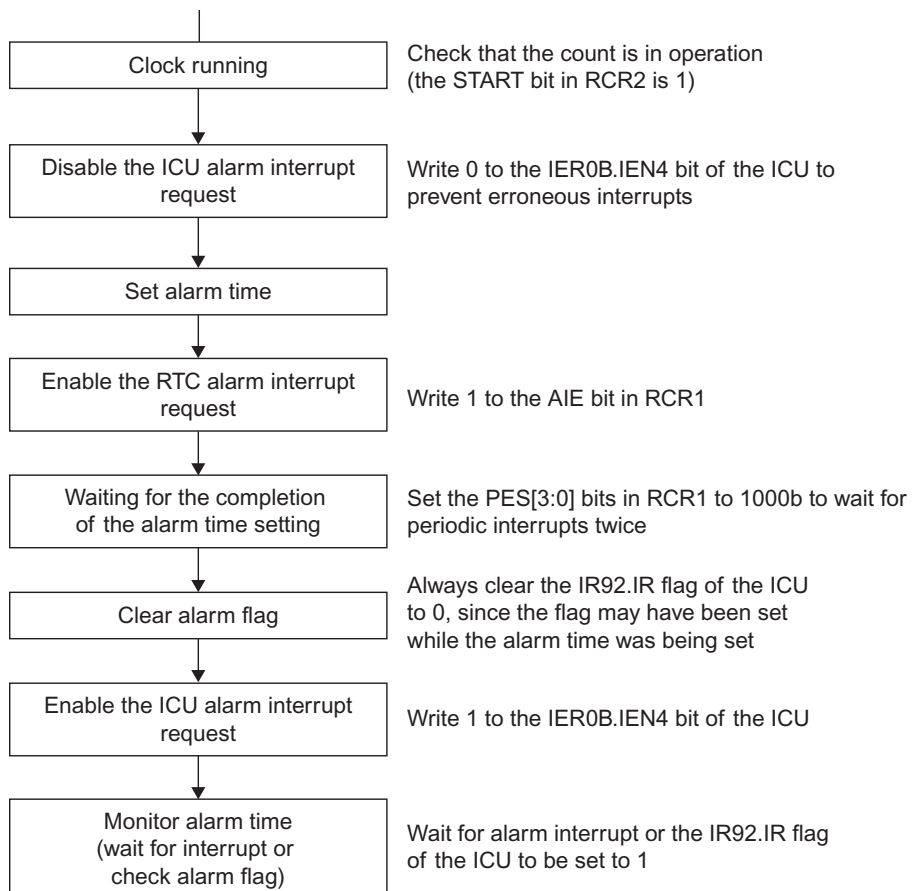


Figure 8.34 Using alarm function [1], page 1072.

enable bit to be set. We then clear the alarm interrupt request flag in the ICU in case it has been set while we were setting the alarm. Our last step before the interrupt is ready to be used is to enable the interrupt in the ICU. Now we can return to our normal program, and once the counters match the enabled alarm registers the interrupt will trigger.

8.6 ADVANCED EXAMPLES

Now that we have covered the more advanced concepts to using these features we will now go over examples implementing these concepts in code. The code will follow along with the examples in the earlier sections.

8.6.1 Using a Cascaded Timer with 16-Bit Time Constant Registers

In this example our program will once again cause the LEDs on the board to blink in a rotating sequence, but this time with a 1s delay between blinks. We will implement this delay using a 16-bit cascaded timer and its interrupt.

We will be using the LEDs in these examples so the first part of our code will be the definitions for the LED ports. After the LED definitions, we declare our first global variable, which will keep track of which LED is currently lit. Also we set a global variable we will use to indicate whether the timer interrupt has triggered or not. This is known as a flag, and such usage will be covered in more depth in a later chapter.

```
1. int Current_LED = 1;
2. int TimerInterruptFlag = 0;
```

Next we have to declare our functions.

```
1. void main(void);
2. void InitTimer(void);
3. void Rotate_LED(void);
```

Our main() function doesn't contain much code. First we enable the LEDs with a macro on line 3, and then we call the timer setup function on line 4. Nothing happens in our while(1) loop until the TimerInterruptFlag variable is set by the interrupt. Note that the interrupt will run upon the timer triggering, and there will be some time delay between when the variable is set and the program returns to the main function and the LED is rotated. Because of this, the timing of the LED rotation won't be exactly one second, but that is acceptable because LEDs aren't time critical and can be off by a few milliseconds without hurting anything. It is bad programming practice to include the function call in the interrupt itself because it requires more time overhead in the ISR along with the need to save and restore all processor registers.

```
1. void main(void)
2. {
3.     ENABLE_LEDS;
4.     InitTimer();
5.
6.     while(1)
7.     {
8.         if(TimerInterruptFlag)
9.         {
10.            LED_Rotate();
```

```
11.         TimerInterruptFlag = 0;
12.     }
13. }
14. }
```

The most important part of this example is our `InitTimer()` function. On lines 2 and 3 we enable and set a priority for the compare match A interrupt. We then enable timer unit 0 channels one and two (TMR0 and TMR1) on lines 5 and 6. On lines 8 and 9 the TMR1 count source is set to $PCLK/1024$, which gives us a count every $42.66 \mu s$. This is done by writing the appropriate values to the TCCR register. Then on line 11 we set the count source for TMR0 to TMR1, so now TMR0 counts once every time TMR1 overflows. Now we have a total of 2.8 s between timer overflows. In order to make the timer reset every 1 s we need to write the appropriate value to the TCORA(timer constant A) register and set the timer to reset on ever compare match A event. In Section 8.4.1 we calculated the needed value as 23405. We convert this into hex, separate it into a higher and lower byte, and then write the higher byte to TMR0 and the lower byte to TMR1 on lines 14 and 15. On line 12 we set the bit in the TCR that enables resets on compare match A event.

```
1. void InitTimer(void) {
2.     IEN(TMR0, CMIA0) = 1;
3.     IPR(TMR0, CMIA0) = 3;
4.
5.     MSTP(TMR0) = 0;    //Activate TMR0 unit
6.     MSTP(TMR1) = 0;    //Activate TMR1 unit
7.
8.     TMR1.TCCR.BIT.CSS = 1;
9.     TMR1.TCCR.BIT.CKS = 5;    //Count source is PCLK/1024 for TMR1
10.
11.    TMR0.TCCR.BIT.CSS = 3;
12.    TMR0.TCR.BIT.CCLR = 1;    //Count source is TMR1 for TMR0
13.
14.    TMR0.TCORA = 0x5B;    //Set TCORA to 23405
15.    TMR1.TCORA = 0x6D;    //(0x5B6D hex)
16.
17.    TMR0.TCR.BIT.CMIEA = 1;
18. }
```

The only remaining code in our main C file is our `LED_Rotate` function which we have already covered.

The last code we need to consider is our interrupt. For this example, unlike our basic example, we will be using the compare match A interrupt.

```
1. #pragma interrupt (Excep_TMR0_CMI0A(vect = VECT_TMR0_CMIA0))
2. void Excep_TMR0_CMI0A(void);
3.
4. //TMR0_CMI0A
5. void Excep_TMR0_CMI0A(void){LED_Rotate();}
```

If we look in the [1] RX63N User's Manual: Hardware we will see that the compare match A interrupt is at vector 170. This code defines an interrupt routine at that vector and places the LED_Rotate() function inside of it.

Now we have a program that once compiled and downloaded to the board will cause the LEDs to blink in a rotating sequence. The LEDs will advance at a rate of 1 per second as defined by our timer setup. This program demonstrates a timer function that makes use of a 16-bit cascaded timer with a compare match interrupt and reset on compare match event. This provides greater precision and a broader range of times to count.

8.6.2 Setting Up Pulse Output Mode to Control a Servo Motor

In this example we will use our calculations from Section 8.5.2 to write a program that will control our theoretical servo motor. We will be setting up a timer for the pulse output mode and then make two functions that will alter our timer setup such that the servo will rotate left or right.

Our program will only need the default iodef.h file, so we won't need any LED definitions or code for the graphical LCD.

We begin our main program by defining our function prototypes.

```
1. void main(void);
2. void InitTimer(void);
3. void Turn_Left(void);
4. void Turn_Right(void);
```

As you can see, once again we will only need a function to set up the timer initially, then we have two functions that when called will alter the timer setup to give us the needed pulse output to turn left or right.

```
1. void main(void){
2.     float i;
3.
4.     InitTimer();
5.
6.     while(1){
```

```
7.
8.     for(i = 0; i < 10000000; i++);
9.     Turn_Left();
10.    for(i = 0; i < 10000000; i++);
11.    Turn_Right();
12.    }
13. }
```

Also, once again, our main program is very simple. We merely create the variable *i* as a method to create a delay. Once we call the function to initialize our timer we go into our while(1) loop. In that loop we repeatedly pause, call the function to turn left, pause again, then call the function to turn right. This represents a very simple method of setting up motor control in C. The for() loops merely create an arbitrary delay between the duty cycle changes which is long enough that we can observe the difference. In a normal program we would not make a delay this way; this is merely for the sake of demonstration.

```
1. void InitTimer(void){
2.     MSTP(TMR0) = 0;    //Activate TMR0 unit
3.     MSTP(TMR1) = 0;    //Activate TMR1 unit
4.
5.
6.     TMR1.TCCR.BIT.CSS = 1;
7.     TMR1.TCCR.BIT.CKS = 2;    //Count source is PCLK/64 for TMR1
8.
9.     TMR0.TCCR.BIT.CSS = 3;
10.    //Count source is TMR1 for TMR0
11.
12.    TMR0.TCR.BIT.CCLR = 1;    //Timer resets at compare match A
13.
14.    TMR0.TCSR.BIT.OSA = 2;    //1-output at compare match A
15.    TMR0.TCSR.BIT.OSB = 1;    //0-output at compare match B
16.
17.    TMR0.TCORA = 0xFF;    //Frequency
18.    TMR1.TCORA = 0xFF;
19.
20.    TMR0.TCORB = 0x00;    //Duty cycle
21.    TMR1.TCORB = 0x00;
22.
23.    //Pulse outputs to TMR0, which is pin number 26 (Port 2.2)
24. }
```


Next in our code is our timer initialization function. This will set up the timer unit 0 channels one and two for the pulse output we desire. We will use the values we calculated earlier in Section 8.5.2. First we activate the timer channels on lines 2 and 3, because we cannot alter the registers in the unit until it is activated. Our next step is to set the timer 1 count source to the PCLK/64 prescaler on lines 6 and 7. On lines 9 and 10 we set the count source for timer 0 as timer 1. We now have a 16-bit cascaded timer so any settings made for clearing in the timer 0 TCR are effective for the entire cascaded unit. On line 12 we set the unit to reset on a compare match A event. We then set the timer output port to go to one output on compare match A events, and to zero on compare match B events. Remember that because the unit is now 16-bits, the time constant registers are now spanned into single 16-bit registers, with the upper byte in the timer 0 time constant register and the lower byte in the timer 1 time constant registers. Any value we want to write to the compare match registers must first be converted to hex, and then the upper and lower bytes written to the appropriate registers. Lines 17 and 18 set our time count for compare match A events, thus setting the period and therefore frequency of our waveform. Lines 20 and 21 set our initial duty cycle to zero, so at this point our timer is set up but we are not yet outputting a waveform because the wave is constantly held low by the compare match B event at time count 0x0000.

```

1. void Turn_Left(void) {
2.
3.     TMR0.TCORB = 0x0B;    //Duty cycle
4.     TMR1.TCORB = 0xB8;
5.
6. }
7.
8. void Turn_Right(void) {
9.
10.    TMR0.TCORB = 0x17;    //Duty cycle
11.    TMR1.TCORB = 0x70;
12.
13. }
```

Now all we need are our functions to turn left and right. These functions are very simple; they merely alter the values in the time constant B registers so that the duty cycle is either 1 ms or 2 ms. In the `Turn_Left()` function we write the value for 1 ms and in the `Turn_Right()` function we write the value for 2 ms.

After being compiled and downloaded to the board this program will initially not give an output, then begin to toggle the output between a 22 ms wave with 1 ms high pulse and 2 ms high pulse after an arbitrary delay created by the `for()` loops in our `while(1)` code.

8.6.3 Using the Real Time Clock's Alarm and Periodic Interrupts

This program example begins with the program we wrote in Section 8.3, so we already have a program that sets the real time clock, then reads it and displays the count. Initially the program will behave like our basic example: set the time, then begin counting, and display the time on the LCD. Then when the time reaches 12:00:15 the LEDs will be enabled by the alarm interrupt and begin to blink in a circular pattern at a rate determined by the periodic interrupt.

For review on the code we have already written refer to Section 8.3. In this section we will only focus on the parts we are adding to give the alarm and periodic interrupt functionality, which will not require the removal or modification of any old code.

```
1. void Set_Alarm(void);
2. void LED_Rotate(void);
```

Our first addition to the basic example is the addition of two new function prototypes. We are adding a function to set the alarm time and also we will be using our LED_Rotate function once again to make the LEDs rotate in a circular sequence.

```
1. void main(void){
2.     int i;
3.     ENABLE_LEDS;
4.     ALL_LEDS_OFF;
5.     DISABLE_LEDS;
6.     lcd_initialize();
7.     InitTimer();
8.     Set_Alarm();
9.     while(1){
10.         for(i = 0; i < 10000; i++);
11.         DisplayTime();
12.     }
13. }
```

As you can see, our main function is the same save for some additions. The first addition is lines 3 through 5; this code enables the LEDs and turns them off, then disables them once again. Initially our program doesn't use the LEDs, so this makes sure LEDs left lit from previously running programs are turned off and then disables them so they won't be lit until re-enabled by the alarm interrupt. The LCD is initialized using the lcd_initialize() function (line 6) defined in lcd.h. The other addition is the Set_Alarm() function call on line 8 after we initialize the real time clock.

```
1. void Set_Alarm(void){
2.
3.     //Check clock running
4.     if(RTC.RCR2.BIT.START == 1){
5.
6.         //Disable ICU alarm interrupt
7.         IEN(RTC,ALARM) = 0;
8.         IEN(RTC,PRD) = 1;
9.
10.        //Set alarm
11.        RTC.RSECAR.BYTE = 0x15;
12.        RTC.RMINAR.BYTE = 0x00;
13.        RTC.RHRAR.BYTE = 0x12;
14.        RTC.RWKAR.BYTE = 0x02;
15.        RTC.RDAYAR.BYTE = 0x21;
16.        RTC.RMONAR.BYTE = 0x10;
17.        RTC.RYRAR.WORD = 0x15;
18.
19.        RTC.RSECAR.BIT.ENB = 0x01;
20.        RTC.RMINAR.BIT.ENB = 0x01;
21.        RTC.RHRAR.BIT.ENB = 0x01;
22.        RTC.RWKAR.BIT.ENB = 0x01;
23.        RTC.RDAYAR.BIT.ENB = 0x01;
24.        RTC.RMONAR.BIT.ENB = 0x01;
25.        RTC.RYRAREN.BIT.ENB = 0x01;
26.
27.        //Enable RTC alarm
28.        RTC.RCR1.BIT.AIE = 1
29.        while(RTC.RCR1.BIT.AIE == 0)    //Wait for it to be written
                                         before continuing
30.            ;
31.        //Use periodic interrupt to wait 1/64 second
32.        IR(RTC,PRD) = 0;
33.        RTC.RCR1.BIT.PES = 0x02;    //Set periodic interrupt to 1/64s
34.        while(IR(RTC,PRD) == 0)    //Wait for flag to be set
35.            ;
36.        //Clear alarm flag
37.        IR(RTC,ALARM) = 0;
38.
39.        //Enable ICU alarm interrupt
```

```
40.         IEN(RTC,ALARM) = 1;
41.         IPR(RTC,ALARM) = 3;
42.         }
43.         else {
44.             //error handling code
45.         }
46.
47.         //Set up Periodic interrupt to trigger ISR every 0.5s
48.         RTC.RCR1.BIT.PES = 0x05;//Set periodic interrupt to 0.5s
49.         IR(RTC,PRD) = 0;    //Clear periodic interrupt flag
50.         IEN(RTC,PRD) = 1;    //Enable periodic interrupt in ICU
51.         IPR(RTC,PRD) = 4;    //Set priority level
52.     }
```

Our most important addition to the basic program is our `Set_Alarm()` function. The code in this function follows the flowchart in Figure 8.22. First on line 4 we have an if statement that checks if the real time clock is counting, this is in case we call the function and have forgotten to initialize the real time clock or somehow the clock has ceased to count. On line 43 we have an else statement where error handling code would be put, but we will not worry about what to put there yet. The next step is to disable the alarm interrupt in the ICU; this ensures we aren't interrupted by the alarm while we are setting it. We also disable the periodic interrupt in the ICU since we are using it to set the alarm but do not want the ISR routine interrupting our configuration code. This is done on line 7.

With the periodic interrupt disabled, we can set the alarm registers for the time we want the alarm interrupt to occur; this is handled on lines 11 through 25. In this example we utilize all of the alarm registers and set it to occur fifteen seconds after the initial time set by the clock. Take note on lines 19–25 that we set the enable bit for each of the registers, otherwise they won't be compared. Also take note that because the year alarm register encompasses an entire word and doesn't have an extra bit set aside, there is a separate register we must set a 1 to in order to enable it, the `RYRAREN` register on line 25. After that we set the alarm enable bit in the `RCR1` register on line 28. On line 29 we get stuck in a while loop until the bit gets set, because the `RCR1` register only gets updated at the rate of the real time clocks internal clock. On line 32 through 34 we clear the periodic interrupt request flag and then set the periodic interrupt for $\frac{1}{64}$ of a second.

Then we have a while loop that will hold the program until the periodic interrupt sets the request flag again. After all of this we can be assured that the alarm interrupt enable bit has been set and we enable and set a priority for the alarm interrupt on lines 40 and 41. That is all of the code we need to set our alarm, but in this program example we are also using the periodic interrupt, so we include code to set that up for the rest of our program as well. On line 48 we set the periodic interrupt to occur at 0.5 second intervals. Then on lines 49 through 51 we clear the interrupt flag, and then enable it and set a priority level.

Also before the next snippet of code make sure to insert our LED_Rotate() function from previous examples. We won't cover it since we aren't covering any older code.

```

1. //RTC_PRD
2. #pragma interrupt (Excep_RTC_PRD(vect = VECT_RTC_PRD))
3. void Excep_RTC_PRD(void);
4.
5. //RTC_ALARM
6. #pragma interrupt (Excep_RTC_ALM(vect = VECT_RTC_ALARM))
7. void Excep_RTC_ALM(void);
8.
9. //RTC_PRD
10. void Excep_RTC_PRD(void){LED_Rotate();}
11.
12. //RTC_ALM
13. void Excep_RTC_ALM(void){ENABLE_LEDS;}

```

With any program using interrupt routines it is necessary to define where our interrupt is. On lines 2, 3, 6, and 7 we define the name of our interrupt service routines and their vectors, which are given in the [1] *RX63N User's Manual: Hardware* in Section 15.3. Then on lines 10 and 13 are our service routine functions. On line 10 is our periodic interrupt routine which will call our LED_Rotate() function, so once the LEDs are enabled they will blink in a rotating sequence at a rate of one LED per 0.5 s. On line 13 is our alarm interrupt function that contains our macro for enabling the LEDs, so no LEDs will light up from the periodic interrupts routine until the alarm interrupt enables them. Note once again this code includes a function call in an ISR for simplicity and illustration purposes, however, in an actual program this would be bad practice and should be avoided.

Once this program is built and downloaded to the board, at first it will seem the same as our basic example where it begins to display the time starting with when we set the clock to. Then after fifteen seconds the alarm interrupt will call and enable the LEDs. Afterwards the LEDs will blink in a circular sequence at a rate of one per 0.5 s for the duration of the programs running time.

8.7 RECAP

In this chapter we covered the capabilities of the 8-bit timer peripherals on the Renesas RX63N. We started with a brief overview of the timer concepts. Then we covered how to cascade two 8-bit timers into one 16-bit unit. We also covered pulse output operation that allows us to generate a steady frequency square wave whose duty cycle and frequency are maintained by the timer unit. Additionally we covered the Real Time Clock feature, which

allows the RX63N to easily and accurately track the time and date. In the advanced concepts section we showed how to take more control of a cascaded timer by using the 16-bit time constant register. We then went over how to calculate and precisely control frequency in pulse output mode, and gave an example of controlling a servo motor. For our final example we showed how to set up and use the Real Time Clock's alarm interrupt.

8.8 REFERENCES

[1] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013.

8.9 EXERCISES

1. What registers would you use when setting up the 8-bit timer unit 0 in cascaded mode?
2. Briefly describe three events that can happen when a compare match event occurs.
3. Explain the algorithm used and describe the purpose of the steps used when initially setting the RTC.
4. Give sample code that will set up a basic 1 kHz square wave with a 40% duty cycle.
5. Assume you have set up a 16-bit cascaded timer and now you want its interrupt to occur every 3 seconds. Name the registers you would write to, and the values you would write to them.
6. Assume you have set up a 16-bit cascaded timer for pulse output mode, what registers and what values would you write to them to get an output that is high for 3 ms and low for 18 ms?
7. Name two advantages to using the time constant registers.
8. Give at least one advantage to using the periodic interrupt over setting up an 8-bit timer in order to get a 1 s recurring interrupt.
9. Besides triggering an ISR at the exact time specified by the real time clock alarm registers, what is another action the alarm interrupt performs?

Using Interrupts with Peripherals

9.1 LEARNING OBJECTIVES

No doubt so far in this book you have seen interrupts mentioned several times. This book is only meant to touch on and explain concepts having to do with embedded systems and the peripherals of the RX63N, yet in the case of most peripherals covered so far it has been impossible to give even a brief overview without using interrupts in some way. In this chapter we will be covering more thoroughly exactly what interrupts are and how they work on a microcontroller. Using interrupts in an embedded application gives a greatly increased capacity for efficiency over a purely linear program.

In the basic concepts section we will give an in depth look at how an interrupt is triggered between a peripheral and the Interrupt Control Unit, and explain the process of setting up an interrupt and what is going on when we do so. In the advanced concepts section we will cover why keeping our code minimal in interrupts is important to prevent bugs. Also we will cover handling the passage of data from interrupts. After a brief overview of state machine programming design, we will pull all of this together by giving an example of a state machine whose state is controlled via interrupts.

9.2 BASIC CONCEPTS

Basic programs will read and execute in order from beginning to end in a mostly linear fashion save for control logic such as `if()` and `while()` loops. The problem with this is embedded systems are meant to interface with the real world, which does not often occur in such a predictable linear manner. Almost all embedded systems will depend on an external event and may even need to critically execute some given code immediately at that event, and we need a means to signal this in the program, stop what we are doing, handle another task, then return to the previous program execution. But how do we do that?

9.2.1 Using Interrupts for Tasks versus Other Methods

One method of gathering outside data into a program is via polling. For example, say you are getting ready for work in the morning and you want to brew a pot of coffee. The coffee

takes at least five minutes to boil and then steep. If we were to act in a manner similar to polling we would set the water in the pot then watch (poll) it until it is boiling. That is five minutes of time that we are staring at a pot and not getting other things done that we could potentially be doing. Instead, we can set a kettle and then go about our routine and don't worry about 'processing' the coffee until the kettle whistles to signal the water is boiling. Once we are notified via this signal we 'interrupt' our routine to pour a cup and then return to what we were doing. There are also alternative methods of occasionally stepping back into the room to check if the water is boiling, which is similar to polling methods used for keypads. In more complex situations you will need to worry about multiple interrupts occurring; e.g., the dog wants out, the phone rings, someone knocks at the door. In a situation like this you will need some way to handle scheduling the interrupts and to make sure some lower priority interrupts don't interrupt more critical code that needs to execute faster. In these situations it is handy to use a Real Time Operating System, which is covered in a later chapter. For now we will start with the simple single interrupt method.

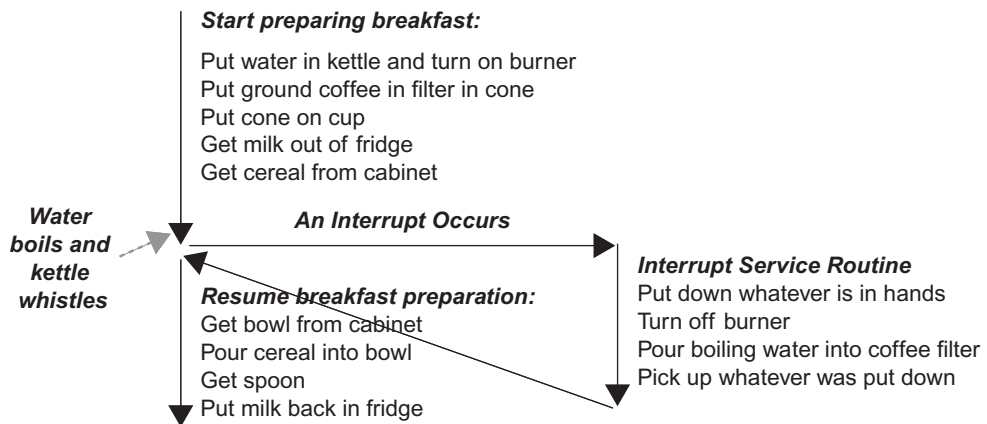


Figure 9.1 Preparing coffee flowchart.

9.3 INTERRUPTS

One good example of how interrupts are used is a robot with an IR sensor. Consider how the robot uses the IR sensor to detect and avoid obstacles. The robot continuously polls for a signal from the IR sensor, which tells the robot when an obstacle is close. The robot may be running lots of tasks, so if it gets stuck in a long process, the polling process is halted until the long task is executed. If the signal from the IR sensor occurs while the robot is processing, the robot will bump into the obstacle. Interrupts are an alternative to polling in these situations.

An interrupt is an external or internal event that takes the Program Counter (PC) from the current point of the code to a subroutine in the code called the Interrupt Service Routine (ISR) which has a higher priority of execution. The address to the ISRs is listed out in the Interrupt Vector Table (IVT) which is defined in each processor memory. Whenever an in-

errupt occurs, the processor goes to the IVT and determines the location of the ISR; it then executes the subroutine present at that address. For example, consider the above situation of polling the signal from the sensor for detecting the obstacle. Instead of polling the signal, we can setup an interrupt which runs a subroutine whenever there is a change in the logic level. When a processor is running a long task we do not need to worry that we would lose the signal from the sensor as the interrupt is set up. The subroutine will be the ISR for the interrupt, and when the processor executes the ISR it means that an obstacle has occurred. So the function of the subroutine should be to avoid the obstacle, either change the path or stop the robot before bumping into the obstacle. The ISRs should contain very little code in them.

There are two types of interrupts: Maskable and Non-Maskable. Non-Maskable interrupts (NMI) are interrupts that cannot be ignored by the processor. When a non-maskable interrupt occurs, the processor should stop whatever it is executing and attend it first. The non-maskable interrupts are usually used for non-recoverable errors and serious hardware errors that need immediate attention. One example of a non-maskable interrupt is the reset pin.

The Interrupt Control Unit (ICU) receives signals from peripherals such as timers, ADCs, and external pins of the microcontroller. The interrupt sources available for the RX63N/RX631 Group are listed in Table 9.1. The block diagram of the ICU is shown Figure 9.2. This chapter deals with the interrupts generated using software and the external pins of the microcontrollers.

The following registers are used to setup and read the status of the interrupts:

- Interrupt Request Register n (IR n)
- Interrupt Request Enable Register m (IER m)
- Interrupt Source Priority Register n (IPR n)
- Fast Interrupt Set Register (FIR)
- Software Interrupt Activation Register (SWINTR)
- IRQ Control Register i (IRQCR i)
- Non-Maskable Interrupt Status Register (NMISR)
- Non-Maskable Interrupt Enable Register (NMIER)
- Non-Maskable Interrupt Status Clear Register (NMICLR)
- NMI Pin Interrupt Control Register (NMICR)

Interrupt Request Register n (IR n) (n = interrupt vector number)

The least significant bit of the interrupt request register indicates the status of a particular interrupt source. The value n of the interrupt request register corresponds to different interrupt sources in the vector table. For edge- detected sources, only 0 can be written to this bit, which clears the flag, and writing 1 to the bit is prohibited. Writing is not possible if the source is level- detected. For the interrupt sources and corresponding interrupt vector numbers, refer to the Interrupt Vector Table of the hardware manual ([1] page 361, Table 15.3).

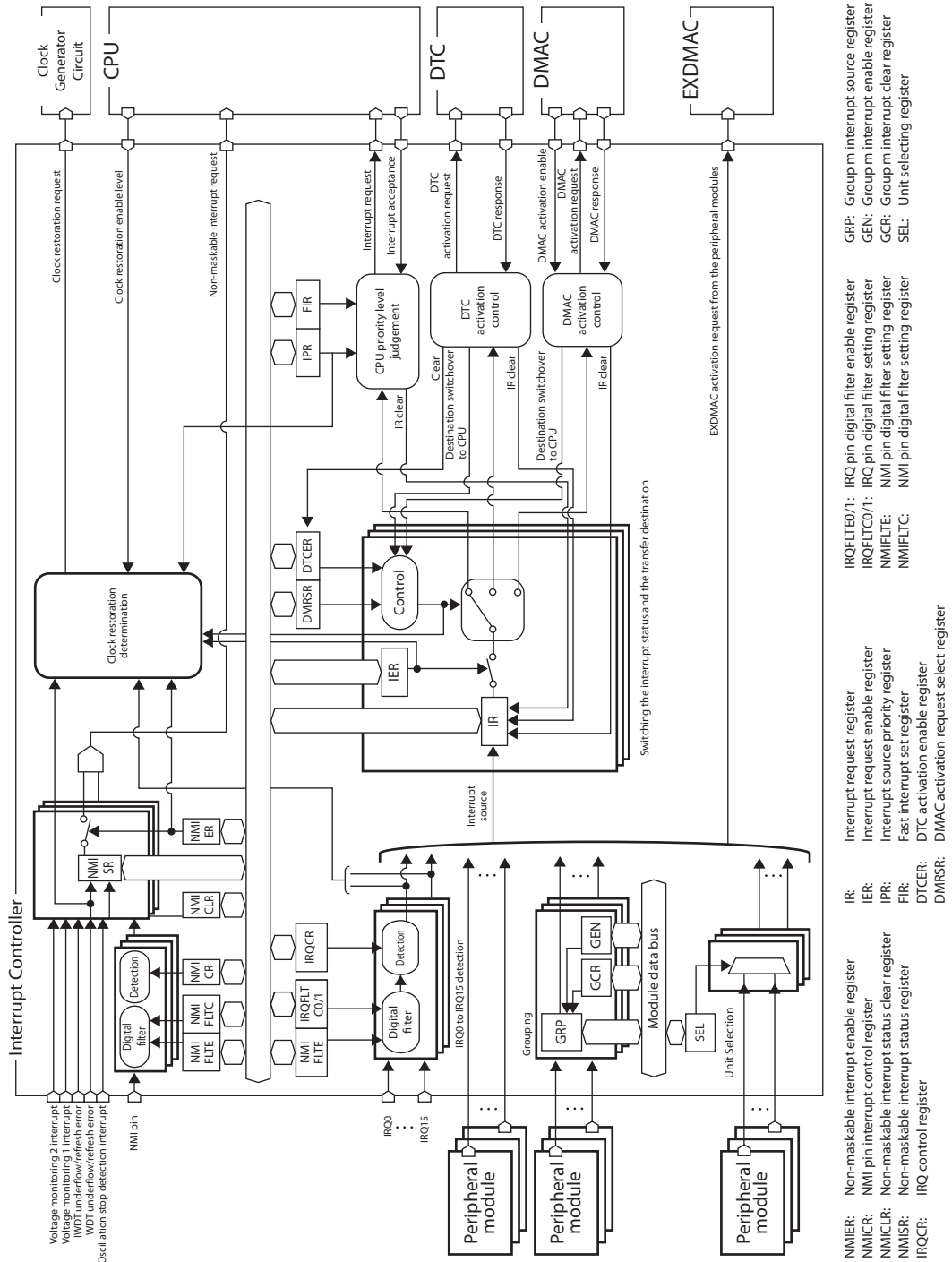


Figure 9.2 Block diagram of Interrupt Control Unit [1], Figure 15.1, page 335.

TABLE 9.1 Specifications of ICU [1], Table 15.1, page 334.

ITEM		DESCRIPTION
Interrupts	Peripheral function interrupts	<ul style="list-style-type: none"> ■ Interrupts from peripheral modules ■ Number of sources: 146 ■ Interrupt detection: Edge detection/level detection Edge detection or level detection is determined for each source of connected peripheral modules.
	External pin interrupts	<ul style="list-style-type: none"> ■ Interrupts from pins IRQ15 to IRQ0 ■ Number of sources: 16 ■ Interrupt detection: Low level, falling edge, rising edge, both rising and falling edges One of these detection methods can be set for each source.
	Software interrupt	<ul style="list-style-type: none"> ■ Interrupt generated by writing to a register ■ One interrupt source
	Interrupt priority	Specified by registers.
	Fast interrupt function	Faster interrupt processing of the CPU can be set only for a single interrupt source.
	DTC/DMACA control	<ul style="list-style-type: none"> ■ The DTC and DMACA can be activated by interrupt sources. ■ Number of DTC activating sources: 102 (85 peripheral function interrupts + 16 external pin interrupts + 1 software interrupt) ■ Number of DMACA activating sources: 45(41 peripheral function interrupts + 4 external pin interrupts)
Non-maskable interrupts	NMI pin interrupts	<ul style="list-style-type: none"> ■ Interrupt from the NMI pin ■ Interrupt detection: Falling edge/rising edge
	Power-voltage falling detection	Interrupt during power-voltage fall detection
	Oscillation stop detection	Interrupt during oscillation stop detection
Return from power-down modes		<ul style="list-style-type: none"> ■ Sleep mode: Return is initiated by non-maskable interrupts or any other interrupt source. ■ All-module clock stop mode: Return is initiated by non-maskable interrupts, IRQ15 to IRQ0 interrupts, WDT interrupts, timer interrupts, USB resume interrupts, or RTC alarm interrupts. ■ Software standby mode: Return is initiated by non-maskable interrupts, IRQ15 to IRQ0 interrupts, USB resume interrupts, or RTC alarm interrupts.

TABLE 9.2 Bit Description of Interrupt Request Register [1], page 336.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	IR	Interrupt status flag	0: No interrupt request is generated	R/W*
b7 to b1	—	Reserved	These bits are read as 0. The write value should always be 0.	R/W

Note: *For edge-detected sources, only 0 can be written to this bit, which clears the flag, and writing 1 to the bit is prohibited. Writing is not possible if the source is level-detected.

IR Flag (Interrupt Status Flag)

When a particular interrupt request is generated, the corresponding vector number IR flag will be set to 1. The interrupt request detection can be set to edge detection or level detection for each interrupt by the setting of the IRQMD[1:0] bits in IRQCRi ($i = 0$ to 15).

Interrupt Request Enable Register m (IER m) ($m = 02$ to 1Fh):

Address: 0008 7202h to 0008 721Fh

	b7	b6	b5	b4	b3	b2	b1	b0
	IEN7	IEN6	IEN5	IEN4	IEN3	IEN2	IEN1	IEN0
Value after reset:	0	0	0	0	0	0	0	0

Figure 9.3 Interrupt Request Enable Register [1], page 337.

The Interrupt Request Enable Register (IER m) is used to enable and disable the interrupt requests to the CPU.

IEN j bits (Interrupt Request Enable) ($j = 0$ to 7): When the IEN j bit is set to 1, the CPU accepts that particular interrupt request and handles the interrupt. When this bit is set to 0, the CPU ignores that particular request. The m and j values in IER m and IEN j are for enabling and disabling particular interrupts that can be referenced in the Interrupt Vector Table in the hardware manual ([1] page 361, Table 15.3).

EXAMPLE

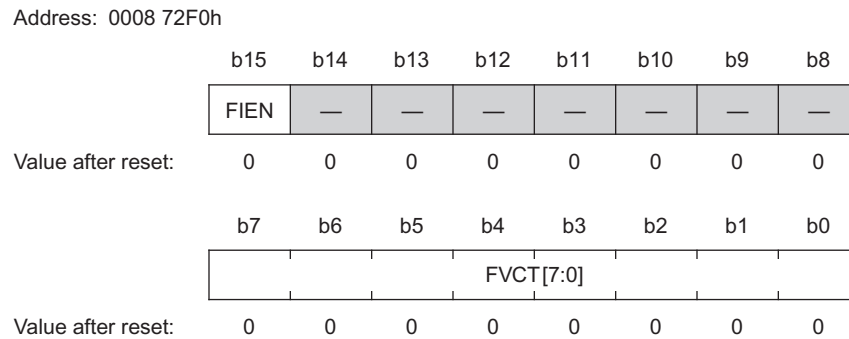
External pin interrupt IRQ0 is referred using the IER register as IER08.IEN0.
The timer1 overflow interrupt OVI1 is referred using the IER register as IER16.IEN

Interrupt Priority Register m (IPR m) ($m = 000$ to 253)

The Interrupt Priority Register is used to set the priority for each interrupt source. The interrupt source should be disabled while setting the priority level. The possible priority levels are listed in Table 9.3. Each interrupt source has its own reserved IPR[3:0] bits. For the IPR[3:0] bits of each interrupt source, refer to the Interrupt Vector Table in the hardware manual ([1] page 361, Table 15.3). The interrupt sources with a higher priority than the priority level set by IPL[3:0] bits in PSW are accepted. If the interrupt priority level of two interrupts are the same and are requested at the same time, then the interrupt source with the smallest vector number will have the higher priority. These bits should be written while an interrupt request is disabled (IER m .IEN j bit = 0).

TABLE 9.3 Bit Description of Interrupt Priority Register [1], page 338.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	IPR[3:0]	Interrupt Priority Level	b3 b0	R/W
		Select	0 0 0 0: Level 0 (interrupt disabled)	R/W
			0 0 0 1: Level 1	
			0 0 1 0: Level 2	
			:	
1 1 1 1: Level 15 (highest)				
b7 to b4	—	Reserved	These bits are read as 0. The write value should always be 0.	R/W

Fast Interrupt Set Register (FIR)**Figure 9.4** Fast Interrupt Register [1], page 339.

This FIR register is used to set a particular interrupt source as a fast interrupt. The fast interrupt function cannot be used to trigger the peripherals like DTC, DMAC, etc. The fast interrupt function should not be set up for reserved interrupts in the interrupt vector table.

FVCT[7:0]: These bits are used to mention the interrupt vector number of the interrupt source, which should function as a fast interrupt.

FIEN: This bit should be set to 1 for the interrupt source mentioned in FVCT[7:0] to function as a fast interrupt.

Software Interrupt Activation Register (SWINTR)**TABLE 9.4** Bit Description of SWINTR [1], page 340.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	SWINT	Software Interrupt	This bit is read as 0.	R/W*
		Activation	Writing 1 issues a software interrupt request.	
			Writing 0 to this bit has no effect.	
b7 to b1	—	Reserved	These bits are read as 0. The write value should always be 0.	R/W
Note: Only 1 can be written.				

The SWINTR register is used to create a software interrupt request.

When the SWINT bit is set to 1, the interrupt occurs in vector 27 and the interrupt request for vector 27 is also set to 1. If DTC Activation Enable Register 27 (DTCER27) is set to 0, then a CPU interrupt is generated. If it is cleared to 0, then a DTC activation request is generated.

IRQ Control Register i (IRQCRI) (i = 0 to 15)

IRQ Control Register i (IRQCRI) (i = 0 to 15)

Address: 0008 7500h to 0008 750Fh

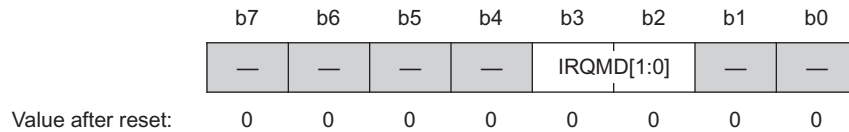


Figure 9.5 IRQ Control Register i (IRQCRI) [1], page 342.

The (IRQCRI) register is used to select the type of external interrupts, which are either edge detection or level detection. The IRQCRI.IRQMD[1:0] bits are used to set up the type of external interrupts. These settings should only be done when the interrupt is disabled and after the interrupt is set up. The interrupt request bit for the particular external interrupt should be cleared and the interrupt enable bit should be set to 1.

IRQMD[1:0]: The possible values for the IRQMD[1:0] bits and the corresponding setting for the interrupts are shown in Table 9.5.

TABLE 9.5 Bit Description for IRQ Control Register [1], page 342.

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b1, b0	—	Reserved	These bits are read as 0. The write value should always be 0.	R/W
b3, b2	IRQMD[1:0]	IRQ Detection Sense Select	b3 b2	
			0 0: Low level	
			0 1: Falling edge	
			1 0: Rising edge	
		1 1: Rising and falling edges		
b7 to b4	—	Reserved	These bits are read as 0. The write value should always be 0.	R/W

Non-Maskable Interrupt Enable Register (NMIER)

The Non-Maskable Interrupt Enable Register (NMIER) is an 8-bit register that is used to enable or disable the NMI interrupts. The NMIER has control over three NMI interrupts: oscillation stop detection, power-voltage detection, WDT refresh, IWDT refresh, and NMI pin interrupts.

Address(es): 0008 7581h

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	LVD2EN	LVD1EN	IWDTEN	WDTEN	OSTEN	NMIEN
Value after reset:	0	0	0	0	0	0	0	0

Figure 9.6 Non-Maskable Interrupt Enable Register (NMIER) [1], Page 349.

NMIEN (NMI pin interrupt enable) bit: When this bit is set to 1, the interrupt request from the NMI pin will be sent to the CPU; otherwise the request will be ignored.

OSTEN (Oscillation stop detection interrupt enable) bit: When this bit is set to 1, the oscillation stop detection interrupt request will be sent to the CPU; otherwise the request will be ignored.

LVD1EN (Voltage-monitoring 1 interrupt enable) bit: When this bit is set to 1, the power voltage falling detection interrupt 1 request will be sent to the CPU; otherwise the request will be ignored.

LVD2EN (Voltage-monitoring 2 interrupt enable) bit: When this bit is set to 1, the power voltage falling detection interrupt request will be sent to the CPU; otherwise the request will be ignored.

WDTEN Bit (WDT Underflow/Refresh Error Enable) bit: When this bit is set to 1, the power voltage falling detection interrupt request will be sent to the CPU; otherwise the request will be ignored.

IWDTEN Bit (IWDT Underflow/Refresh Error Enable) bit: When this bit is set to 1, the power voltage falling detection interrupt request will be sent to the CPU; otherwise the request will be ignored.

NOTE:

For all of the bits described in Figure 9.6, writing “1” is accepted only once—subsequently writing 0 or 1 to these bits is disabled. In other words, we cannot disable the NMI interrupts after enabling them.

Non-Maskable Interrupt Status Register (NMISR)

The NMISR register is a read only 8-bit register. This register is used to read the status of three non-maskable interrupts: oscillation stop detection interrupt (OSTST), power-voltage falling detection interrupt (LVDST), and non-maskable pin interrupt (NMIST).

Address: 0008 7580h

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	LVD2ST	LVD1ST	IWDTST	WDTST	OSTST	NMIST
Value after reset:	0	0	0	0	0	0	0	0

Figure 9.7 Non-Maskable Interrupt Status Register (NMISR) [1], page 347.

Figure 9.7 shows the following about the Non-Maskable Interrupt Status Register:

- **NMIST (NMI status flag) bit:** This bit is set to 1 when the edge specified by the NMIMD bit in the NMICR occurs at the NMI pin. When this bit is set to 1, the interrupt request from the NMI pin will be generated to the CPU. This bit is cleared to 0 only when the NMICLR bit in NMICLR register is set to 1.
- **OSTST (Oscillation stop detection status flag) bit:** This bit is set to 1 when the oscillation stop detection interrupt is generated and is cleared to 0, and when the OSTCLR bit in NMICLR register is set to 1.
- **LVD1ST (Power- voltage falling detection status flag) bit:** This flag indicates the request for voltage-monitoring 1 interrupt. This bit is set to 1 when the power-voltage falling detection interrupt 1 is generated and is cleared to 0, and when the interrupt is cleared by the interrupt source.
- **LVD2ST (Power- voltage falling detection status flag) bit:** This flag indicates the request for voltage-monitoring 2 interrupt. This bit is set to 1 when the power-voltage falling detection interrupt 2 is generated and is cleared to 0, and when the interrupt is cleared by the interrupt source.
- **WDTST Flag (WDT Underflow/Refresh Error Status bit):** This flag indicates the WDT underflow/refresh error interrupt request. The WDTST flag is read-only. This bit is set to 1 when the WDT underflow/refresh error interrupt is generated and is cleared to 0 when 1 is written to the NMICLR.WDTCLR bit.
- **IWDTST Flag (WDT Underflow/Refresh Error Status bit):** This flag indicates the IWDT underflow/refresh error interrupt request. The IWDTST flag is read-only. This bit is set to 1 when the IWDT underflow/refresh error interrupt is generated and is cleared to 0 when 1 is written to the NMICLR.IWDTCLR bit.

Non-Maskable Interrupt Status Clear Register (NMICLR)

The Non-Maskable Interrupt Status Clear Register (NMICLR) is an 8-bit register that is used to clear the status flags of the NMI interrupts. The status flags of NMI pin and the oscillation stop detection interrupts can be cleared by this register.

Address: 0008 7582h

	b7	b6	b5	b4	b3	b2	b1	b0
	—	—	LVD2CLR	LVD1CLR	IWDTCLR	WDTCLR	OSTCLR	NMICLR
Value after reset:	0	0	0	0	0	0	0	0

Figure 9.8 Non-Maskable Interrupt Status Clear Register (NMICLR) [1], page 350.

Figure 9.8 shows the following:

- NMICLR (NMI clear) bit: When this bit is set to 1, the NMIST flag in the NMISR register will be cleared to 0.
- OSTCLR (OST clear) bit: When this bit is set to 1, the OSTST flag in the NMISR register will be cleared to 0.
- WDTCLR (WDT Clear) bit: When this bit is set to 1, the WDTST flag in the NMISR register will be cleared to 0.
- IWDTCLR (IWDT Clear) bit: When this bit is set to 1, the IWDTST flag in the NMISR register will be cleared to 0.
- LVD1CLR (LVD1 Clear) bit: When this bit is set to 1, the LVD1ST flag in the NMISR register will be cleared to 0.
- LVD2CLR (LVD2 Clear) bit: When this bit is set to 1, the LVD2ST flag in the NMISR register will be cleared to 0.

NOTE:

We do not need to clear the NMICLR and the OSTCLR bits to 0. As soon as the corresponding status flag becomes 0, the NMICLR and the OSTCLR bits are also cleared to 0.

NMI Pin Interrupt Control Register (NMICR)

The NMI Pin Interrupt Control Register (NMICR) is an 8-bit register in which only 1 bit is used to set the type of edge detection of the interrupt to either the falling edge or the rising edge. The edge detection should be set before enabling the NMI interrupt.

Figure 9.9 illustrates how to address the NMI Pin Interrupt Control Register (NMICR). When this bit is set to 1, the interrupt request is generated on the rising edge input to the NMI pin. When this bit is cleared to 0, the interrupt request is generated on the falling edge input to the NMI pin.

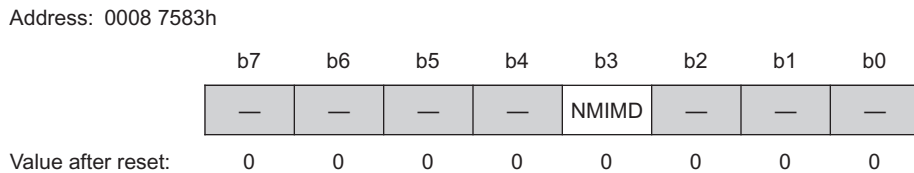


Figure 9.9 NMI Pin Interrupt Control Register (NMICR) [1], page 351.

9.3.1 Interrupt Vector Table

The Interrupt Vector Table (IVT) in the RX63N microcontroller has 256 interrupts, with each interrupt source occupying 4 bytes in the table. In total, the size of IVT is 1024 bytes (4 bytes \times 256 sources). Each address space specifies the location of the interrupt service routine for the interrupt. When the CPU accepts an interrupt, it acquires the 4 byte address from the IVT and executes the code specified at that particular interrupt service routine. Refer to Table 15.3 located in the hardware manual of the RX63N microcontroller for the vector address for the interrupt sources.

9.3.2 Interrupt Operation

The interrupt control unit (ICU) performs the following operations while setting up the interrupts:

- Detecting the interrupts.
- Enabling and disabling the interrupts.
- Selecting the interrupt destination.
- Determining the priority.

The ICU first detects the interrupts. Detecting the interrupt requests is by way of either edge detection of the interrupt signal (edge triggered interrupts), or level detection of the interrupt signal (level triggered interrupts).

Edge Detection

The interrupt status flag is set to 1 when the microcontroller responds to the interrupt request, and the bit is cleared to 0 when the particular module or I/O pin interrupt request is accepted. Figure 9.10 shows how the interrupt status flag operates for edge triggered interrupts. The IR flag for the particular interrupt is set to 1 as soon as the interrupt signal goes high. If the interrupt is a CPU interrupt, the IR flag is cleared to 0 when the interrupt is accepted by the CPU. If the interrupt is a DMACA or DTC activation interrupt, the IR flag is cleared to 0 once the transfer by the DTC or DMACA has been completed.

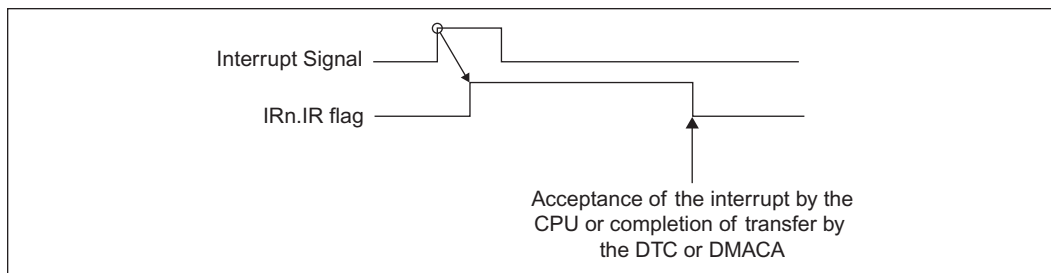


Figure 9.10 Interrupt status flag for edge triggered interrupts [1], Figure 15.6, page 372.

If the source of the interrupt generation is disabled and after the interrupt status flag goes high, the IR flag remains in the high state. For example after the IR flag for DTC activation interrupt goes high, if the DTC is disabled, then the IR flag of the DTC activation interrupt remains in the high state until the DTC is enabled and the transfer is done. Figure 9.11 shows how the IR flag operates when the source of the interrupt is disabled.

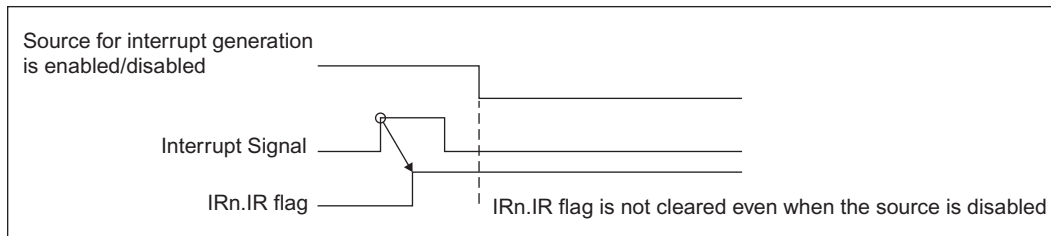


Figure 9.11 Interrupt status flag when the source of the interrupt is disabled [1], Figure 15.7, page 372.

Level Detection

The interrupt status flag remains set to 1 when the interrupt is requested and being sent to the destination. The bit is cleared to 0 when the source of the interrupt request is cleared. Figure 9.11 shows the operation of the IR flag for level-triggered interrupts. As shown in Figure 9.12, the IR flag remains in the high state until the source of the device requesting the interrupt is cleared.

The edge detection and the level detection of the interrupts can be selected using the $IRQCRi.IRQMD[1:0]$ bits ($i = 0$ to 15). When the level detection is selected for the interrupt requests, the interrupt status flag should not be cleared to 0.

After detecting the interrupts, the ICU checks to see if the interrupt is disabled or enabled. Enabling and disabling the interrupts can be performed by using the bits in $IERN$ register. Refer to Table 11.4 of the hardware manual for information about the corresponding bit for each interrupt. If the interrupt is disabled, the ICU ignores the interrupt. If the interrupt is enabled, the ICU checks for the destination of the interrupt. The possible desti-

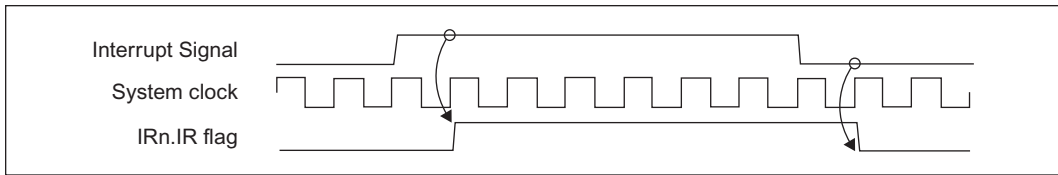


Figure 9.12 Interrupt status flag for edge triggered interrupts [1], Figure 15.8, page 373.

nations for the interrupt would be the CPU, or DTC or DMACA activation. The destination for any interrupt is the CPU by default. The destination of the interrupt can be modified using the bits in the DTCER and DMRCR registers. For the interrupt vector number of a particular interrupt, refer to Table 1.3 of the hardware manual ([1] page 360).

If two or more interrupts occur at the same time, the ICU fetches the interrupt requests based upon the interrupt priority set up by the IPRn register. An interrupt selected as a fast interrupt will have the highest priority. After that, the highest value in the IPR[3:0] bits of IPRm will have the next highest priority. If interrupts with same priority level occur at the same time, the interrupt source with smallest vector number will have higher priority.

9.3.3 Setting Up an Interrupt for a Peripheral

All interrupts in the RX63N are handled via the Interrupt Control Unit (ICU). When setting up an interrupt there are two places where we make configuration settings, in the peripheral itself and in the ICU. When an interrupt occurs a signal is sent from the peripheral to the ICU, the ICU then processes the request and sends the interrupts to the CPU as needed.

Setting Up an Interrupt

The steps to set up an interrupt for a peripheral are as follows:

1. The peripheral or port pin must be enabled and configured.
2. Set an interrupt priority for the interrupt source (IPR() macro) to a value greater than 0 (0 = disabled).
3. Enable the interrupt in the peripheral (local enable bit).
4. Enable the interrupt in the ICU (IEN macro).

NOTE:

The procedure is slightly different for setting an I/O pin as an interrupt; refer to section *Registers Set in the ICU for an Interrupt* under the definition for the IRQCRi register.)

As can be seen, first off the peripheral must be enabled and configured; it can't signal an interrupt if it isn't on or configured to operate. The next steps don't necessarily need to be

handled in the given order. A priority must be set for the interrupt in the ICU, you may have noticed in previous chapters we have done this using the `IPR()` macro. Using the provided macros from Renesas simplifies the process by only having us need to know the name of the peripheral and its interrupt in order to set its priority and enable it in the ICU. These can be found, along with the vector numbers for the interrupts, in the RX63N hardware manual or in Appendix A: Interrupt Vector Table of this text. We must also enable the interrupt in the peripheral itself. Where this is done is dependent on the peripheral, and could vary from setting an enable bit in a control register to a variety of settings in a separate register specifically for the interrupt. The interrupt must also be enabled in the ICU itself in order for the ICU to send it to the CPU.

Besides enabling the registers for the interrupt we need to define the Interrupt Service Routine to be used when the interrupt is triggered. The vector for each interrupt is available in the Interrupt Vector Table. In the case of the interrupts we will be using, the location the vector points to is variable and can be defined using a `#pragma` and another macro feature provided by Renesas. We put the code we want to run as an ISR in a subroutine, and then we define the subroutine as an interrupt and place a pointer to its memory address with the following code, where `SUBROUTINE_NAME` is the name of the subroutine and `VECTORNUMBER` is the number of the vector located in the Interrupt Vector Table.

```
1. #pragma interrupt (SUBROUTINE_NAME(vect = VECTORNUMBER))
2. void SUBROUTINE_NAME(void);
```

We place this code at the beginning of our program or in a separate `.h` file. Then we put the code for our ISR in the subroutine with the rest of our program's functions or in a separate `.c` file allocated for our interrupt code.

```
1. //Name of Interrupt
2. void SUBROUTINE_NAME(void){
3.     //ISR Code
4. }
```

Registers Set in the ICU for an Interrupt

Each of the following registers is not a single register, but a representation of a type of register. In the RX63N there are several of these. The one which services the interrupt we will use is determinable by looking in the Interrupt Vector Table. However, we need not worry about any details besides the abbreviation for the peripheral, the abbreviation for the interrupt, and the vector number, because everything is handled in the Renesas `IR()`, `IPR()`, and `IEN()` macros. We will cover the registers here just to help understand the interrupt process.

The Interrupt Request Register (shown in Figure 9.2) is merely a flag holder that indicates a request signal has been sent from the peripheral. When a signal is received in the

ICU, the Interrupt Status Flag bit will be set to 1, and will return to 0 when the CPU accepts the interrupt. In the event that an interrupt is enabled in a peripheral and not in the ICU, this flag can still be set. It is possible to clear this register to 0 before an interrupt occurs by writing a 0 to it.

To clear a flag via the `IR()` macro we merely enter the code as:

```
1. IR("PERIPHERAL", "INTERRUPT") = 0;
```

Where `PERIPHERAL` is the abbreviation of the peripheral and `INTERRUPT` is the abbreviation for the interrupt name (available in the Interrupt Vector Table). To check a flag via the `IR()` macro we enter the code as:

```
1. VARIABLE = IR("PERIPHERAL", "INTERRUPT");
```

or

```
1. if(IR("PERIPHERAL", "INTERRUPT") == 1){
2.     //Code if flag is set
3. }
```

The Interrupt request enable register (shown in Figure 9.13) enables whether the ICU will process the interrupt request flag once it is set by a signal from the peripheral. The address of the IEN register and the bit of the register that needs to be set for each interrupt is once again available in the Interrupt Vector Table, but we don't need to worry about that. We only need to know the `IEN()` macro, which operates just like the `IR()` macro.

To set or clear the bit corresponding to an interrupt in the IER register we only need to enter the following code, where `PERIPHERAL` and `INTERRUPT` are the abbreviations for the peripheral in the Interrupt Vector Table.

```
1. IEN("INTERRUPT", "PERIPHERAL") = 1;
2. //'1' to enable, or '0' to disable
```

The Interrupt Priority Register (shown in Figure 9.14) allows the priority of the interrupt to be specified. A priority level from one to fifteen is allowed, fifteen being the highest. Interrupts with higher priority are handled first. If interrupts occur simultaneously with the same priority, the interrupt with the lower vector number is handled first. If a priority level isn't set, the interrupt will not be handled.

In case you are using an I/O pin to trigger an interrupt, you would use this register to determine how it is triggered. The number of the IRQ register for each I/O pin corresponds to the number of the interrupt request pin. Please refer to the RX63N schematic to determine where to connect to that pin physically. The only pins we are concerned with in this book are

Interrupt Request Register m (IERm) ($m = 02h$ to $1Fh$)

Address: 0008 7202h to 0008 721Fh

b7	b6	b5	b4	b3	b2	b1	b0
IEN7	IEN6	IEN5	IEN4	IEN3	IEN2	IEN1	IEN0
Value after reset:	0	0	0	0	0	0	0

BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b0	IEN0	Interrupt Request Enable 0	0: Interrupt request is disabled	R/W
b1	IEN1	Interrupt Request Enable 1	1: Interrupt request is enabled	R/W
b2	IEN2	Interrupt Request Enable 2		R/W
b3	IEN3	Interrupt Request Enable 3		R/W
b4	IEN4	Interrupt Request Enable 4		R/W
b5	IEN5	Interrupt Request Enable 5		R/W
b6	IEN6	Interrupt Request Enable 6		R/W
b7	IEN7	Interrupt Request Enable 7		R/W
Note: Write 0 to the bit that corresponds to the vector number for reservation. These bits are read as 0.				

Figure 9.13 Interrupt Request Enable Register [1], page 337.

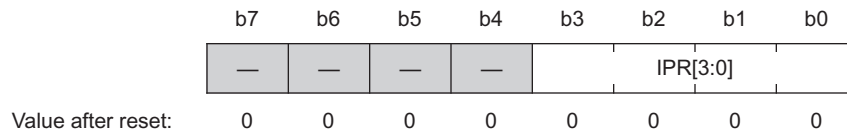
the pins connected to Switch 1, 2, and 3 which are IRQ pins; and 8, 9, and 10, respectively. Take note you must also enable the port as an input when using it to trigger an interrupt. It is important when setting up an I/O pin as an interrupt to do it in this order:

1. Clear the IEN bit.
2. Enable or confirm the I/O pin as an input.
3. Set the detection method in the IRQCR register.
4. Clear the IR flag.
5. Set the IEN bit.

Take note of Step 2. Alongside writing the ports data direction register to set it as an input, you must also write a 1 to the Port Mode Register (PMR; page 64) in the I/O registers. This must be done any time you are using an input pin to control a peripheral, in this case the peripheral is the ICU. You will have to refer to the schematic to see which port number and bit correspond to the IRQ input, and then write to that PMR bit. In the case of the three on

Interrupt Priority Register m (IPRm) ($m = 00h$ to $8Fh$)

Address: 0008 7300h to 0008 738Fh



BIT	SYMBOL	BIT NAME	DESCRIPTION	R/W
b3 to b0	IPR[3:0]	Interrupt Priority Level	b3 b0	R/W
		Select	0 0 0 0: Level 0 (interrupt prohibited)	
			0 0 0 1: Level 1	
			0 0 1 0: Level 2	
			1 1 1 1: Level 15 (highest)	
b7 to b4	—	Priority	This bit is read as 0. The write value should always be 0.	R/W

Figure 9.14 Interrupt Priority Register [1], page 338.

board switches 1, 2, and 3, the ports are PORT4.0, PORT4.1 and PORT4.4 respectively. So for switch one you would write a 1 to PORT4.PMR.BIT.0.

9.3.4 How an Interrupt Operates

So, now that we know how to set up an interrupt and a bit of the inner workings of the ICU, we will briefly explain the process of what happens when an interrupt is triggered. When conditions are met in a peripheral to trigger an interrupt, the first process that happens is the sending of the request to, and the processing of that request by, the ICU.

1. Conditions met for interrupt in peripheral, peripheral flag set.
2. Signal sent to ICU, peripheral flag cleared.
3. IR flag set in ICU.
4. If the interrupt is enabled in the ICU and no higher priority interrupts are currently running, the interrupt is sent to the CPU.
5. Interrupt accepted by CPU, IR flag cleared.

Once the interrupt is sent to the CPU the following process occurs in the program:

1. Finish processing current instruction.
2. Save program counter and flags to memory.
3. Run interrupt service routine.
4. Restore program counter and flags from stack.
5. Resume main program.

The stack is a dynamically allocated resource that contains current working data to do with our program. If too many interrupts occur, the stack can fill up pretty quickly and may overflow. This can become a problem if not well monitored. Another reason to keep ISRs small and short is so that they get back to the main program quickly and don't interfere with other interrupts.

This, of course, is just a very basic overview of the process that occurs. The detailed order of this process and instructions used to perform it are more complex and processor specific. But hopefully this gives an overview and helps you understand the process involved with setting up and using interrupts.

9.4 BASIC EXAMPLES

9.4.1 Polling a Switch for Input versus Using an Interrupt

Aim: Demonstrate checking the status of a hardware switch via polling and with an interrupt.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit.

Details: In this example, we will setup the RX63N processor to check the status of switch one (SW1). If the switch is pressed, the lit LED will rotate clockwise once until the switch is pressed again. We will first do this via a polling method, and then with an interrupt. We will compare and contrast the differences.

Procedure: First we will set up SW1 and check it with a polling method.

```
1. #include "iodefine.h"
2.
3. //Function definitions
4. void main(void);
5. void LED_Rotate(void);
6.
```

```

7. //Define global variables
8. int Current_LED;
9.
10.
11. void main(void){
12.     ENABLE_LEDS
13.     ENABLE_SWITCHES
14.     Current_LED = 1;
15.
16.     while(1){
17.         if(SW1 == 0){
18.             LED_Rotate();
19.             while(SW1 == 0)    //Note that this code does not handle
                                switch debouncing.
20.                 ;
21.         }
22.     }
23. }

```

All of this should be familiar; the `LED_Rotate` function rotates the LEDs one step in a clockwise sequence every time it is called. `Current_LED` is used to keep track of which LED is currently lit. For more reference on how to implement this function, refer to Chapter 8 where it is first used.

Lines 17 through 22 are where we check the status of SW1. SW1 is active low so once it is pressed the input will become a zero. Every time the program cycles through the `while(1)` loop it will check if SW1 is a zero yet. If it is a zero it will rotate the LED clockwise and then get stuck in the `while (SW == 0)`; until the switch is released. Note that on line 19 there is a comment noting that this code does not account for debouncing. Debouncing accounts for how a switch will, for a brief time after being pressed, rapidly switch back and forth (or “bounce”) between an ON and OFF position rather than cleanly switching between states. Usually this state is accounted for by calling a brief timer loop before checking ON or OFF, and indicating pressed or depressed. This method was left out in this example for simplicity.

Another method would be to replace lines 16 through 22 with the following code:

```

1. while(1){
2.     while(SW1 == 1);
3.     LED_Rotate();
4.     while(SW1 == 0)
5.         ;
6. }
7. }

```

With this method, we avoid problem number one of the last method by pausing the program until the switch is pressed. This solves that problem, but now this makes problem number two even worse. The program will be hung up entirely and no other calculations will be performed until the switch is pressed and released each time the while(1) loop repeats. To solve both problems we will use an interrupt.

```
1. #include "iodefine.h"
2.
3. //Define SW1 interrupt
4. #pragma interrupt(SW1_Int(vect = VECT_IRQ8))
5. void SW1_Int(void);
6.
7. //Function definitions
8. void main(void);
9. void LED_Rotate(void);
10. void EnableIRQ8(void);
11.
12. //Define global variables
13. int Switch_Press = 0;
14. int Current_LED;
15.
16. void main(void){
17.     ENABLE_LEDS
18.     EnableIRQ8();
19.     Current_LED = 1;
20.
21.     while(1){
22.         if(Switch_Press){
23.             LED_Rotate();
24.             Switch_Press = 0;
25.         }
26.     }
27. }
```

First take note of the addition on lines 3 through 5. SW1 is connected to IRQ8, if we look up IRQ8 in the Interrupt Vector Table we will see that it is at vector 72. This code defines the ISR for IRQ8 as SW1_Int and places a pointer to its memory address at vector 72, and also defines the function SW1_Int. Also on line 10 we define a new function EnableIRQ8 which is called on line 18 to perform all of the necessary operations to set up the switch to

trigger an interrupt. In our while(1) loop nothing will happen unless the Switch_Press flag is set in the switches interrupt routine. If it does, the LED_Rotate function is called and the flag is reset to 0.

```

1. void EnableIRQ8(void) {
2.     IEN(ICU, IRQ8) = 0;
3.     PORT4.ICR.BIT.B0 = 1;
4.     ICU.IRQCR[8].BIT.IRQMD = 0x01;
5.     ENABLE_SWITCHES
6.     IPR(ICU, IRQ8) = 0x03;
7.     IR(ICU, IRQ8) = 0;
8.     IEN(ICU, IRQ8) = 1;
9. }
```

You may notice this code follows the procedure defined for setting a switch for an interrupt in Section 9.3.3 in the description of the IRQCR_{*i*} register. First, as a precaution we disable the interrupt in the ICU in case it has been enabled in our program. This is on line 2. Then on line 3 we write a 1 to the input control register on Port4.0, the port that SW1 is connected to. This passes a signal to the ICU when the switch is pressed. Then we set the triggering method for IRQ8 on line 4. The switch is active when low, and it goes from a one to zero when pressed, so we set the trigger as a falling edge. Line 5 is our macro to set up the switches as inputs. By default the ports are inputs when the program starts, and we have also already called this macro in the main program; but this is a precautionary measure in case we decide to put this function in other programs where this hasn't already been done. Now that all of this is done, all we have to do is set up the interrupt in the ICU by defining its priority level, clearing the request flag in case it has been generated during setup, and then enabling the interrupt on lines 7 through 9.

```

1. void SW1_Int(void) {
2.     Switch_Press = 1;
3. }
```

Our last piece of code is for the SW1 Interrupt Subroutine. This sets the flag indicating the interrupt was triggered then returns to the main function. Because we set the trigger for the interrupt as a falling edge on the switch, it will only trigger when the button is pushed. Once the button is pushed, the subroutine is called and whatever code we want to address is executed. The switch is not ignored. Also, there is no waiting because the main program is halted for only as long as it takes to address the ISR. Though the setup is slightly more complex, the interrupt method is superior in efficiency.

9.4.2 Setting up the ADC with an Interrupt

Aim: Demonstrate using the interrupt with a peripheral.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit, RX63N Graphical LCD Code package.

Details: In this example, we will set up the RX63N processor to read the value of the potentiometer. Our program will use an interrupt, a device interrupt as a trigger, and a subroutine. TMR0 will trigger the A/D conversion every one second. When the A/D conversion is done it will call a subroutine to store the conversion in a variable. The main program will use this variable to display the conversion value on the LCD.

Procedure: First we need to set up our definitions and global variables:

```
1. #include "iodefine.h"
2. //Glyph Includes
3. #include "s12adc.h"
4. #include <stdlib.h>
5. #include <stdio.h>
6. #include "platform.h"
7.
8. //Define interrupt for AD1
9. #pragma interrupt (AD_Interrupt(vect = VECT_AD0_ADIO))
10. void AD1_Interrupt(void);
11.
12. //Function definitions
13. void main(void);
14. void InitADC(void);
15. void InitTimer(void);
16. void LED_Rotate(void);
17.
18. //Define global variables
19. int Current_LED;
20. int ADCResult = 0;
21. char buffer [30];
```

From line 1 to 6 we have included all I/O files for the RX63N and the LCD. On line 8 through 10 we define our interrupt function for the A/D conversion done interrupt, and place a pointer at its vector in the interrupt table. Notice in our function definitions on lines 13 to 17 that we

have made a function for initializing the ADC and timer. Also note on line 20 that we have made the global variable `ADCResult`, where we will hold the value read from the A/D conversion. The array on line 21 will be used to store the ASCII conversion of the `ADCResult` that is sent to the LCD.

Next is our main function and `while(1)` loop:

```

1. void main(void){
2.     long int i;
3.     InitADC();
4.     InitTimer();
5.     lcd_initialize();
6.     lcd_display(LCD_LINE1, "ADC Int Example");
7.     lcd_display(LCD_LINE2, "Potentiometer Value:");
8.     while(1){
9.         for(i = 0; i < 100000; i++);
10.        sprintf(buffer, "%d", ADCResult);
11.        lcd_display(LCD_LINE3, buffer);
12.    }
13. }
```

We create the variable `i` on line 2 to make our arbitrary delay loop on line 9. On lines 3 and 4 we call our functions to set up the timer and the A/D converter. Line 5 initializes the LCD. In lines 6 and 7 we display on the LCD some information concerning the program that is running. Then in our `while(1)` loop, repeatedly, after an arbitrary delay, we will convert our value from the A/D conversion to an ASCII string and write it to line 3 of the LCD. The rest of the code is LCD control code.

```

1. void InitADC(void){
2.     MSTP(AD) = 0;
3.     AD1.ADCSR.BIT.ADIE = 1;
4.     AD1.ADCSR.BIT.ADST = 0;
5.     AD1.ADCSR.BIT.CH = 0x000;
6.
7.     AD1.ADCR.BIT.MODE = 0;
8.     AD1.ADCR.BIT.CKS = 3;
9.     AD1.ADCR.BIT.TRGS = 2;
10.    IPR(AD0, ADI0) = 0x03;
11.    IR(AD0, ADI0) = 0;
12.    IEN(AD0, ADI0) = 1;
13. }
```

This is our function to set up the A/D converter to read the value from the potentiometer. We will set it up to do a single conversion every time it receives a trigger from TMR0. First we enable the peripheral on line 2. Then on line 3 we enable the interrupt in the A/D peripheral; this will trigger the interrupt service routine every time a conversion finishes. We set the conversion to not start yet on line 4, and then select channel AN4 on line 5. It is indicated in the RX63N schematic that AN4 corresponds to the pin that is connected to the potentiometer. On line 7 we set the mode to single conversion, so every time the converter is triggered it will do one conversion then stop. We select the clock source for the A/D converter as the peripheral clock on line 8. On line 9 we select the trigger as a Compare Match A event on TMR0. Every time a Compare Match A event occurs in TMR0 a signal will be sent to the A/D converter. This requires some set up in TMR0 as well; we will see that code shortly. On lines 10 through 12 we have the code to set the priority level, clear the request flag, and then enable the interrupt in the ICU.

```
1. void InitTimer(void) {
2.     MSTP(TMR0) = 0;
3.     MSTP(TMR1) = 0;
4.
5.     TMR1.TCCR.BIT.CSS = 1;
6.     TMR1.TCCR.BIT.CKS = 5;
7.
8.     TMR0.TCCR.BIT.CSS = 3;
9.     TMR0.TCR.BIT.CCLR = 1;
10.
11.     TMR0.TCORA = 0x5B;
12.     TMR1.TCORA = 0x6D;
13.
14.     TMR0.TCSR.BIT.ADTE = 1;
15. }
```

Here is our code to set up a 16-bit cascaded timer that resets and generates a Compare Match A signal every one second. The code from lines 3 through 13 configures the timer to generate a one second interval; details are in the timer chapter of this text. The only code we need to examine here is on line 14, where we set the unit to send a trigger to the A/D converter every time there is a Compare Match A or every one second.

```
1. void AD1_Interrupt(void) {
2.     ADCResult = AD.ADDRA;
3. }
```


Our last bit of code is our interrupt subroutine for the A/D conversion. Every time a conversion finishes this routine will interrupt to write the latest conversion value to our variable, and then the program will return to its previous task.

So, to review, this program begins by initializing the A/D converter and the TMR0. TMR0's interrupt routine is not enabled, but the Compare Match A interrupt in the peripheral will send a signal to the A/D converter every one second. Once triggered the A/D conversion will begin, and once finished it will trigger its own interrupt. This interrupts the main program for long enough to write the conversion value to a variable, then returns. Inside the main program there is a constant loop writing the A/D conversion to the LCD after a short delay. When run, the LCD screen should display "ADC Int Example" on line 1 of the LCD and "Potentiometer Value:" on line 2. On roughly one second intervals the screen should update with a new value for the potentiometer.

This example illustrates two uses of interrupts, and an alternative use of interrupt signals to triggering subroutines. By now you should be pretty familiar with the process of setting up an interrupt to trigger a subroutine as well as the concept of using them to trigger processes in other peripherals.

9.5 ADVANCED CONCEPTS

9.5.1 Minimizing the Amount of Code in Interrupts

In example 9.4.1, Polling a Switch for Input versus Using an Interrupt, it was pointed out that excessive function calls, or code in general, inside of an interrupt routine is bad. If a function call is made in an interrupt routine it requires that all the processor register information be stored to the stack, which makes the compiler blind to register usage. Also, as mentioned several times in this book, it just simply adds more time and overhead to the interrupt, and we want to avoid this as much as possible.

So how do we do this? Often an ISR is used only to set flags or alter very small amounts of data. Then these flags or data are used to alter something in the main program. A flag can be a global variable that is toggled between one and zero. Once the program returns from the interrupt, some control statement will eventually use this as an indicator to change the program flow in some way.

For example, say we have a program that is constantly checking the value of a thermistor but we only want it to update the value on the LCD screen every second. We would set up a timer to interrupt periodically every second, and when it interrupts it writes a one to a variable named `Timer_Flag`. In our main program there is an if statement that checks the timer flag. When the `Timer_Flag` variable is 1 the function to write the value to the LCD is called. This way we still get the benefits of the interrupt, but keep our code in the interrupt minimal.

9.5.2 Brief Introduction to State Machines

In the next section we will cover how to make an interrupt controlled state machine. But first, in this section we need to give a brief overview of what a state machine is and how to program one. State machines are simply a method that makes it easier to abstract a process we want to perform in real life and convert it into a program.

So far we have thought of programs as sequential processes. One process is executed, then some others, repeat. Sometimes that flow is altered slightly due to something happening, such as an interrupt or control loops, but with an embedded system we still will restart in our while(1) loop eventually and the program will repeat and execute the same processes again. With state machines we think of our program as having ‘states.’ In each state there is a different flow of operations to perform. Depending on some change in data or a triggering event, the state will change. The program will continue to perform the functions in this state until conditions are met to go into another state. We will implement the state machine by making a variable to represent the current state of the machine, and then using a switch statement to check that variable in the while(1) loop. If the variable is changed the state will change, otherwise the code in the current state will continue to run repeatedly. We can also make states that perform one task and then immediately switch to another state without to another state by default.

In order to better understand a state machine, let’s imagine a vending machine as a state machine. The vending machine can be in a ‘state’ depending on what task it needs to perform at the current moment. In each state the program is focused on a particular function such as accepting money, returning change, or vending drinks. In the case of the coin return state, it will return the proper amount of coins and then by default return to the Accept Money state. The same for the vend state, which automatically goes to the Coin Return state (which we assume simultaneously checks to see if coins are needed to be returned at all). In the case of the Accept Money state, the state will not change until a selection is made or the coin return button is pressed. In the case of the Check Correct Change state it will immediately go to either state 4 or 1, depending on if the right amount of change was deposited for the selection. This is how a state machine works on a very basic level. A full implementation of a vending machine state machine would require many more states such as “jammed coin,” “machine tilt,” “coolant problem,” “out of order,” etc. In order to address the real world well embedded systems must get very intricate. This is just a simple illustrative example.

9.5.3 State Machines and Using Them with Interrupts

So now that we know what a basic state machine looks like, we are going to demonstrate how to implement one effectively using interrupts to switch states. You’ll notice in the vend-

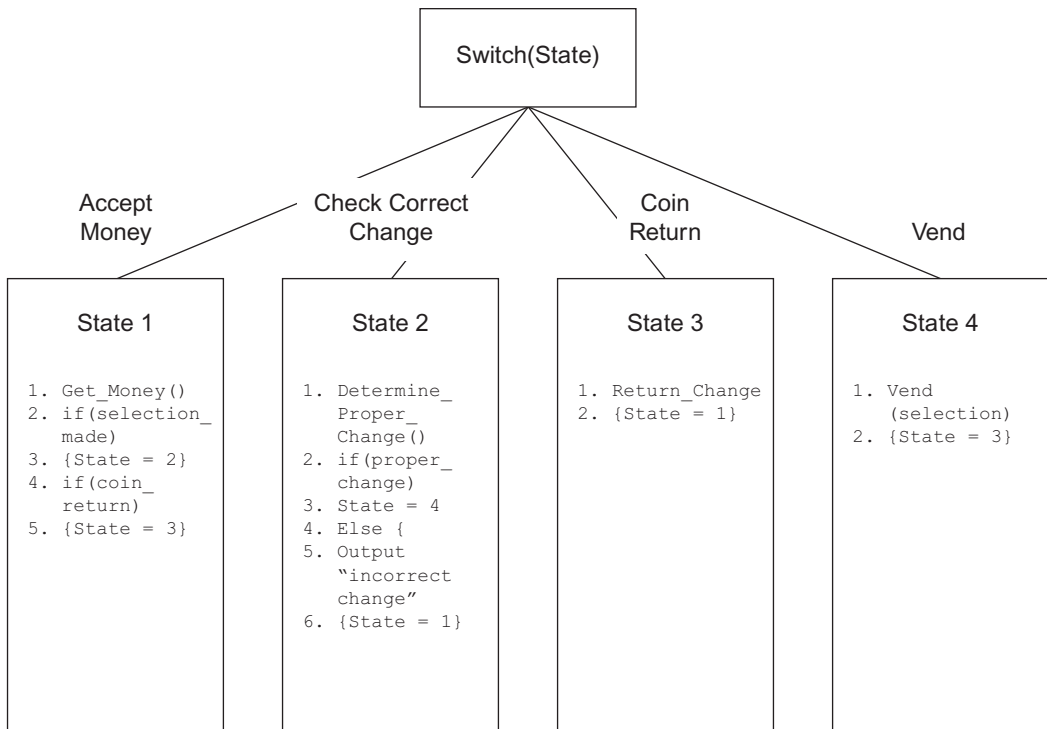


Figure 9.15 Vending machine state machine example.

ing machine examples that different actions triggered a state change, such as `coin_return` or `selection_made`. These actions were represented as a variable of some sort and were checked by an `If` statement; if these variables were a one or higher the state was changed. Do these variables look familiar to something else we talked about in this chapter? These are simply the flags we talked about in Section 9.5.1, *Minimizing the Amount of Code in Interrupts*. So by setting flags with an interrupt we can have code in our states check these flags and change states based on input. Once again let's use an example to illustrate.

For this example let's use the RX63N. We will make a state machine that will have three states. In one state the machine will rotate the LEDs in a circular sequence. In the second state we will display the value of the potentiometer on the LCD. In the third state the LCD will display the number of seconds elapsed since the program has started. Each time switch one is pressed the board will cycle to the next state, once it goes beyond state three it will return to state one. We will make it that each state performs its actions at one second intervals.

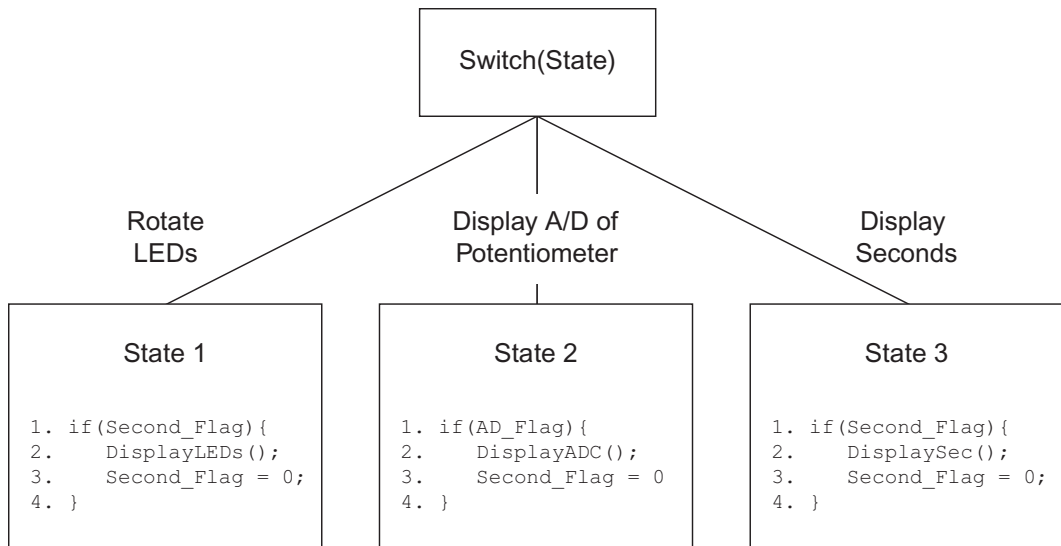


Figure 9.16 RX63N state machine example with interrupts.

With state machines this implementation is very simple. We only need three states as specified. The flag indicating which state is currently active is rotated using the ISR for switch one, defaulting to state one on start. Every second the timer will interrupt and set a flag that a second has passed, this flag will trigger actions in States 1 and 3. Note that the DisplayLEDs function in State 1 will include a function call to rotate the LEDs as well as display information on the LCD, thus rotating the LEDs. In the case of State 2 we are using the A/D converter, so we will use a flag set by its own ISR to trigger this state's actions. This will occur on roughly one second intervals since the A/D itself will be set to be triggered by a signal from the Timer device. This is a full, very basic state machine that uses interrupts to switch states. We will give a coding example of this in the advanced examples section.

9.6 ADVANCED EXAMPLES

9.6.1 Using an ADC Interrupt with Flags to Process Data

Aim: Demonstrate using flags with an interrupt to minimize the time spent in an ISR.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit.

Details: In this example, we will set up the A/D converter once again to perform a conversion, except in this example the A/D will trigger an interrupt when the conversion is done. This interrupt will set a flag that is checked in the main code to trigger, writing the new data to the LCD.

Procedure: The code is mostly the same as our example in Section 9.4.2, Setting up the ADC with an Interrupt, except with modifications so that it now operates around the A/D interrupt. Our variable and function prototypes are mostly the same.

```

1. #include "iodefine.h"
2. //Glyph Includes
3. #include "s12adc.h"
4. #include <stdlib.h>
5. #include <stdio.h>
6. #include "src\glyph\glyph"
7.
8. //Define interrupt for AD0
9. #pragma interrupt (AD0_Interrupt(vect = VECT_AD0_ADI0))
10. void AD1_Interrupt(void);
11.
12. //Function definitions
13. void main(void);
14. void InitADC(void);
15. void InitTimer(void);
16. void LED_Rotate(void);
17. void lcd_display(int8_t aLine, char *aText);
18. #define LCD_LINE1 0
19. #define LCD_LINE2 1
20. #define LCD_LINE3 2
21. #define LCD_LINE4 3
22.
23. //Define global variables
24. T_glyphHandle G_lcd;
25. int Current_LED;
26. int ADCResult = 0;
27. char AD_Flag = 0;
28. char buffer [30];

```

The only difference here is we have added the `AD_Flag` variable on line 27. It is initialized to zero to indicate the interrupt has not been triggered yet.

```
1. void main(void){
2.     ENABLE_LEDS
3.     InitADC();
4.     InitTimer();
5.
6.     if(GlyphOpen(&G_lcd, 0) == GLYPH_ERROR_NONE){
7.         /* use Glyph full access direct functions */
8.         GlyphNormalScreen(G_lcd);
9.         GlyphSetFont(G_lcd, GLYPH_FONT_HELV10);
10.        GlyphClearScreen(G_lcd);
11.
12.        lcd_display(LCD_LINE1, "ADC Int Flag Example");
13.        lcd_display(LCD_LINE2, "Potentiometer Value:");
14.
15.        while(1){
16.            if(AD_Flag){
17.                ADCResult = AD.ADDRA;
18.                sprintf(buffer, "%d", ADCResult);
19.                lcd_display(LCD_LINE3, buffer);
20.                AD_Flag = 0;
21.            }
22.        }
23.    }
24.    else{}
25.
26.    GlyphClose(&G_lcd);
27. }
```

Our main code has only been modified so all code to do with reading the A/D conversion value and writing it to the LCD has been placed in an If statement. When the `AD_Flag` variable becomes a 1 or higher this will cue the code to execute, then the flag will be reset to 0. The code will not execute again until the flag has been set to 1 again.

We won't cover the `InitADC` or `InitTimer` functions again as they are identical to a previous example. We are once again setting a one second interval timer. The timer generates a Compare Match A signal after one second that resets the timer and sends a signal to the A/D converter to start converting. Once done, the A/D converter will trigger its own interrupt that will call an ISR.

```

1. void AD1_Interrupt(void){
2.     AD_Flag = 1;    //Set A/D conversion flag
3. }

```

Now the A/D conversion ISR will set the flag to one, indicating the conversion is done.

Conclusion: We have effectively altered our old program to use an interrupt and a flag to indicate data is ready from an external device. The flag now triggers the execution of a large amount of code in the main program. Keeping this code out of the interrupt service routine improves responsiveness for other ISRs.

9.6.2 A Simple State Machine Controlled by Interrupts

Aim: Demonstrate a state machine whose state is altered by an interrupt.

Requirements: PC with High-performance Embedded Workshop 4.0 or 4.0+, RX63N Development kit, RX63N Graphical LCD Code package.

Details: In this example, we will set up a state machine on the RX63N. When SW1 is pressed, the machine will rotate states. In State 1 the LEDs will blink clockwise at a rate of one LED per second. In State 2 the LCD will display the current ADC reading across the board's potentiometer every second. In State 3 the LCD will display the number of seconds elapsed since the program started. If the switch is pressed again the state will rotate back to State 1.

Procedure: First we once again need to set up our definitions and global variables:

```

1. #include "iodef.h"
2. //Glyph Includes
3. #include "s12adc.h"
4. #include <stdlib.h>
5. #include <stdio.h>
6. #include "src\glyph\glyph"
7.
8. //Define SW1 interrupt
9. #pragma interrupt (SW1_Int(vect = VECT_IRQ8))
10. void SW1_Int(void);
11.
12. //Define interrupt for TMR0 Compare Match A
13. #pragma interrupt (TMR0_CompareMatchA_Interrupt
    (vect = VECT_TMR0_CMIA0))

```

```
14. void TMR0_CompareMatchA_Interrupt(void);
15.
16. //Define interrupt for AD1
17. #pragma interrupt (AD1_Interrupt(vect = VECT_AD1_AD11))
18. void AD1_Interrupt(void);
19.
20. //Function definitions
21. void main(void);
22. void InitADC(void);
23. void InitTimer(void);
24. void EnableIRQ8(void);
25. void LED_Rotate(void);
26. void DisplaySec(void);
27. void DisplayADC(void);
28. void DisplayLEDs(void);
29. void lcd_display(int8_t aLine, char *aText);
30. #define LCD_LINE1 0
31. #define LCD_LINE2 1
32. #define LCD_LINE3 2
33. #define LCD_LINE4 3
34.
35. //Define global variables
36. T_glyphHandle G_lcd;
37. int Current_LED;
38. int State = 1;
39. int Second_Flag;
40. int AD_Flag;
41. int SecCount;
42. int ADCResult = 0;
43. char buffer [30];
```

For this example we will use three ISRs. One each for the switch interrupt, the A/D conversion interrupt, and the TMR0 interrupt. These are defined on lines 8 through 18. On lines 22 to 24 we define our functions to set up each of these peripherals. We have also defined functions to call to display these on lines 26 through 28. On line 38 we create our state variable; altering this variable will alter which state we are in. On lines 39 to 40 we create flags for each interrupt, so when the interrupt is triggered the ISRs will set these flags, and then the main program will use these to trigger code to handle the events. On line 41 we create a global variable that counts the number of seconds the program has run.

Now we have our main program code, which is very simple.


```
1. void main(void){
2.     ENABLE_LEDS
3.     InitADC();
4.     InitTimer();
5.     EnableIRQ8();
6.
7.     if(GlyphOpen(&G_lcd, 0) == GLYPH_ERROR_NONE){
8.         /* use Glyph full access direct functions */
9.         GlyphNormalScreen(G_lcd);
10.        GlyphSetFont(G_lcd, GLYPH_FONT_HELV10);
11.        GlyphClearScreen(G_lcd);
12.
13.        lcd_display(LCD_LINE1, "State Machine");
14.
15.        while(1){
16.            switch(State){
17.                case 1:
18.                    if(Second_Flag){
19.                        DisplayLEDs();
20.                        Second_Flag = 0;
21.                    }
22.                    break;
23.                case 2:
24.                    if(AD_Flag){
25.                        DisplayADC();
26.                        AD_Flag = 0;
27.                    }
28.                    break;
29.                case 3:
30.                    if(Second_Flag){
31.                        DisplaySec();
32.                        Second_Flag = 0;
33.                    }
34.                    break;
35.                default:
36.                    //In the off chance that the State variable is set
37.                    //to something other than 1 through 3
38.                    //we will be informed via this default state.
39.                    lcd_display(LCD_LINE1, "Error");
40.                    break;
41.            }
42.        }
43.    }
```

```
41.     }
42.   }
43.   else{}
44.
45.   GlyphClose(&G_lcd);
46. }
```

First on lines 2 through 5 we call our macros and functions to enable the LEDs and each of our peripherals (the A/D, timer and SW1). After the code to set up the LCD we enter our while(1) loop, where the only code we have is our state machine. This is implemented via a switch statement that uses the state variable to control it. In State 1 we will check the Second_Flag; every time it is set we will call the DisplayLEDs function which will update the LCD to display our state and then rotate the LEDs. In State 2 we check the A/D conversion finish flag, as the A/D conversion itself is triggered by the timer interrupt and we don't want to write the A/D value until the conversion is finished. When the flag is set, we will call the DisplayADC function which updates the LCD for the state and displays the conversion of the voltage across the potentiometer. In State 3 we check the second flag and once it is set we call the DisplaySec function, which updates our LCD for the state and displays the number of seconds elapsed on the screen.

Now we will go over our peripheral setup functions.

```
1. void InitADC(void){
2.     MSTP(AD) = 0;
3.     AD.ADCSR.BIT.ADIE = 1;
4.     AD.ADCSR.BIT.ADST = 0;
5.     AD.ADCSR.BIT.CH = 0x000;
6.
7.     AD.ADCR.BIT.MODE = 0;
8.     AD.ADCR.BIT.CKS = 3;
9.     AD.ADCR.BIT.TRGS = 2;
10.
11.     IPR(AD0,ADI0) = 0x03;
12.     IR(AD0,ADI0) = 0;
13.     IEN(AD0,ADI0) = 1;
14. }
15.
16. void InitTimer(void){
17.     MSTP(TMR0) = 0;
18.     MSTP(TMR1) = 0;
19. }
```

```
20.     TMR1.TCCR.BIT.CSS = 1;
21.     TMR1.TCCR.BIT.CKS = 5;
22.
23.     TMR0.TCCR.BIT.CSS = 3;
24.     TMR0.TCR.BIT.CCLR = 1;
25.
26.     TMR0.TCOR = 0x5B;
27.     TMR1.TCOR = 0x6D;
28.
29.     TMR0.TCSR.BIT.ADTE = 1;
30.     TMR0.TCR.BIT.CMIEA = 1;
31.
32.     IPR(TMR0, CMIA0) = 3;
33.     IR(TMR0, CMIA0) = 0;
34.     IEN(TMR0, CMIA0) = 1;
35. }
36.
37. void EnableIRQ8(void) {
38.     IEN(ICU, IRQ8) = 0;
39.     PORT4.ICR.BIT.B0 = 1;
40.     ICU.IRQCR[8].BIT.IRQMD = 0x01;
41.     ENABLE_SWITCHES
42.     IPR(ICU, IRQ8) = 0x03;
43.     IR(ICU, IRQ8) = 0;
44.     IEN(ICU, IRQ8) = 1;
45. }
```

Each of these peripherals is set up as in previous examples so we won't have to review the code extensively. AD1 is set up to be triggered every time TMR0 sends it a Compare Match A signal, once triggered it will convert the voltage across the board's potentiometer and then trigger its ISR. TMR0 will generate a Compare Match A signal and trigger its ISR every second. SW1 will trigger its ISR every time it is pressed via IRQ8.

```
1. void DisplayLEDs(void) {
2.     LED_Rotate();
3.     lcd_display(LCD_LINE2, "State 1");
4.     lcd_display(LCD_LINE3, "Rotating LEDs");
5.     lcd_display(LCD_LINE4, " ");
6. }
```

```
7.
8. void DisplayADC(void){
9.     ADCResult = AD1.ADDRA;
10.    sprintf(buffer, "%d", ADCResult);
11.    lcd_display(LCD_LINE2, "State 2");
12.    lcd_display(LCD_LINE3, "Potentiometer Value:");
13.    lcd_display(LCD_LINE4, buffer);
14. }
15.
16. void DisplaySec(void){
17.    sprintf(buffer, "%d", SecCount);
18.    lcd_display(LCD_LINE2, "State 3");
19.    lcd_display(LCD_LINE3, "Seconds Count:");
20.    lcd_display(LCD_LINE4, buffer);
21. }
```

Our display functions are quite similar. As said before, each one updates the LCD and performs necessary actions based on which interrupt it is related to. The DisplayLEDs function calls the LED_Rotate function. The DisplayADC function updates the variable that contains the conversion result, and converts it to ASCII before sending it to the LCD. The DisplaySec function merely converts the seconds count variable to ASCII as the variable is updated in the ISR.

Now we will cover our interrupt functions themselves.

```
1. //Timer 0 Compare Match A Interrupt
2. void TMR0_CompareMatchA_Interrupt(void){
3.     Second_Flag = 1;
4.     SecCount++;
5. }
6.
7. //AD1 Conversion Finished Interrupt
8. void AD1_Interrupt(void){
9.     AD_Flag = 1;
10. }
11.
12. //SW1 Interrupt
13. void SW1_Int(void){
14.     State++;
15.     if(State >= 4){
16.         State = 1;
17.     }
18. }
```

Each ISR is kept very simple. The TMR0 ISR merely sets the second flag and increments the count of the number of seconds. The AD1 interrupt only sets its flag. The SW1 interrupt increments the state, if it is 4 or greater the state is reset to 1.

Once compiled and run the state machine should start off in State 1. The LEDs will once again rotate on a one second interval with the state displayed on the LCD. Once SW1 is pressed, the state will increment to State 2 where the A/D conversion result from the potentiometer will update on the LCD every one second along with the state information. When SW1 is pressed again, the seconds count will be displayed on the screen along with State 3's info.

9.7 RECAP

In this chapter we have made a broad overview of the interrupt features on the RX63N and how they can be used with the different peripherals. We started by covering reasons for using an interrupt for tasks as compared to other techniques. Then we covered the full process of setting up an interrupt as it may apply to any peripheral. In the advanced concepts section we went over the reasons for keeping code minimal in interrupts. Then an example of a full implementation of interrupts was presented by introducing state machines and then describing a state machine controlled purely by peripheral interrupts.

9.8 REFERENCES

[1] Renesas Electronics, Inc., *RX63N Group, RX631 Group User's Manual: Hardware, Rev.1.60*, February 2013.

9.9 EXERCISES

1. You want to set up one of the switches on the RX63N board to trigger an interrupt. List the registers you need to modify and the values you need to assign to them.
2. List at least three advantages of using an interrupt to signal data ready from a device rather than polling.
3. List at least five examples of an application where using an interrupt to signal data from a processor peripheral would greatly speed up a program.
4. Choose one of these examples and write pseudocode explaining how you would program this. Include descriptions of the interrupt function, your interrupt initialization function, and your main function.

5. Explain how you would use a flag to signal and process data from a device with an interrupt.
6. Why would you use a flag to signal processing of the data in the main program instead of placing all of the code in the interrupt?
7. What advantages does a state machine approach have over a purely sequential approach to embedded programming?
8. Give some examples of where a state machine would be a good choice of design approach.
9. Choose one of those examples and make a simple state machine design such as the one in Section 9.5.2, Brief Introduction to State Machines.

Designing Responsive and Real-Time Systems

10.1 LEARNING OBJECTIVES

Most embedded systems have multiple independent tasks running at the same time. Which activity should the microprocessor perform first? This decision determines how **responsive** the system is, which then affects how determines how fast a processor we must use, how much time we have for running intensive control algorithms, how much energy we can save, and many other factors. In this chapter we will discuss how the microprocessor schedules its tasks.

10.2 MOTIVATION

Consider an embedded system which controls a doorbell in a house. When a person at the front door presses the switch, the bell should ring inside the house. The system's **responsiveness** describes how long it takes from pressing the switch to sounding the bell. It is easy to create a very responsive embedded system with only one task. The scheduling approach shown below is an obvious and simple approach.

```
1. void main (void){
2.     init_system();
3.     while(1){
4.         if(switch == PRESSED){
5.             Ring_The_Bell();
6.         }
7.     }
8. }
```

Our doorbell is very responsive. In fact, we like it so much that we decide to add in a smoke detector and a very loud beeper so we can be warned about a possible fire. We also add a burglar detector and another alarm bell. This results in the code shown on the next page.

```
1. void main (void){
2.     init_system();
3.     while(1){
4.         if(switch == PRESSED){
5.             Ring_The_Doorbell();
6.         }
7.         if(Burglar_Detected() == TRUE){
8.             Sound_The_Burglar_Alarm();
9.         }
10.        if(Smoke_Detected() == TRUE){
11.            Sound_The_Fire_Alarm();
12.        }
13.    }
14. }
```

Going from one task to three tasks has complicated the situation significantly.¹ How should we share the processor's time between these tasks?

- How long of a delay are we willing to accept between smoke detection and the fire alarm sounding? And the delay between the switch being pressed and the doorbell sounding?
- Should the system try to detect smoke or burglars while the doorbell is playing?
- Should the doorbell work while the smoke alarm is being sounded? What about when the burglar alarm is sounding?
- Which subsystem should the processor check first: the doorbell, the smoke detector, or the burglar detector? Or should it just alternate between them?
- Should the doorbell switch be checked as often as the smoke and burglar detectors, or at a different rate?
- What if the person at the door presses the switch again before the doorbell finishes sounding? Should that be detected?

Now that we have to share the processor, we have to worry about how long the bell rings and the alarms sound. If we use a doorbell ringtone which lasts for thirty seconds, then `Ring_The_Bell` will take at least thirty seconds to run. During this time, we won't know if our house is burning or being robbed. Similarly, what if the firemen come when the alarm is sounding? How quickly should the doorbell respond in that case?

¹ In fact, any number of tasks greater than one complicates the situation!

10.3 SCHEDULING FUNDAMENTALS

This example reveals the two fundamental issues in scheduling for responsive systems.

- If we have multiple tasks ready to run, which one do we run first? This decision defines the **ordering** of task execution.
- Do we allow one task to interrupt or **preempt** another task (or even itself)?

Both of these decisions will determine the system's **responsiveness** (measured by response time):

- How long will it take for the **most important** task to **start running?** To **finish running?** Does this depend on how long any other tasks take to run, and how often they run?
- How long will it take for the **least important** task to **start running?** To **finish running?** We expect it will depend on how long all the other tasks take to run, and how often they run.
- If we allow tasks to preempt each other, then a task may start running very soon but finish much later, after multiple possible preemptions.

These response times in turn affect many performance-related issues, such as these:

- How fast must the processor's clock rate be to ensure that nothing happens "late"?
- How much time do we have available for running compute-intensive algorithms?
- How much energy can we save by putting the processor to sleep?
- How much power can we save by slowing down the processor?

Figure 10.1 shows a visual representation of some arbitrary scheduling activity. Task A is released (becomes ready to run) at the first vertical bar. There is some **latency** between the release and when the task starts running, due to other processing in the system and scheduler overhead. Similarly, there is a **response time** which measures how long it takes task A to complete its processing. Some scheduling approaches allow a task to be preempted (delayed) after it has started running, which will increase the response time.

10.3.1 Task Ordering

The first factor affecting response time is the **order in which we run tasks**. We could always follow the same order by using a **static** schedule. The code shown for the Doorbell/

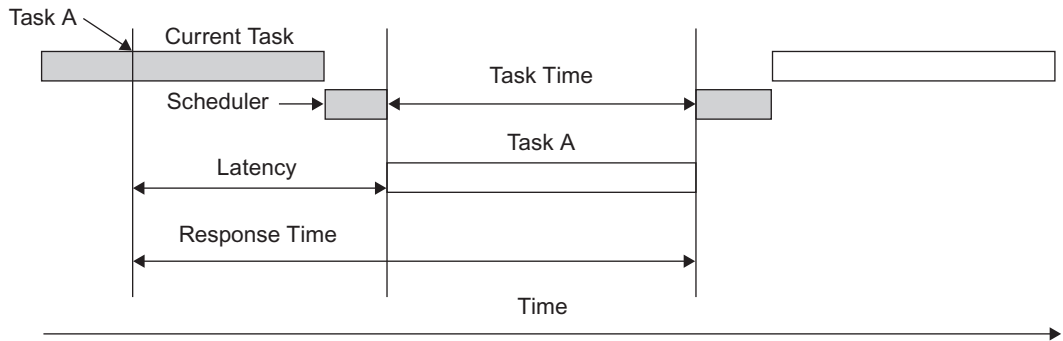


Figure 10.1 Diagram and definitions of scheduler concepts.

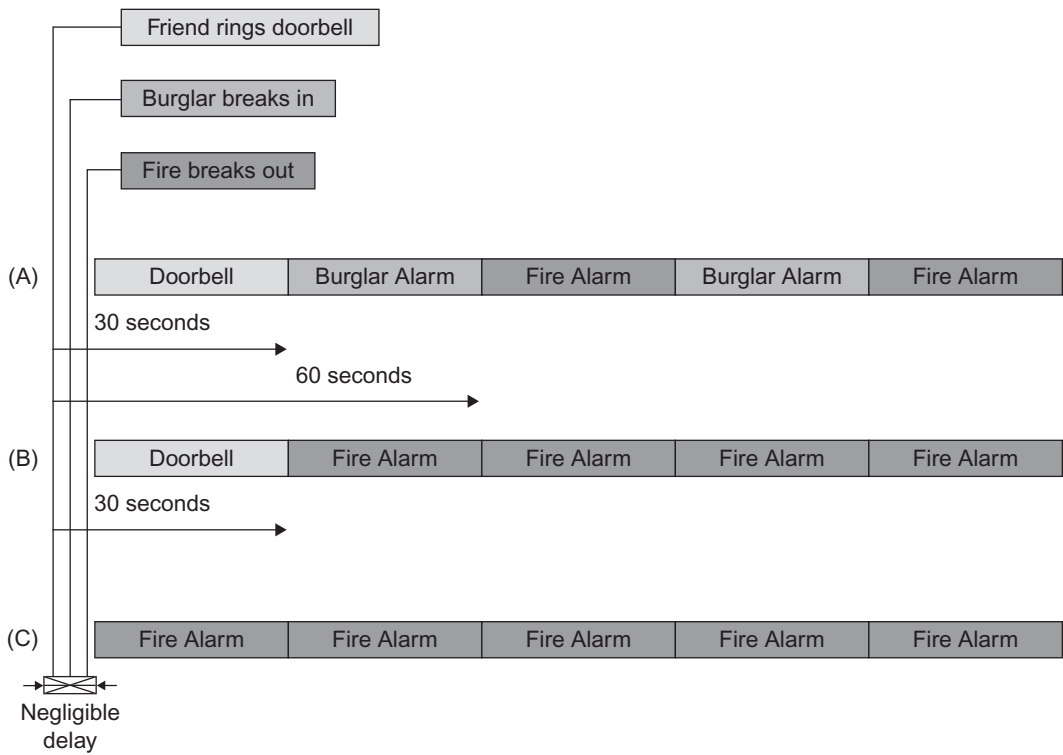


Figure 10.2 Doorbell/fire alarm/burglar alarm system behavior with different scheduling approaches.

Fire Alarm/Burglar Alarm uses a static schedule. Figure 10.2a shows an interesting case. If a burglar broke in and a fire broke out just after someone pressed the switch to ring the doorbell; we wouldn't find out about the burglar for almost thirty seconds and the fire for about sixty seconds. We probably do not want these large delays for such critical notifications.

We can change the order based on current conditions (e.g., if the house is on fire) using a **dynamic** schedule. An obvious way to do this is to reschedule after finishing each task. A dynamic schedule lets us improve the responsiveness of some tasks at the price of delaying other tasks. For example, let's prioritize fire detection over burglar detection over the doorbell.

```

1. void main (void){
2.     init_system();
3.     while(1){
4.         if(Smoke_Detected() == TRUE){
5.             Sound_The_Fire_Alarm();
6.         } else if (Burglar_Detected() == TRUE) {
7.             Sound_The_Burglar_Alarm();
8.         } else if (switch == PRESSED) {
9.             Ring_The_Doorbell();
10.        }
11.    }
12. }
```

Notice how this code is different—there are **else** clauses added, which change the schedule to a dynamic one. As long as smoke is detected, `Sound_The_Fire_Alarm()` will run repeatedly. The burglar alarm and doorbell will be ignored until no more smoke is detected. Similarly, burglar detection will disable the doorbell. This is shown in Figure 10.2b.

This **strict prioritization** may or may not be appropriate for a given system. We may want to ensure some **fairness**, perhaps by limiting how often a task can run. Later in this chapter we present a periodic table-based approach which is much better than this hard-coded design.

10.3.2 Task Preemption

The second aspect to consider is whether one task can **preempt** another task. Consider our thirty-second doorbell ringtone—the task `Ring_The_Doorbell` will **run to completion** without stopping or yielding the processor.

What if a burglar breaks the window a split second after an accomplice rings the doorbell? In this worst-case scenario, we won't find out about the burglar (or a possible fire) for thirty seconds.² Let's say we'd like to find out within one second. We have several options:

- Limit the maximum duration for the doorbell ringtone to one second.
- Add another microprocessor which is dedicated to playing the doorbell ringtone. This will raise system costs.
- Break the `Ring_The_Doorbell` function into thirty separate pieces (e.g., with a state machine or separate functions), each of which takes only one second to run. This code will be hard to maintain.
- Allow the smoke and burglar detection code to preempt `Ring_The_Doorbell`. We will need to use a more sophisticated task scheduler which can (1) preempt and resume tasks, and (2) detect events which trigger switching and starting tasks. We will not need to break apart any source code. This will make code maintenance easier. However, we introduce the vulnerability to race conditions for shared data, and we also will need more memory (enough to hold each task's stack simultaneously).

Let's apply this preemption option to our system. We assign the highest priority to fire detection, then burglar detection, and then the doorbell. Now we have the response timeline shown in Figure 10.2c. The system starts sounding the doorbell after the switch is pressed, but as soon as the fire is detected, the scheduler preempts the `Ring_The_Doorbell` and starts running `Sound_The_Fire_Alarm`. We find out about the fire essentially immediately, without having to wait for the doorbell to finish sounding.

As with the previous example, we have strict prioritization without control of how often tasks can run. As long as smoke is detected, `Sound_The_Fire_Alarm()` will run repeatedly. The burglar alarm and doorbell will be ignored until no more smoke is detected. Similarly, burglar detection will disable the doorbell.

10.3.3 Fairness and Prioritization

These examples all show one weakness of our system: prioritizing some tasks over others can lead to starvation of lower priority tasks (they may never get to run). For some systems this is acceptable, but for others it is not. Here are two ways of providing some kind of fairness:

- We can allow multiple tasks to share the same priority level. If both tasks are ready to run, we alternate between executing each of them (whether by allowing each task to run to completion, or by preempting each periodically).

² Imagine what Thomas Crown, James Bond, or Jason Bourne could do in that time!

- We can limit how often each task can run by defining the task frequency. This is the common approach used for designers of real-time systems. Note that we can still allow only one task per priority level.

10.3.4 Response Time and Preemption

For the two non-preemptive examples in Figure 10.2, notice how the response time for the fire alarm and the burglar alarm depends on **how long the doorbell sounds**. However, for the preemptive approach those response times are **independent** of how long the doorbell sounds. This is the major benefit of a preemptive scheduling approach: it makes a task's response time essentially **independent** of all processing by lower priority tasks.³ Instead, only **higher priority** tasks can delay that task.

In Figure 10.3 we present these relationships in a graph. Tasks and ISRs are nodes, while edges (or arcs) are timing dependences. For example, the edge from B to C indicates

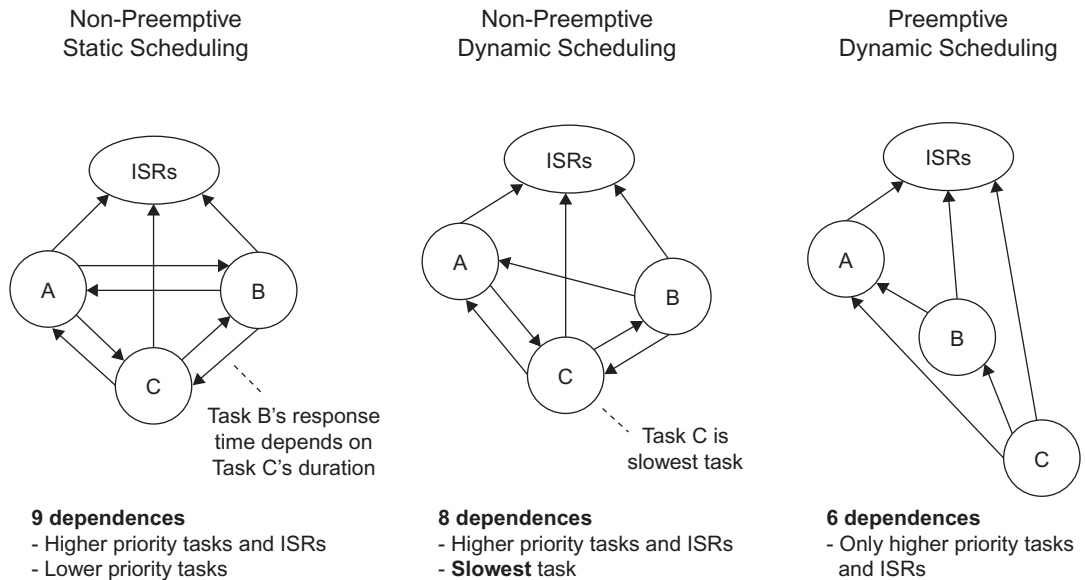


Figure 10.3 Timing dependences of different scheduling approaches.

³ There are exceptions when tasks can communicate with each other with semaphores and other such mechanisms, but that is beyond the scope of this introductory text.

that task B's response time depends on task C's duration. We can now compare timing dependences for these three classes of scheduler.

- With the non-preemptive static scheduler, each task's response time depends on the duration of all other tasks and ISRs, so there are nine dependences.⁴
- With the non-preemptive dynamic scheduler, we assign priorities to tasks ($A > B > C$). In general, a task no longer depends on lower priority tasks, so we have more timing independence and isolation. This accounts for six dependences. The exception is the **slowest** or longest duration task, which is C in this example. If task C has started running, it will delay any other task, regardless of priority. So the higher priority tasks A and B each have a dependence edge leading to task C in Figure 10.3, which results in a total of eight dependences.
- With the preemptive dynamic scheduler, we also prioritize the tasks ($A > B > C$). Because a task can preempt any lower priority task, the slowest task no longer matters. Each task can be preempted by an ISR, so there are three dependence edges to begin with. Task A cannot be preempted by B or C, so it adds no new edges. Task B can be preempted by task A, which adds one edge. Finally, task C can be preempted by task A or B, which adds two more edges. As a result we have only six dependences. Most importantly, these dependence edges **all point upwards**.⁵ This means that in order to determine the response time for a task, we only need to consider **higher priority tasks**. This makes the analysis much easier.

The real-time system research and development communities have developed extensive precise mathematical methods for calculating worst-case response times, determining if deadlines can ever be missed, and other characteristics of a system. These methods consider semaphores, task interactions, scheduler overhead, and all sorts of other complexities of practical implementations. We do not discuss them here as they are beyond the scope of this text.

10.3.5 Stack Memory Requirements

The non-preemptive scheduling approaches do not require as much data memory as the preemptive approaches. In particular, the non-preemptive approach requires only **one call stack**, while a preemptive approach typically requires **one call stack per task**.⁶

⁴ Of course, if task code can disable interrupts, then there will be three more edges leading from the ISRs back to the tasks! That would be a total of twelve dependences, which is quite a few to handle.

⁵ This is called a DAG or directed acyclic graph.

⁶ There are several ways to reduce the number of stacks needed for preemptive scheduling, but they are beyond the scope of this text.

The function call stack holds a function's state information such as return address and limited lifetime variables (e.g., automatic variables, which only last for the duration of a function). Without task preemption, task execution does not overlap in time, so all tasks can share the same stack. Preemption allows tasks to preempt each other at essentially any point in time. Trying to reuse the same stack space for different tasks would lead to corruption of this information on the stack. For example, task B is running. Function B3 in task B calls function B4. The scheduler then preempts task B to run the higher priority task A, which was running function A2. Function A2 completes and it expects to return to function A1, which called A2. However, the call stack has function B3's information on the stack, so task A will start executing function B3! And so the system fails to operate correctly.

As a result of these memory requirements for preemptive scheduling approaches, there are many cost-sensitive embedded systems which use a non-preemptive scheduler to minimize RAM sizes and therefore costs.

10.3.6 Interrupts

Interrupts are a special case of preemption with dedicated hardware and compiler support. They can be added to any of these scheduling approaches in order to provide faster, time-critical processing. In fact, for many systems **only** interrupt service routines are needed for the application's work. The main loop is simply an infinite loop which keeps putting the processor into a low-power idle mode.

When designing a system which splits between ISRs and task code, one must strike a balance. The more work which is placed in an ISR, the slower the response time for other processing (whether tasks or other ISRs⁷). The standard approach is to perform time-critical processing in the ISR (e.g., unloading a character from the UART received data buffer) and deferring remaining work for task code (pushing that character in a FIFO from which the task will eventually read). ISR execution duration affects the response time for other code, so it is included in the response time calculations described in Section 10.3.4 and in Figure 10.3.

There are many good texts which suggest approaches for architecting ISRs; please see the references list.

⁷ It is possible to make ISRs interruptable, but this introduces many new ways to build the system wrong. Hence it is discouraged.

10.4 TASK MANAGEMENT

10.4.1 Task States

A task will be in one of several possible states. The scheduler and the task code itself both affect which state is active. With a **non-preemptive dynamic scheduler**, a task can be in any one of the states⁸ shown in Figure 10.4a:

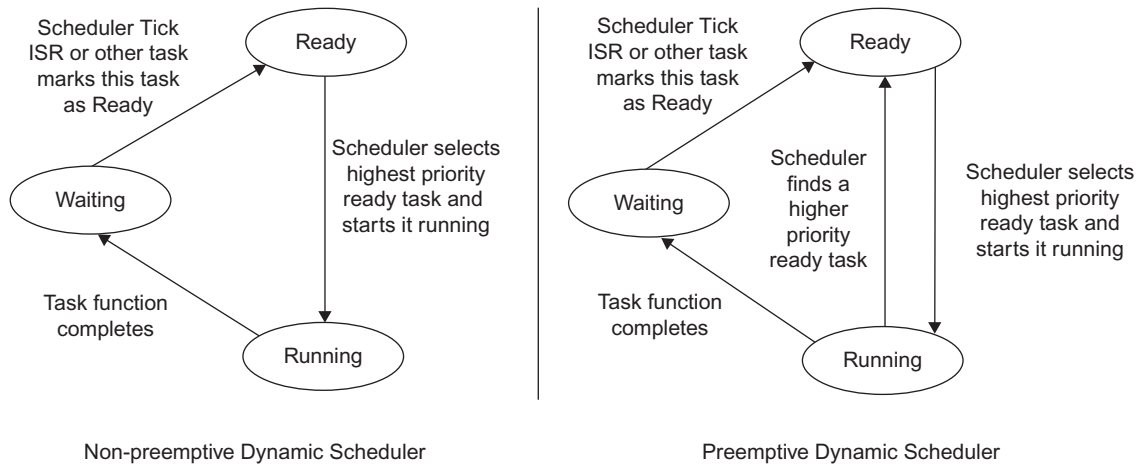


Figure 10.4 Task states and transitions for different schedulers. a) Non-preemptive and b) Preemptive

- **Waiting** for the scheduler to decide that this task is ready to run. For example, a task which asked the scheduler to delay it for 500 ms will be in this state for that amount of time.
- **Ready to start running** but not running yet. There may be a higher-priority task which is running. As this task has not started running, no automatic variables have been initialized, and there is no activation record.
- **Running** on the processor. The task **runs to the completion** of the task function, at which point the scheduler resumes execution and the task is moved to the waiting state. Automatic variables have been initialized, and there is at least one activation record on the stack frame for this task. A single processor system can have only one task in this state.

⁸ We consider preemption by an ISR as a separate state. However, since it operates automatically and saves and restores system context, we consider it as a separate enhancement to the RTC scheduler and leave it out of our diagrams. In fact, the scheduler relies on a tick ISR to track time and move tasks between certain states.

Consider a task which needs to write a block of data to flash memory. After issuing a write command to the flash memory controller, it may take some significant amount of time (e.g., 10 ms) to program the block. We have two options with a non-preemptive kernel:

- Our task can use a busy wait loop until the flash block programming is complete. The task remains in the **running** state while programming. This approach delays other processing and wastes processor cycles.
- We can break the task into a state machine so that task state one issues the write command, task state two checks to see if the programming is done, and task state three continues with the task's processing. The task executes task state two each time it is called as long as programming is not done. The task spends most of its time **waiting**, with occasional brief periods **running** when executing the code for task state two. This approach complicates program design but is practical for smaller systems. However, it grows unwieldy for complex systems.

Allowing tasks to **preempt** each other reduces response time and simplifies application design. With preemption, each task need not be built with a run-to-completion structure. Instead, the task can yield the processor to other tasks, or it can be preempted by a higher-priority task with more urgent processing. For example, our task can tell the scheduler "I don't have anything else to do for the next 10 ms, so you can run a different task." The scheduler then will save the state of this task, and swap in the state of the next highest priority task which is ready to run. This introduces another way to move from running to waiting, as well as a way to move from running to ready. We examine these in detail next.

10.4.2 Transitions between States

We now examine the ways in which a task can move between the various states. These rules govern how the system behaves, and therefore set some ground rules for how we should design our system.

- The transition from **ready to running**:
 - In a non-preemptive system, when the scheduler is ready to run a task, it selects the highest priority ready task and moves it to the running state, typically by calling it as a subroutine (as there is no context to restore).
 - In a preemptive system, when the kernel is ready to run a task, it selects the highest priority ready task and moves it to the running state by restoring its context to the processor.
- The transition from **running to waiting**:
 - In a non-preemptive system, the only way a task can move from running to waiting is if it **completes** (returns from the task function). At this point there is

- no more execution context for the task (return addresses, automatic variables), so there is no data to save or restore.
- In a preemptive system, the task can yield the processor.⁹ For example, it can request a delay (“Hey, RTOS! Wake me up in at least 10 ms!”) or it can wait or **pend** on an event (“Hey, RTOS! Wake me up when I get a message in my mailbox called foo!”). This makes application programming much easier, as mentioned before. At this point there still is execution context, so the kernel must save it for later restoration.
 - The transition from **waiting to ready**:
 - In a non-preemptive system such as the RTC scheduler above, the timer tick ISR moves the task by setting the run flag. Alternatively, another task can set the run flag to request for this task to run.
 - In a preemptive system, the kernel is notified that some event has occurred. For example, time delay has expired, or a task has sent a message to the mailbox called foo. The kernel knows which task is waiting for this event, so it moves that particular task from the waiting state to the ready state.
 - The transition from **running to ready**:
 - In a non-preemptive system this transition does not exist, as a task cannot be preempted.
 - In a preemptive system, when the kernel determines a higher priority task is ready to run, it will save the context of the currently running task, and move that task to the ready state.

10.4.3 Context Switching for Preemptive Systems

In preemptive systems, some of these state transitions require the scheduler to save a task’s execution context and restore another task’s context to ensure programs execute correctly. This is called **context switching** and involves accessing the processor’s general-purpose registers.

Figure 10.5 shows a view of a simple processor (not the RX63N) and its memory as it is executing task A in a system with two tasks (A and B). The CPU uses the program counter PC to fetch the next instruction to execute, and various pointer registers refer to locations in memory such as the task’s stack, etc. The CPU also has general purpose registers which are used to hold the programs data and intermediate computation results.

In order to perform a context switch from task A to task B correctly, we must first copy all of this task-specific processor register information to a storage location (e.g., task

⁹ What happens if the task function finishes executing depends on the RTOS. The task could move to the waiting state, or to a terminated state.

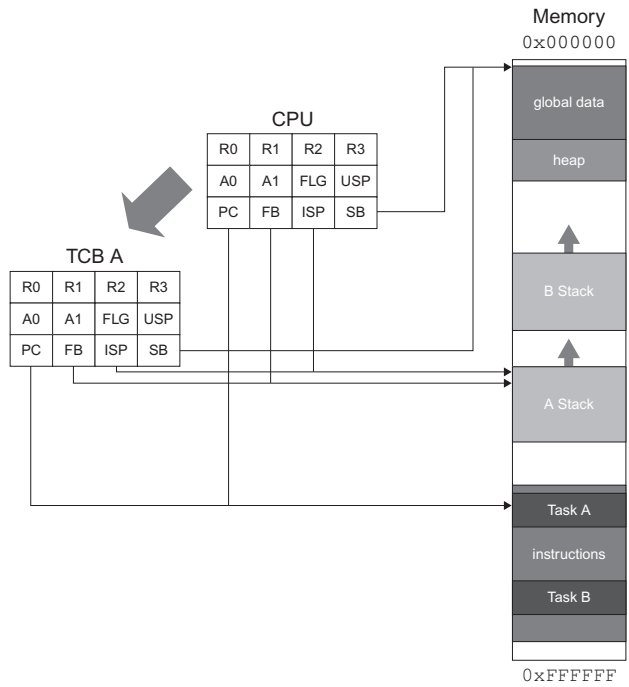


Figure 10.5 Saving task A's context from the CPU.

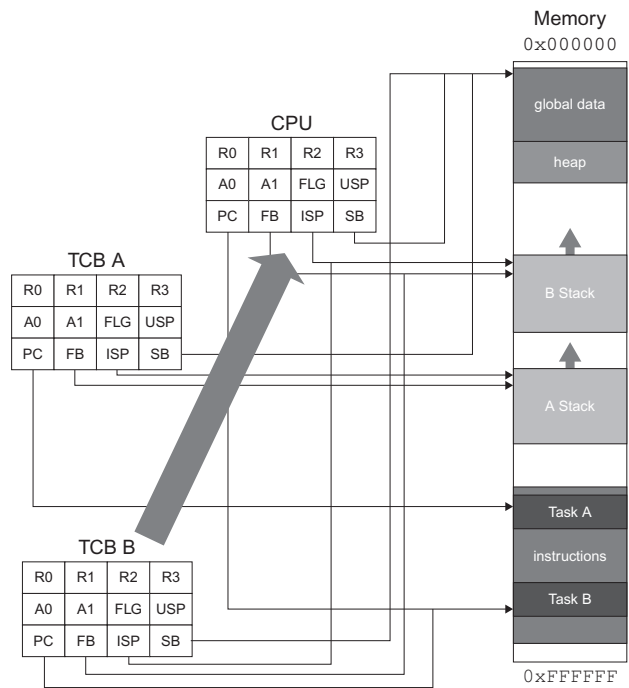


Figure 10.6 Restoring task B's context to the CPU.

control block (TCB) A). Second, we must copy all of the data from TCB B into the CPU's registers. This operation is shown in Figure 10.6. Now the CPU will be able to resume execution of task B where it left off.

10.5 SHARING DATA SAFELY

Preemption among tasks introduces a vulnerability to data race conditions. Now a task can be considered to be as bug-prone and difficult to debug as an ISR! The system can fail in new ways when:

- Multiple tasks or ISRs share data,¹⁰ or
- Multiple instances of a function can execute concurrently.

In order to prevent these failures we need to be careful when designing our system.

10.5.1 Data Shared Objects

If a data object is accessed by code which can be interrupted (is not *atomic*), then there is a risk of data corruption. *Atomic* code is the smallest part of a program that executes without interruption. Generally a single machine instruction is atomic,¹¹ but sequences of instructions are not atomic unless interrupts are disabled.

Consider an example where task A starts modifying object O. Task B preempts it before it finishes. At this point in time object O is corrupted, as it is only partially updated. If task B needs to read or write O, the computation results will be incorrect and the system will likely fail.

```

1. unsigned time_minutes, time_seconds;
2. void task1 (void){
3.     time_seconds++;
4.     if(time_seconds >= 60){
5.         time_minutes++;
6.         time_seconds = 0;
7.     }
8. }
```

¹⁰ Hardware registers which change outside of the program's control also introduce problems but we do not discuss them further here.

¹¹ Some instruction sets have long instructions (e.g., string copy, block move) which can be interrupted, in which case those instructions are not atomic.

```

9. void task2 (void){
10.     unsigned elapsed_sec;
11.     elapsed_seconds = time_minutes * 60 + time_seconds;
12. }

```

Here is a more specific example. Our shared object is a pair of variables which measure the current time in minutes and seconds. Task1 runs once per second to increment the seconds, and possibly the minutes as well. Task2 calculates how many total seconds have elapsed since time zero. There are data races possible:

- If task1 is preempted between lines 4 and 5 or lines 5 and 6, then when task2 runs it will only have a partially updated version of the current time, and elapsed_seconds will be incorrect.
- If task2 is preempted during line 11, then it is possible that timeinutes is read **before** task1 updates it and time_seconds is read **after** task 1 updates it. Again, this leads to a corrupted elapsed_seconds value.

10.5.2 Function Reentrancy

Another type of shared data problem comes with the use of non-reentrant functions. In this case, the problem arises from multiple instances of the **same function** accessing the same object. Consider the following example:

```

1. void task1 ( ){
2.     . . . . .
3.     swap(&x, &y);
4.     . . . . .
5. }
6. void task2 ( ){
7.     . . . . .
8.     swap(&p, &q);
9.     . . . . .
10. }
11. int Temp;
12. void swap (*i, *j ){
13.     Temp = *j;
14.     *j = *i;
15.     *i = Temp;
16. }

```

Suppose task1 is running and calls the swap function. After line 13 is executed, task2 becomes ready. If task2 has a higher priority, task1 is suspended and task2 is serviced. Later, task1 resumes to line 14. Since Temp is a shared variable, it is not stored in the TASK subroutine shared data stack. When task1 line 15 is executed, variable x (of task1 pointed by variable pointer i) gets the wrong value. Such function executions should not be suspended in between or shared by more than one task. Such functions are called **non-reentrant**. The code which can have multiple simultaneous, interleaved, or nested invocations which will not interfere with each other is called reentrant code. These types of code are important for parallel processing, recursive functions or subroutines, and for interrupt handling. An example of a reentrant code is as follows:

```
1. void swap (*i, *j ){
2.     static int Temp;
3.     Temp = *j;
4.     *j = *i;
5.     *i = Temp;
6. }
```

Since the variable `Temp` is declared within the function, if any other task interrupts the execution of the `swap` function, the variable `Temp` will be stored in the corresponding task's stack and will be retrieved when the task resumes its function. In most cases, especially in a multi-processing environment, the non-reentrant functions should be eliminated. A function can be checked for its reentrancy based on these three rules:

1. A reentrant function may not use variables in a non-atomic way unless they are stored on the stack of the calling task or are the private variables of that task.
2. A reentrant function may not call other functions which are not reentrant.
3. A reentrant function may not use the hardware in a non-atomic way.

10.5.3 High-Level Languages and Atomicity

We can identify **some but not all** non-atomic operations by examining high-level source code. Since the processor executes machine code rather than a high-level language such as C or Java, we can't identify all possible non-atomic operations just by examining the C source code. Something may seem atomic in C but actually be implemented by multiple machine instructions. We need to examine the assembly code to know for sure. Let's examine the following function and determine whether it is reentrant or not:

EXAMPLE 1

```
1. static int event_count;
2. void event_counter (void){
3.     ++event_count;
4. }
```

Example 1 in assembly language:

```
1. MOV.L #0000100CH, R4
2. MOV.L [R4], R5
3. ADD #1H, R5
4. MOV.L R5, [R4]
5. RTS
```

Consider example 1, and then apply the first rule. Does it use shared variable `event_count` in an atomic way? The `++event_count` operation is not atomic, and that single line of C code is implemented with three lines of assembly code (lines two through four). The processor loads R4 with a pointer to `event_count`, copies the value of `event_count` into register R5, adds 1 to R5, and then stores it back into memory. Hence, example 1 **is non-reentrant**.

However, what if the processor instruction set supports in-place memory operations? The RX architecture does not, but many others do. In that case, the assembly code could look like this:

Example 1 in assembly language, compiled for a different processor architecture:

```
1. MOV.L #0000100CH, A0
2. ADD #1H, [A0]
3. RTS
```

This code **is reentrant**, since there is only one instruction needed to update the value of the event count. Instruction 1 is only loading a pointer to the event count, so interrupting between 1 and 2 does not cause a problem.

EXAMPLE 2

```
1. void add_sum (int *j){
2.     ++(*j);
3.     DisplayString(LCDLINE1, Int_to_ascii(*j);
4. }
```

Now consider example 2. Even though line 2 in this example is not atomic, the variable `*j` is task's private variable, hence rule 1 is not breached. But consider line 3. Is the function `DisplayString` reentrant? That depends on the code of `DisplayString`, which depends on the user. Unless we are sure that the `DisplayString` function is reentrant, example 2 is considered to be non-reentrant. So every time a user codes a function, he has to make sure the function is reentrant to avoid erroneous results.

10.5.4 Shared-Data Solutions and Protection

In the previous section, we discussed the problems of using shared data in a RTOS environment. In this section we shall study some methods to protect the shared data. The solutions provided in this section may not be ideal for all applications. The user must judge which solution may work best for the application.

Disable Interrupts

One of the easiest methods is to disable the interrupts during the critical section of the task. Disabling the interrupts may not take more than one machine cycle to execute, but will increase the worst case response time of all other code, including other interrupt service routines. Once the critical section, or shared variable section, of the code is executed, the interrupt masking be restored to its previous state (either enabled or disabled). The user must be cautious while disabling or enabling interrupts, because if interrupts are disabled for too long, the system may fail to meet the timing requirements. See Chapter 9, *Using Interrupts with Peripherals*, to find out how to disable and restore interrupt masking state. A simple example of disabling interrupts is as follows:

```

1. #define TRUE 1
2. #define FALSE 0
3. static int error;
4. static int error_count;
5. void error_counter ( ){
6.     if(error == TRUE){
7.         SAVE_INT_STATE;
8.         DISABLE_INTS;
9.         error_count++;
10.        error = FALSE;
11.        RESTORE_INT_STATE;
12.    }
13. }
```


Disabling and restoring the interrupt masking state requires only one or a few machine cycles. Disabling interrupts must take place only at critical sections to avoid increasing response time excessively. Also, while restoring the interrupt masking state the user must keep in mind the need to enable only those interrupts that were active (enabled) before they were disabled. Determining the interrupt masking status can be achieved by referring to the **interrupt mask register**. The interrupt mask register keeps track of which interrupts are enabled and disabled.

Use a Lock

Another solution is to associate every shared variable with a lock variable, which is also declared globally. If a function uses the shared variable, then it sets the lock variable and once it has finished process, it resets the lock variable. Every function must test the lock variable before accessing it. If the lock variable is already set, the task should inform the scheduler to be rescheduled once the variable becomes available. Since only one variable has to be checked every time before accessing the data, using lock variables simplifies the data structure and I/O devices access. Consider the following example for using a lock:

```

1. unsigned int var;
2. char lock_var;
3. void task_var ( ){
4.     unsigned int sum;
5.     if(lock_var == 0){
6.         lock_var = 1;
7.         var = var + sum;
8.         lock_var = 0;
9.     }
10.    else {
11.        /* message to scheduler to check var
12.        and reschedule */
13.    }
14. }
```

Since it takes more than one clock cycle to check whether a variable is available and use a lock on it, the interrupts have to be disabled. Once again when the lock has to be released, the interrupts should be disabled since locking and releasing the variable is a critical part of the code. Interrupts must be enabled whenever possible to lower the interrupt service response time. If the variable is not available, the scheduler is informed about the lock and the task goes into a waiting state.

Microprocessors such as the Renesas RX support Bit Test and Set instructions can perform a test and set in one atomic machine instruction, and therefore do not require an interrupt disable/enable lock around semaphore usage.

The challenge with this approach is determining what to do in lines 11 and 12 if there is no scheduler support. There may be no easy way to tell the scheduler to reschedule this task when the lock variable becomes available again.

RTOS-Provided Semaphore

Most operating systems provide locks to shared variables through the use of *semaphores*. A semaphore is a mechanism that uses most of the multitasking kernels to protect shared data and to synchronize two tasks. A semaphore is very much similar to the variable lock process explained in the Section 10.4.3. The main difference is that the OS takes care of initializing and handling the locks, so the implementation is much more likely to be correct than if you try to create your own lock.

There are two types of semaphores—*binary semaphores* and *counting semaphores*. Binary semaphores take two values, 0 or 1. A counting semaphore takes a value between 0 and $2^N - 1$, where N is the number of bits used for the semaphore. In this book we consider only the binary semaphore. A semaphore usually has three tasks: *initialization/create*, *wait*, and *signal*.

A non-zero number or value is assigned to the semaphore once it is created. At this point no task is waiting for the semaphore. Once a task requires a data, the task performs a *wait* operation on the semaphore. The OS checks the value of the semaphore; for example, if the semaphore is available (semaphore value is non-zero), the OS changes the value of the semaphore to zero and assigns the semaphore to the task. If the semaphore value is zero during the wait operation, the task that requested the *wait* operation is placed on the semaphore's waiting list. Once the semaphore becomes available based on the priority of the tasks waiting for it, the OS decides which task to assign to the semaphore.

The tasks added to the semaphore's waiting list wait only for a certain amount of time. If the time expires, the task sends an error code to the semaphore seeking function and resumes its work. When the task has attained the semaphore and all its operations are complete, the task performs a *signal* operation, announcing that the semaphore is free. The OS checks if any other task is waiting for the semaphore and then transfers the semaphore to the task without changing the semaphore's value. If no task is waiting for the semaphore, the semaphore is incremented to a non-zero number. The wait operation is also referred to as *Take* or *Pend* or *P* and signal operation is referred to as *Release* or *Post* or *V*. The following example shows how wait and signal operations are performed:

```
1. typedef int semaphore;  
2. float temp;  
3. semaphore var_temp  
4. void Task1 (void){
```

```
5.     wait (var_temp);
6.     temp = (9/5) (temp + 32); /* Celsius into Fahrenheit */
7.     Signal (var_temp);
8. }
9. void Task2 (void){
10.    wait(var_temp);
11.    temp = ADDR0; /* Read ADC value from thermistor */
12.    temp = ADCtotemp_conversion();
13.    Signal (var_temp);
14. }
```

In the previous example two tasks share the variable `temp`. The `Task2` subroutine reads the temperature value from a thermistor and saves it on `temp`, while `Task1` converts the temperature from Celsius to Fahrenheit. Just before the tasks enter the critical section, they request the semaphore and only then perform the operation on the shared variable.

RTOS-Provided Messages

The RTOS provides other mechanisms besides semaphores for allowing tasks to communicate, such as message queues and mailboxes. It may be possible to structure your program to use messages to pass information rather than sharing data objects directly. We leave further discussion of this approach to the many RTOS-oriented books and articles already available.

Disable Task Switching

If no other method seems to work, one unattractive option is to disable the scheduler. If the scheduler is disabled, the task switching does not take place and the critical sections or shared data can be protected by other tasks. This method is counter-productive; disabling the scheduler increases response times and makes analysis much more difficult. This is considered bad practice and must be properly justified; hence consider this method as a last resort.

10.6 NONPREEMPTIVE DYNAMIC SCHEDULER

10.6.1 Concepts

We will now examine a flexible nonpreemptive scheduler for periodic and aperiodic tasks. We call it the RTC (run-to-completion) scheduler. This simple tick-based scheduler is quite flexible and offers the following major benefits:

- We can configure the system to run each task with a given period (e.g., every 40 ms) measured in time ticks. This simplifies the creation of multi-rate systems.

- We can define task priorities, allowing us to design the system's response (which tasks are executed earlier) when there are multiple tasks ready to run.
- We can selectively enable and disable tasks.

This scheduler has three fundamental parts.

- **Task Table:** This table holds information on each task, including:
 - The address of the task's root function.
 - The period with which the task should run (e.g., 10 ticks).
 - The time delay until the next time the task should run (measured in ticks).
 - A flag indicating whether the task is ready to run.
- **Tick ISR:** Once per time tick (say each 1 millisecond) a hardware timer triggers an interrupt. The interrupt service routine decrements the time delay (**timer**) until the next run. If this reaches zero, then the task is ready to release, so the ISR sets its **run** flag.
- **Task Dispatcher:** The other part of the scheduler is what actually runs the tasks. It is simply an infinite loop which examines each task's run flag. If it finds a task with the **run** flag set to 1, the scheduler will clear the **run** flag back to 0, execute the task, and then go back to examining the **run** flags (starting with the highest-priority task in the table).

Figure 10.7 shows a simple example of how this works with three tasks. Task 1 becomes active every twenty time intervals, and takes one time interval to complete. Task 2 is active every ten time intervals, and takes two time intervals to complete. Task 3 becomes active every five time intervals and takes one time interval to complete.

If more than one task becomes ready simultaneously (as seen at elapsed time ten), the higher priority task is serviced first. When the higher priority task finishes, the next highest ready task is executed. This repeats until there are no ready tasks.

Another example of a run-to-completion dynamic scheduling with interrupts is shown in Figure 10.8. A new task, Task 4, is added, which becomes active every three time intervals and runs for one time interval.

As shown in Figure 10.8, at time = 20, tasks T1, T2, T3 all become active and T2 is run based on priority. At time = 21, task T4 becomes active and is scheduled to run at time = 22. T1 runs at time = 23, but before T3 gets a chance to run, T4 becomes active again and gains the processor. At time = 25, T3 misses a turn since T3 becomes active again and the T3 is serviced as if it were active only once. This is an example of an overload situation which leads to one of the tasks missing its turn.¹²

¹² We could use a counter rather than a flag for the run variable, to allow for processing backlogs. In this case the ISR would increment run rather than set it, and the scheduler function would decrement it rather than clear it. This could be useful in some situations, but it would complicate the analysis.

	Priority		Length		Frequency																																	
Task 1	2		1		20																																	
Task 2	1		2		10																																	
Task 3	3		1		5																																	
Task 4	0		2		3																																	
Elapsed time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30							
Task executed				T4	T3	T4				T4	T2		T4	T4	T3	T4	T2	T4	T4	T1	T4	T3	T4															
Task T1	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	20	19	18	17	16	15	14	13	12	11	10							
Task T2	10	9	8	7	6	5	4	3	2	1	10	9	8	7	6	5	4	3	2	1	10	9	8	7	6	5	4	3	2	1	10							
Task T3	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5	4	3	2	1	5							
Task T4	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3	2	1	3							
Run T1																					W	W	W	W	W	W	R											
Run T2											W	R									R																W	
Run T3						R					W	W	W	W	W	W	W	R			W	W	W	W	W	W	W	W	W	R	W							
Run T4				R		R			R			W	R		R				R			W	R		R			R								R		

R = Running on processor W = Ready and waiting for processor

Figure 10.9 Overload example of run-to-completion dynamic scheduling.

Figure 10.9 shows a complex overloaded example where the scheduler fails to service every task that is ready.

10.6.2 Implementation

Task Table

A scheduler uses a table to store information on each task. Each task has been assigned a timer value. A task becomes active at regular intervals based on this value. This timer value is decremented each tick by the timer tick ISR. Once the timer value reaches zero, the task becomes ready to run. To reset this value after it has reached zero, an initial Timer Value variable is used to store the time at which the task has to be active. Two variables, *enabled* and *run*, are used to signal when a task is *enabled* and when it is ready to run. Variables *enabled* and *run* are used to indicate to the scheduler if a task is enabled and if it is ready to run. The function pointer **task* indicates to the scheduler which function to perform.

The task’s priority is defined by its position within this array. Entry 0 has the highest priority; whenever the scheduler needs to find a task to run, it begins at entry 0 and then works its way through the table.

The scheduler's task table is defined as follows:

```
1. #define MAX_TASKS 10
2. #define NULL ((void *)0)
3. typedef struct {
4.     int initialTimerValue;
5.     int timer;
6.     int run;
7.     int enabled;
8.     void (* task)(void);
9. } task_t;
10. task_t GBL_task_table [MAX_TASKS];
```

Before running the scheduler, the application must initialize the task table as follows:

```
1. void init_Task_Timers(void){
2.     int i;
3.     /* Initialize all tasks */
4.     for(i = 0; i < MAX_TASKS; i++){
5.         GBL_task_table[i].initialTimerValue = 0;
6.         GBL_task_table[i].run = 0;
7.         GBL_task_table[i].timer = 0;
8.         GBL_task_table[i].enabled = 0;
9.         GBL_task_table[i].task = NULL;
10.    }
11. }
```

Managing Tasks

Once the initialization is completed, tasks must be added to the task structure. The new tasks can be added before starting the scheduler or during the scheduler's execution time. When adding a task, the following must be specified: the time interval in which the task has to be active, its priority, and the function on which the task has to operate. The following code shows how adding a task is added:

```
1. int Add_Task(void (*task)(void), int time, int priority){
2.     /* Check for valid priority */
3.     if(priority >= MAX_TASKS || priority < 0)
4.         return 0;
5.     /* Check to see if we are overwriting an already scheduled
6.        task */
7.     if(GBL_task_table [priority].task != NULL)
```

```
7.     return 0;
8.     /* Schedule the task */
9.     GBL_task_table[priority].task = task;
10.    GBL_task_table[priority].run = 0;
11.    GBL_task_table[priority].timer = time;
12.    GBL_task_table[priority].enabled = 1;
13.    GBL_task_table[priority].initialTimerValue = time;
14.    return 1;
15. }
```

We can remove an existing task:

```
1. void removeTask(void (* task)(void)){
2.     int i;
3.     for(i = 0; i < MAX_TASKS; i++){
4.         if(GBL_task_table[i].task == task){
5.             GBL_task_table[i].task = NULL;
6.             GBL_task_table[i].timer = 0;
7.             GBL_task_table[i].initialTimerValue = 0;
8.             GBL_task_table[i].run = enabled = 0;
9.             return;
10.        }
11.    }
12. }
```

We can also selectively enable or disable a task by changing its **enabled** flag:

```
1. void Enable_Task(int task_number){
2.     GBL_task_table[task_number].enabled = 1;
3. }
4.
5. void Disable_Task(int task_number){
6.     GBL_task_table[task_number].enabled = 0;
7. }
```

Finally, we can change the period with which a task runs:

```
1. void Reschedule_Task(int task_number, int new_timer_val){
2.     GBL_task_table[task_number].initialTimerValue =
3.     new_timer_val;
4.     GBL_task_table[task_number].timer = new_timer_val;
5. }
```


Tick Timer Configuration and ISR

A run-to-completion dynamic scheduler uses a timer to help determine when tasks are ready to run (are released). A timer is set up to generate an interrupt at regular intervals. Within the interrupt service routine the timer value for each task is decremented. When the timer value reaches zero, the task becomes ready to run. In this code we have configured the 8-bit timer to generate an interrupt every 0.5 milliseconds. For details on how to set up a timer see Chapter 8.

```

1. void Init_RTC_Scheduler(void) {
2.     IEN(TMR0,CMIA0) = 0;
3.     IPR(TMR0,CMIA0) = 3;
4.     MSTP(TMR0) = 0;
5.     TMR0.TCNT = 0x00;
6.     TMR0.TCORA = 78;
7.     TMR0.TCSR.BYTE = 0xE2;
8.     IEN(TMR0,CMIA0) = 1;
9.     TMR0.TCCR.BYTE = 0x0C;
10.    TMR0.TCR.BYTE = 0x48;
11. }

```

In the next example timer 0 is set to compare the match mode with timer constant A. An interrupt occurs every 0.5 milliseconds. The timer is configured in a continuous mode and re-sets every time a compare match is made.

```

1. void Excep_TMR0_CMIOA(void) {
2.     int i;
3.     for(i = 0; i < MAX_TASKS; i++){
4.         if(GBL_task_table[i].task != NULL) &&
5.         (GBL_task_table[i].enabled == 1) &&
6.         (GBL_task_table[i].timer > 0))
7.         {
8.             if(--GBL_task_table[i].timer == 0){
9.                 GBL_task_table[i].run = 1;
10.                GBL_task_table[i].timer =
11.                GBL_task_table[i].initialTimerValue;
12.            }
13.        }
14.    }
15. }

```

Scheduler

The scheduler looks for ready tasks starting at the top of the table (highest priority task). It runs every ready task it finds, calling it as a function (in line 16).

```

1. void Run_RTC_Scheduler(void) {
2.     int i;
3.     /* Loop forever */
4.     while(1) {
5.         /* Check each task */
6.         for(i = 0; i < MAX_TASKS; i++){
7.             /* check if valid task */
8.             if(GBL_task_table[i].task != NULL) {
9.                 /* check if enabled */
10.                if(GBL_task_table[i].enabled == 1) {
11.                    /* check if ready to run */
12.                    if(GBL_task_table[i].run == 1) {
13.                        /* Reset the run flag */
14.                        GBL_task_table[i].run = 0;
15.                        /* Run the task */
16.                        GBL_task_table[i].task();
17.                        /* break out of loop to start at entry 0 */
18.                        break;
19.                    }
20.                }
21.            }
22.        }
23.    }
24. }

```

10.6.3 Example Application using RTC Scheduler

Let's use the RTC scheduler to create a toy with red and green LEDs flashing at various frequencies. The grnLED task toggles a green LED (on board LED 6) every one second, and the redLED task toggles a red LED (on board led 12) every 0.25 seconds. The grn_redLED task toggles one red LED and one green LED (on board led 7 and led 8 respectively) every 0.5 seconds.

The tasks and the main program are shown below:

```

1. void grnLED(void) {
2.     if(LED3 == LED_ON)

```

```
3.     LED3 = LED_OFF;
4.     else
5.     LED3 = LED_ON;
6. }
7. void redLED(void){
8.     if(LED4 == LED_ON)
9.     LED4 = LED_OFF;
10.    else
11.     LED4 = LED_ON;
12. }
13. void grn_redLED(void){
14.     if(LED5 == LED_ON)
15.     LED5 = LED9 = LED_OFF;
16.     else
17.     LED5 = LED9 = LED_ON;
18. }
19. void main(void){
20.     ENABLE_LEDS;
21.     init_Task_Timers();
22.     Add_Task(grnLED,10000,0);
23.     Add_Task(redLED,2500,1);
24.     Add_Task(grn_redLED,5000,2)
25.     Init_RTC_Scheduler();
26.     Run_RTC_Scheduler();
27. }
```

10.7 REFERENCES

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10.8 EXERCISES

1. What is the difference between an operating system and a real-time operating system? Why would you consider using a real-time operating system rather than a regular operating system for certain applications?
2. Describe what context switching is and how it is performed.
3. What problems might occur when switching tasks in a real-time operating system? What can be done to prevent these problems from happening?
4. For some task sets, changing from static to dynamic task ordering in a scheduler will provide a major response time improvement for the highest priority task, while for other task sets it will not. Give an example of each and explain the difference.
5. For some task sets, adding preemption to a scheduler will provide a major response time improvement for the highest priority task, while for other task sets it will not. Give an example of each and explain the difference.
6. Describe what semaphores are and how they are used in real-time operating systems.
7. Write C code to implement run-to-completion dynamic scheduling without interrupts to poll the following tasks:
 - a. If switch 1 is pressed Toggle the RED LEDs.
 - b. If switch 2 is pressed read the temperature value from the onboard thermistor and display on LCD.
 - c. If switch 3 is pressed read the potentiometer value and display on the LCD.
 - d. If no switch is pressed Toggle the GREEN LEDs.
8. Write an algorithm which implements the below functionality using run-to-completion dynamic scheduling with interrupts:
 - a. Toggle RED LEDs every 0.5 seconds.
 - b. Toggle GREEN LEDs every 0.25 seconds.
 - c. Read temperature value from onboard thermistor and display on LCD every 1.0 seconds.
 - d. Read potentiometer value and display on LCD every 2.5 seconds.
9. Write C code to implement a round-robin with interrupts algorithm to perform the following tasks:
 - a. Toggle RED LEDs every 0.5 seconds.
 - b. Toggle GREEN LEDs every 0.25 seconds.
 - c. Read temperature value from onboard thermistor and display on LCD every 1.0 seconds.
 - d. Read potentiometer value and display on LCD every 2.5 seconds.
10. Draw a state diagram which implements the following tasks:
 - a. Read the x axis of the on-board accelerometer every 1.5 seconds.
 - b. Read the y axis of the on-board accelerometer every 3 seconds.
 - c. Read the z axis of the on-board accelerometer every 5 seconds.
 - d. Read all axes of the on-board accelerometer whenever button 2 is pressed.
 - e. Display all the values read above on the LCD whenever button 1 is pressed.

11. Write C code to implement the following tasks using a run-to-completion scheduling algorithm with interrupts.
 - a. Read the x axis of the on-board accelerometer once 1.5 seconds.
 - b. Read the y axis of the on-board accelerometer every 3 seconds.
 - c. Read the z axis of the on-board accelerometer every 5 seconds.
 - d. Read all axes of the on-board accelerometer whenever button 2 is pressed.
 - e. Display all the values read above on the LCD whenever button 1 is pressed.
12. Construct a task table which outlines how the tasks of the C code you wrote in Exercise 11 are executed.
13. Fill in the following table to show which tasks the processor will execute and when, as well as scheduler table contents. Assume that timer tick interrupts occur every 1 millisecond, all tasks take 1.2 milliseconds to complete, and initialTimerValue for tasks A, B, and C are 2, 4, and 5 respectively. Note that the entries in the table in column “Right before n ” (e.g., timer, run, enabled) show the variable’s value right before the timer tick interrupt occurs. This means that a task will run on the tick when its timer reaches 0 (but show the value after the tick and after the ISR executes). Assume task A has the highest priority, followed by task B, and then C.

TASK NAME		RIGHT BEFORE	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		N	N	1	2	3	4	5	6	7	8	9	10	11	12	13
A	timer	2														
	run	0														
	enabled	1														
B	timer	3														
	run	0														
	enabled	1														
C	timer	1														
	run	0														
	enabled	1														
	Activity	—														

14. Fill in the table in Exercise 13, if timer tick interrupts occur every 2.0 milliseconds and all tasks take 1.25 milliseconds to complete.

Appendix A

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
—	Reserved	0	0000h	—	x	x	x	x	x	—	—	—
—	Reserved	1	0004h	—	x	x	x	x	x	—	—	—
—	Reserved	2	0008h	—	x	x	x	x	x	—	—	—
—	Reserved	3	000Ch	—	x	x	x	x	x	—	—	—
—	Reserved	4	0010h	—	x	x	x	x	x	—	—	—
—	Reserved	5	0014h	—	x	x	x	x	x	—	—	—
—	Reserved	6	0018h	—	x	x	x	x	x	—	—	—
—	Reserved	7	001Ch	—	x	x	x	x	x	—	—	—
—	Reserved	8	0020h	—	x	x	x	x	x	—	—	—
—	Reserved	9	0024h	—	x	x	x	x	x	—	—	—
—	Reserved	10	0028h	—	x	x	x	x	x	—	—	—
—	Reserved	11	002Ch	—	x	x	x	x	x	—	—	—
—	Reserved	12	0030h	—	x	x	x	x	x	—	—	—
—	Reserved	13	0034h	—	x	x	x	x	x	—	—	—
—	Reserved	14	0038h	—	x	x	x	x	x	—	—	—
—	Reserved	15	003Ch	—	x	x	x	x	x	—	—	—
BSC	BUSERR	16	0040h	Level	0	x	x	x	x	IER02.IEN0	IPR000	—
—	Reserved	17	0044h	—	x	x	x	x	x	—	—	—
—	Reserved	18	0048h	—	x	x	x	x	x	—	—	—
—	Reserved	19	004Ch	—	x	x	x	x	x	—	—	—
—	Reserved	20	0050h	—	x	x	x	x	x	—	—	—
FCU	FIFERR	21	0054h	Level	0	x	x	x	x	IER02.IEN5	IPR001	—
—	Reserved	22	0058h	—	x	x	x	x	x	—	—	—
FCU	FRDYI	23	005Ch	Edge	x	x	x	x	x	IER02.IEN7	IPR002	—
—	Reserved	24	0060h	—	x	x	x	x	x	—	—	—
—	Reserved	25	0064h	—	x	x	x	x	x	—	—	—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
—	Reserved	26	0068h	—	x	x	x	x	x	—	—	—
ICU	SWINT	27	006Ch	Edge	o	o	x	x	x	IER03.IEN3	IPR003	DTCER027
CMT0	CMI0	28	0070h	Edge	o	o	o	x	x	IER03.IEN4	IPR004	DTCER028
CMT1	CMI1	29	0074h	Edge	o	o	o	x	x	IER03.IEN5	IPR005	DTCER029
CMT2	CMI2	30	0078h	Edge	o	o	o	x	x	IER03.IEN6	IPR006	DTCER030
CMT3	CMI3	31	007Ch	Edge	o	o	o	x	x	IER03.IEN7	IPR007	DTCER031
Ether	EINT	32	0080h	Level	o	x	x	x	x	IER04.IEN0	IPR032	—
USB0	D0FIFO0	33	0084h	Edge	o	o	o	x	x	IER04.IEN1	IPR033	DTCER033
	D1FIFO0	34	0088h	Edge	o	o	o	x	x	IER04.IEN2	IPR034	DTCER034
	USBIO	35	008Ch	Edge	o	x	x	x	x	IER04.IEN3	IPR035	—
USB1	D0FIFO1	36	0090h	Edge	o	o	o	x	x	IER04.IEN4	IPR036	DTCER036
	D1FIFO1	37	0094h	Edge	o	o	o	x	x	IER04.IEN5	IPR037	DTCER037
	USB11	38	0098h	Edge	o	x	x	x	x	IER04.IEN6	IPR038	—
RSPIO	SPRIO	39	009Ch	Edge	o	o	o	x	x	IER04.IEN7	IPR039	DTCER039
	SPTIO	40	00A0h	Edge	o	o	o	x	x	IER05.IEN0		DTCER040
	SPIIO	41	00A4h	Level	o	x	x	x	x	IER05.IEN1		—
RSPI1	SPRI1	42	00A8h	Edge	o	o	o	x	x	IER05.IEN2	IPR042	DTCER042
	SPT11	43	00ACh	Edge	o	o	o	x	x	IER05.IEN3		DTCER043
	SPII1	44	00B0h	Level	o	x	x	x	x	IER05.IEN4		—
RSPI2	SPRI2	45	00B4h	Edge	o	o	o	x	x	IER05.IEN5	IPR045	DTCER045
	SPTI2	46	00B8h	Edge	o	o	o	x	x	IER05.IEN6		DTCER046
	SPII2	47	00BCh	Level	o	x	x	x	x	IER05.IEN7		—
CAN0	RXF0	48	00C0h	Edge	o	x	x	x	x	IER06.IEN0	IPR048	—
	TXF0	49	00C4h	Edge	o	x	x	x	x	IER06.IEN1		—
	RXM0	50	00C8h	Edge	o	x	x	x	x	IER06.IEN2		—
	TXM0	51	00CCh	Edge	o	x	x	x	x	IER06.IEN3		—
CAN1	RXF1	52	00D0h	Edge	o	x	x	x	x	IER06.IEN4	IPR052	—
	TXF1	53	00D4h	Edge	o	x	x	x	x	IER06.IEN5		—
	RXM1	54	00D8h	Edge	o	x	x	x	x	IER06.IEN6		—
	TXM1	55	00DCh	Edge	o	x	x	x	x	IER06.IEN7		—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
CAN2	RXF2	56	00E0h	Edge	0	x	x	x	x	IER07.IEN0	IPR056	—
	TXF2	57	00E4h	Edge	0	x	x	x	x	IER07.IEN1		—
	RXM2	58	00E8h	Edge	0	x	x	x	x	IER07.IEN2		—
	TXM2	59	00ECh	Edge	0	x	x	x	x	IER07.IEN3		—
—	Reserved	60	00F0h	—	x	x	x	x	x	—	—	—
—	Reserved	61	00F4h	—	x	x	x	x	x	—	—	—
RTC	CUP	62	00F8h	Edge	0	x	x	x	x	IER07.IEN6	IPR062	—
—	Reserved	63	00FCh	—	x	x	x	x	x	—	—	—
ICU	IRQ0	64	0100h	Edge/Level	0	0	0	0	0	IER08.IEN0	IPR064	DTCER064
	IRQ1	65	0104h	Edge/Level	0	0	0	0	0	IER08.IEN1	IPR065	DTCER065
	IRQ2	66	0108h	Edge/Level	0	0	0	0	0	IER08.IEN2	IPR066	DTCER066
	IRQ3	67	010Ch	Edge/Level	0	0	0	0	0	IER08.IEN3	IPR067	DTCER067
	IRQ4	68	0110h	Edge/Level	0	0	x	0	0	IER08.IEN4	IPR068	DTCER068
	IRQ5	69	0114h	Edge/Level	0	0	x	0	0	IER08.IEN5	IPR069	DTCER069
	IRQ6	70	0118h	Edge/Level	0	0	x	0	0	IER08.IEN6	IPR070	DTCER070
	IRQ7	71	011Ch	Edge/Level	0	0	x	0	0	IER08.IEN7	IPR071	DTCER071
	IRQ8	72	0120h	Edge/Level	0	0	x	0	0	IER09.IEN0	IPR072	DTCER072
	IRQ9	73	0124h	Edge/Level	0	0	x	0	0	IER09.IEN1	IPR073	DTCER073
	IRQ10	74	0128h	Edge/Level	0	0	x	0	0	IER09.IEN2	IPR074	DTCER074
	IRQ11	75	012Ch	Edge/Level	0	0	x	0	0	IER09.IEN3	IPR075	DTCER075
	IRQ12	76	0130h	Edge/Level	0	0	x	0	0	IER09.IEN4	IPR076	DTCER076
	IRQ13	77	0134h	Edge/Level	0	0	x	0	0	IER09.IEN5	IPR077	DTCER077
	IRQ14	78	0138h	Edge/Level	0	0	x	0	0	IER09.IEN6	IPR078	DTCER078
	IRQ15	79	013Ch	Edge/Level	0	0	x	0	0	IER09.IEN7	IPR079	DTCER079
—	Reserved	80	0140h	—	x	x	x	x	x	—	—	—
—	Reserved	81	0144h	—	x	x	x	x	x	—	—	—
—	Reserved	82	0148h	—	x	x	x	x	x	—	—	—
—	Reserved	83	014Ch	—	x	x	x	x	x	—	—	—
—	Reserved	84	0150h	—	x	x	x	x	x	—	—	—
—	Reserved	85	0154h	—	x	x	x	x	x	—	—	—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
—	Reserved	86	0158h	—	x	x	x	x	x	—	—	—
—	Reserved	87	015Ch	—	x	x	x	x	x	—	—	—
—	Reserved	88	0160h	—	x	x	x	x	x	—	—	—
—	Reserved	89	0164h	—	x	x	x	x	x	—	—	—
USB	USBRO	90	0168h	Level	o	x	x	o	o	IEROB.IEN2	IPR090	—
	USBRI	91	016Ch	Level	o	x	x	o	o	IEROB.IEN3	IPR091	—
RTC	ALM	92	0170h	Edge	o	x	x	o	o	IEROB.IEN4	IPR092	—
	PRD	93	0174h	Edge	o	x	x	o	o	IEROB.IEN5	IPR093	—
—	Reserved	94	0178h	—	x	x	x	x	x	—	—	—
—	Reserved	95	017Ch	—	x	x	x	x	x	—	—	—
—	Reserved	96	0180h	—	x	x	x	x	x	—	—	—
—	Reserved	97	0184h	—	x	x	x	x	x	—	—	—
AD0	AD	98	0188h	Edge	o	o	o	x	x	IEROC.IEN2	IPR098	DTCER098
—	Reserved	99	018Ch	—	x	x	x	x	x	—	—	—
—	Reserved	100	0190h	—	x	x	x	x	x	—	—	—
—	Reserved	101	0194h	—	x	x	x	x	x	—	—	—
S12AD	S12ADIO	102	0198h	Edge	o	o	o	x	x	IEROC.IEN6	IPR102	DTCER102
—	Reserved	103	019Ch	—	x	x	x	x	x	—	—	—
—	Reserved	104	01A0h	—	x	x	x	x	x	—	—	—
—	Reserved	105	01A4h	—	x	x	x	x	x	—	—	—
ICU	GROUP0	106	01A8h	Level	o	x	x	x	x	IEROD.IEN2	IPR106	—
	GROUP1	107	01ACh	Level	o	x	x	x	x	IEROD.IEN3	IPR107	—
	GROUP2	108	01B0h	Level	o	x	x	x	x	IEROD.IEN4	IPR108	—
	GROUP3	109	01B4h	Level	o	x	x	x	x	IEROD.IEN5	IPR109	—
	GROUP4	110	01B8h	Level	o	x	x	x	x	IEROD.IEN6	IPR110	—
	GROUP5	111	01BCh	Level	o	x	x	x	x	IEROD.IEN7	IPR111	—
	GROUP6	112	01C0h	Level	o	x	x	x	x	IEROE.IEN0	IPR112	—
—	Reserved	113	01C4h	—	x	x	x	x	x	—	—	—
ICU	GROUP12	114	01C8h	Level	o	x	x	x	x	IEROE.IEN2	IPR114	—
—	Reserved	115	01CCh	—	x	x	x	x	x	—	—	—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
—	Reserved	116	01D0h	—	x	x	x	x	x	—	—	—
—	Reserved	117	01D4h	—	x	x	x	x	x	—	—	—
—	Reserved	118	01D8h	—	x	x	x	x	x	—	—	—
—	Reserved	119	01DCh	—	x	x	x	x	x	—	—	—
—	Reserved	120	01E0h	—	x	x	x	x	x	—	—	—
—	Reserved	121	01E4h	—	x	x	x	x	x	—	—	—
SCI12	SCIX0	122	01E8h	Level	o	x	x	x	x	IER0F.IEN2	IPR122	—
	SCIX1	123	01ECh	Level	o	x	x	x	x	IER0F.IEN3		—
	SCIX2	124	01F0h	Level	o	x	x	x	x	IER0F.IEN4		—
	SCIX3	125	01F4h	Level	o	x	x	x	x	IER0F.IEN5		—
TPU0	TGI0A	126	01F8h	Edge	o	o	o	x	x	IER0F.IEN6	IPR126	DTCER126
	TGI0B	127	01FCh	Edge	o	o	x	x	x	IER0F.IEN7		DTCER127
	TGI0C	128	0200h	Edge	o	o	x	x	x	IER10.IEN0		DTCER128
	TGI0D	129	0204h	Edge	o	o	x	x	x	IER10.IEN1		DTCER129
TPU1	TGI1A	130	0208h	Edge	o	o	o	x	x	IER10.IEN2	IPR130	DTCER130
	TGI1B	131	020Ch	Edge	o	o	x	x	x	IER10.IEN3		DTCER131
TPU2	TGI2A	132	0210h	Edge	o	o	o	x	x	IER10.IEN4	IPR132	DTCER132
	TGI2B	133	0214h	Edge	o	o	x	x	x	IER10.IEN5		DTCER133
TPU3	TGI3A	134	0218h	Edge	o	o	o	x	x	IER10.IEN6	IPR134	DTCER134
	TGI3B	135	021Ch	Edge	o	o	x	x	x	IER10.IEN7		DTCER135
	TGI3C	136	0220h	Edge	o	o	x	x	x	IER11.IEN0		DTCER136
	TGI3D	137	0224h	Edge	o	o	x	x	x	IER11.IEN1		DTCER137
TPU4	TGI4A	138	0228h	Edge	o	o	o	x	x	IER11.IEN2	IPR138	DTCER138
	TGI4B	139	022Ch	Edge	o	o	x	x	x	IER11.IEN3		DTCER139
TPU5	TGI5A	140	0230h	Edge	o	o	o	x	x	IER11.IEN4	IPR140	DTCER140
	TGI5B	141	0234h	Edge	o	o	x	x	x	IER11.IEN5		DTCER141

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAc Activation	sstb Return	sacs Return	IER	IPR	DTCER
TPU6/MTU0	TGI6A(TPU6)/TGIA0(MTU0)	142	0238h	Edge	o	o	o	x	x	IER11.IEN6	IPR142	DTCER142
	TGI6B(TPU6)/TGIB0(MTU0)	143	023Ch	Edge	o	o	x	x	x	IER11.IEN7		DTCER143
	TGI6C(TPU6)/TGIC0(MTU0)	144	0240h	Edge	o	o	x	x	x	IER12.IEN0		DTCER144
	TGI6D(TPU6)/TGID0(MTU0)	145	0244h	Edge	o	o	x	x	x	IER12.IEN1		DTCER145
	TGIE0(MTU0)	146	0248h	Edge	o	x	x	x	x	IER12.IEN2	IPR146	—
	TGIF0(MTU0)	147	024Ch	Edge	o	x	x	x	x	IER12.IEN3		—
TPU7/MTU1	TGI7A(TPU7)/TGIA1(MTU1)	148	0250h	Edge	o	o	o	x	x	IER12.IEN4	IPR148	DTCER148
	TGI7B(TPU7)/TGIB1(MTU1)	149	0254h	Edge	o	o	x	x	x	IER12.IEN5		DTCER149
TPU8/MTU2	TGI8A(TPU8)/TGIA2(MTU2)	150	0258h	Edge	o	o	o	x	x	IER12.IEN6	IPR150	DTCER150
	TGI8B(TPU8)/TGIB2(MTU2)	151	025Ch	Edge	o	o	x	x	x	IER12.IEN7		DTCER151
TPU9/MTU3	TGI9A(TPU9)/TGIA3(MTU3)	152	0260h	Edge	o	o	o	x	x	IER13.IEN0	IPR152	DTCER152
	TGI9B(TPU9)/TGIB3(MTU3)	153	0264h	Edge	o	o	x	x	x	IER13.IEN1		DTCER153
	TGI9C(TPU9)/TGIC3(MTU3)	154	0268h	Edge	o	o	x	x	x	IER13.IEN2		DTCER154
	TGI9D(TPU9)/TGID3(MTU3)	155	026Ch	Edge	o	o	x	x	x	IER13.IEN3		DTCER155
TPU10/MTU4	TGI10A(TPU10)/TGIA4(MTU4)	156	0270h	Edge	o	o	o	x	x	IER13.IEN4	IPR156	DTCER156
	TGI10B(TPU10)/TGIB4(MTU4)	157	0274h	Edge	o	o	x	x	x	IER13.IEN5		DTCER157
	TGIC4(MTU4)	158	0278h	Edge	o	o	x	x	x	IER13.IEN6		DTCER158
	TGID4(MTU4)	159	027Ch	Edge	o	o	x	x	x	IER13.IEN7		DTCER159
	TCIV4(MTU4)	160	0280h	Edge	o	o	x	x	x	IER14.IEN0	IPR160	DTCER160

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
TPU11/MTU5	TGIU5(MTU5)	161	0284h	Edge	o	o	x	x	x	IER14.IEN1	IPR161	DTCER161
	TGIV5(MTU5)	162	0288h	Edge	o	o	x	x	x	IER14.IEN2		DTCER162
	TGIW5(MTU5)	163	028Ch	Edge	o	o	x	x	x	IER14.IEN3		DTCER163
	TGI11A(TPU11)	164	0290h	Edge	o	o	o	x	x	IER14.IEN4	IPR164	DTCER164
	TGI11B(TPU11)	165	0294h	Edge	o	o	x	x	x	IER14.IEN5		DTCER165
POE	OEI1	166	0298h	Level	o	x	x	x	x	IER14.IEN6	IPR166	—
	OEI2	167	029Ch	Level	o	x	x	x	x	IER14.IEN7		—
—	Reserved	168	02A0h	—	x	x	x	x	x	—	—	—
—	Reserved	169	02A4h	—	x	x	x	x	x	—	—	—
TMR0	CMIA0	170	02A8h	Edge	o	o	o	x	o	IER15.IEN2	IPR170	DTCER170
	CMIB0	171	02ACh	Edge	o	o	x	x	o	IER15.IEN3		DTCER171
	OVI0	172	02B0h	Edge	o	x	x	x	o	IER15.IEN4		—
TMR1	CMIA1	173	02B4h	Edge	o	o	x	x	o	IER15.IEN5	IPR173	DTCER173
	CMIB1	174	02B8h	Edge	o	o	x	x	o	IER15.IEN6		DTCER174
	OVI1	175	02BCh	Edge	o	x	x	x	o	IER15.IEN7		—
TMR2	CMIA2	176	02C0h	Edge	o	o	x	x	o	IER16.IEN0	IPR176	DTCER176
	CMIB2	177	02C4h	Edge	o	o	x	x	o	IER16.IEN1		DTCER177
	OVI2	178	02C8h	Edge	o	x	x	x	o	IER16.IEN2		—
TMR3	CMIA3	179	02CCh	Edge	o	o	x	x	o	IER16.IEN3	IPR179	DTCER179
	CMIB3	180	02D0h	Edge	o	o	x	x	o	IER16.IEN4		DTCER180
	OVI3	181	02D4h	Edge	o	x	x	x	o	IER16.IEN5		—
RIIC0	EEO	182	02D8h	Level	o	x	x	x	x	IER16.IEN6	IPR182	—
	RXI0	183	02DCh	Edge	o	o	o	x	x	IER16.IEN7	IPR183	DTCER183
	TXI0	184	02E0h	Edge	o	o	o	x	x	IER17.IEN0	IPR184	DTCER184
	TEI0	185	02E4h	Level	o	x	x	x	x	IER17.IEN1	IPR185	—
RIIC1	EEO	186	02E8h	Level	o	x	x	x	x	IER17.IEN2	IPR186	—
	RXI1	187	02ECh	Edge	o	o	o	x	x	IER17.IEN3	IPR187	DTCER187
	TXI1	188	02F0h	Edge	o	o	o	x	x	IER17.IEN4	IPR188	DTCER188
	TEI1	189	02F4h	Level	o	x	x	x	x	IER17.IEN5	IPR189	—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
RIIC2	EI2	190	02F8h	Level	o	x	x	x	x	IER17.IEN6	IPR190	—
	RX12	191	02FCh	Edge	o	o	o	x	x	IER17.IEN7	IPR191	DTCER191
	TX12	192	0300h	Edge	o	o	o	x	x	IER18.IEN0	IPR192	DTCER192
	TEI2	193	0304h	Level	o	x	x	x	x	IER18.IEN1	IPR193	—
RIIC3	EI3	194	0308h	Level	o	x	x	x	x	IER18.IEN2	IPR194	—
	RX13	195	030Ch	Edge	o	o	o	x	x	IER18.IEN3	IPR195	DTCER195
	TX13	196	0310h	Edge	o	o	o	x	x	IER18.IEN4	IPR196	DTCER196
	TEI3	197	0314h	Level	o	x	x	x	x	IER18.IEN5	IPR197	—
DMAC	DMAC0I	198	0318h	Edge	o	o	x	x	x	IER18.IEN6	IPR198	DTCER198
	DMAC1I	199	031Ch	Edge	o	o	x	x	x	IER18.IEN7	IPR199	DTCER199
	DMAC2I	200	0320h	Edge	o	o	x	x	x	IER19.IEN0	IPR200	DTCER200
	DMAC3I	201	0324h	Edge	o	o	x	x	x	IER19.IEN1	IPR201	DTCER201
EXDMAC	EXDMAC0I	202	0328h	Edge	o	o	x	x	x	IER19.IEN2	IPR202	DTCER202
	EXDMAC1I	203	032Ch	Edge	o	o	x	x	x	IER19.IEN3	IPR203	DTCER203
—	Reserved	204	0330h	—	x	x	x	x	x	—	—	—
—	Reserved	205	0334h	—	x	x	x	x	x	—	—	—
—	Reserved	206	0338h	—	x	x	x	x	x	—	—	—
—	Reserved	207	033Ch	—	x	x	x	x	x	—	—	—
—	Reserved	208	0340h	—	x	x	x	x	x	—	—	—
—	Reserved	209	0344h	—	x	x	x	x	x	—	—	—
—	Reserved	210	0348h	—	x	x	x	x	x	—	—	—
—	Reserved	211	034Ch	—	x	x	x	x	x	—	—	—
—	Reserved	212	0350h	—	x	x	x	x	x	—	—	—
—	Reserved	213	0354h	—	x	x	x	x	x	—	—	—
SC10	RX10	214	0358h	Edge	o	o	o	x	x	IER1A.IEN6	IPR214	DTCER214
	TX10	215	035Ch	Edge	o	o	o	x	x	IER1A.IEN7		DTCER215
	TEI0	216	0360h	Level	o	x	x	x	x	IER1B.IEN0		—
SC11	RX11	217	0364h	Edge	o	o	o	x	x	IER1B.IEN1	IPR217	DTCER217
	TX11	218	0368h	Edge	o	o	o	x	x	IER1B.IEN2		DTCER218
	TEI1	219	036Ch	Level	o	x	x	x	x	IER1B.IEN3		—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
SCI2	RXI2	220	0370h	Edge	o	o	o	x	x	IER1B.IEN4	IPR220	DTCER220
	TXI2	221	0374h	Edge	o	o	o	x	x	IER1B.IEN5		DTCER221
	TEI2	222	0378h	Level	o	x	x	x	x	IER1B.IEN6		—
SCI3	RXI3	223	037Ch	Edge	o	o	o	x	x	IER1B.IEN7	IPR223	DTCER223
	TXI3	224	0380h	Edge	o	o	o	x	x	IER1C.IEN0		DTCER224
	TEI3	225	0384h	Level	o	x	x	x	x	IER1C.IEN1		—
SCI4	RXI4	226	0388h	Edge	o	o	o	x	x	IER1C.IEN2	IPR226	DTCER226
	TXI4	227	038Ch	Edge	o	o	o	x	x	IER1C.IEN3		DTCER227
	TEI4	228	0390h	Level	o	x	x	x	x	IER1C.IEN4		—
SCI5	RXI5	229	0394h	Edge	o	o	o	x	x	IER1C.IEN5	IPR229	DTCER229
	TXI5	230	0398h	Edge	o	o	o	x	x	IER1C.IEN6		DTCER230
	TEI5	231	039Ch	Level	o	x	x	x	x	IER1C.IEN7		—
SCI6	RXI6	232	03A0h	Edge	o	o	o	x	x	IER1D.IEN0	IPR232	DTCER232
	TXI6	233	03A4h	Edge	o	o	o	x	x	IER1D.IEN1		DTCER233
	TEI6	234	03A8h	Level	o	x	x	x	x	IER1D.IEN2		—
SCI7	RXI7	235	03ACh	Edge	o	o	o	x	x	IER1D.IEN3	IPR235	DTCER235
	TXI7	236	03B0h	Edge	o	o	o	x	x	IER1D.IEN4		DTCER236
	TEI7	237	03B4h	Level	o	x	x	x	x	IER1D.IEN5		—
SCI8	RXI8	238	03B8h	Edge	o	o	o	x	x	IER1D.IEN6	IPR238	DTCER238
	TXI8	239	03BCh	Edge	o	o	o	x	x	IER1D.IEN7		DTCER239
	TEI8	240	03C0h	Level	o	x	x	x	x	IER1E.IEN0		—
SCI9	RXI9	241	03C4h	Edge	o	o	o	x	x	IER1E.IEN1	IPR241	DTCER241
	TXI9	242	03C8h	Edge	o	o	o	x	x	IER1E.IEN2		DTCER242
	TEI9	243	03CCh	Level	o	x	x	x	x	IER1E.IEN3		—
SCI10	RXI10	244	03D0h	Edge	o	o	o	x	x	IER1E.IEN4	IPR244	DTCER244
	TXI10	245	03D4h	Edge	o	o	o	x	x	IER1E.IEN5		DTCER245
	TEI10	246	03D8h	Level	o	x	x	x	x	IER1E.IEN6		—
SCI11	RXI11	247	03DCh	Edge	o	o	o	x	x	IER1E.IEN7	IPR247	DTCER247
	TXI11	248	03E0h	Edge	o	o	o	x	x	IER1F.IEN0		DTCER248
	TEI11	249	03E4h	Level	o	x	x	x	x	IER1F.IEN1		—

Interrupt Vector Table

Source of Interrupt Request Generation	Name	Vector No.	Vector Address Offset	Form of Interrupt Detection	CPU Interrupt	DTC Activation	DMAC Activation	sstb Return	sacs Return	IER	IPR	DTCER
SCI12	RX112	250	03E8h	Edge	o	o	o	x	x	IER1F.IEN2	IPR250	DTCER250
	TX112	251	03ECh	Edge	o	o	o	x	x	IER1F.IEN3		DTCER251
	TEI12	252	03F0h	Level	o	x	x	x	x	IER1F.IEN4		—
IEB	IEBINT	253	03F4h	Level	o	x	x	x	x	IER1F.IEN5	IPR253	—
—	Reserved	254	03F8h	—	x	x	x	x	x	—	—	—
—	Reserved	255	03FCh	—	x	x	x	x	x	—	—	—

Lists details of the interrupt vectors

ITEM	DESCRIPTION
Source of interrupt request generation	Name of the source for generation of the interrupt request
Name	Name of the interrupt
Vector no.	Vector number for the interrupt
Vector address offset	Value of the offset from the base address for the vector table.
Form of interrupt detection	“Edge” or “level” as the method for detection of the interrupt
CPU interrupt	“o” in this column indicates usability as a CPU interrupt.
DTC activation	“o” in this column indicates usability as a request for DTC activation.
DMAC activation	“o” in this column indicates usability as a request for DMAC activation.
sstb return	“o” in this column indicates usability as a request for return from software-standby mode.
sacs return	“o” in this column indicates usability as a request for return from all-module clock-stop mode.
IER	Name of the interrupt request enable register (IER) and bit corresponding to the vector number
IPR	Name of the interrupt source priority register (IPR) corresponding to the interrupt source
DTCER	Name of the DTC activation enable register (DTCER) corresponding to the DTC activation source

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