Soft-Timer Driven Transient Kernel Control Flow Attacks and Defense

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The Botnet Threat

- Botnet: a collection of compromised computers under the control of a malicious server or master.
- Malware (e.g., rootkits) on each bot has become increasingly sophisticated and stealthy to evade detection and removal.
- We are mainly interested in the stealthy hiding of malware in the kernel space

Outline

- Soft timers and soft-timer-driven attacks
- Design of the STIR defense
- Implementation and evaluation
- Related work
- Conclusion

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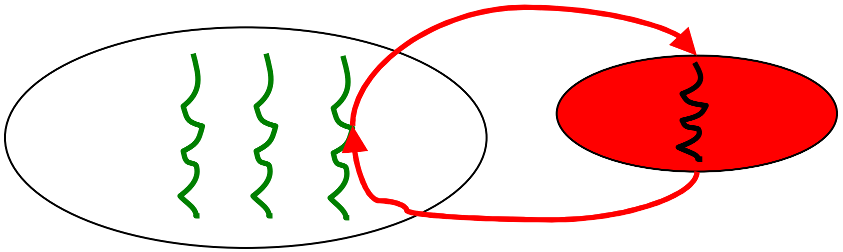
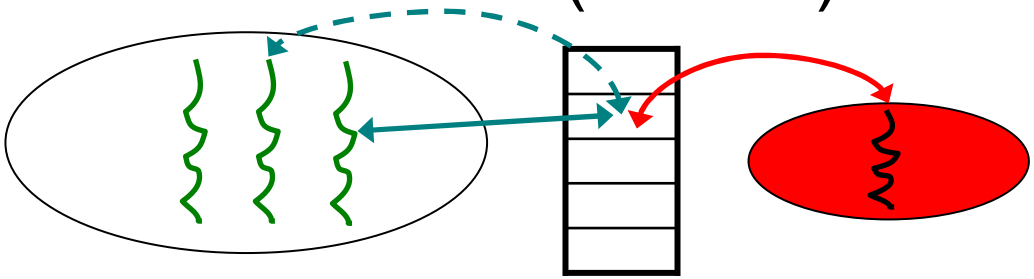
Classification of Stealthy Control Flow Attacks in the Kernel

- Detour attacks



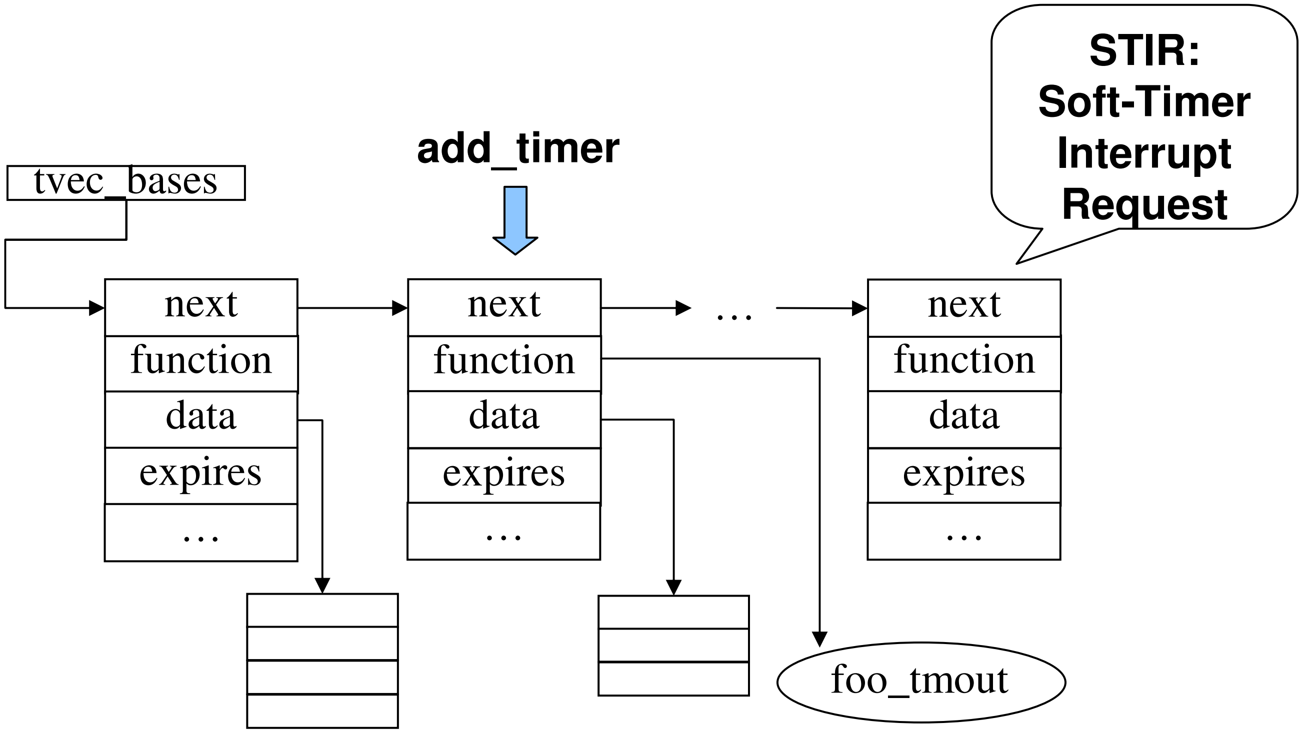
- Persistent control flow attacks (hooks)



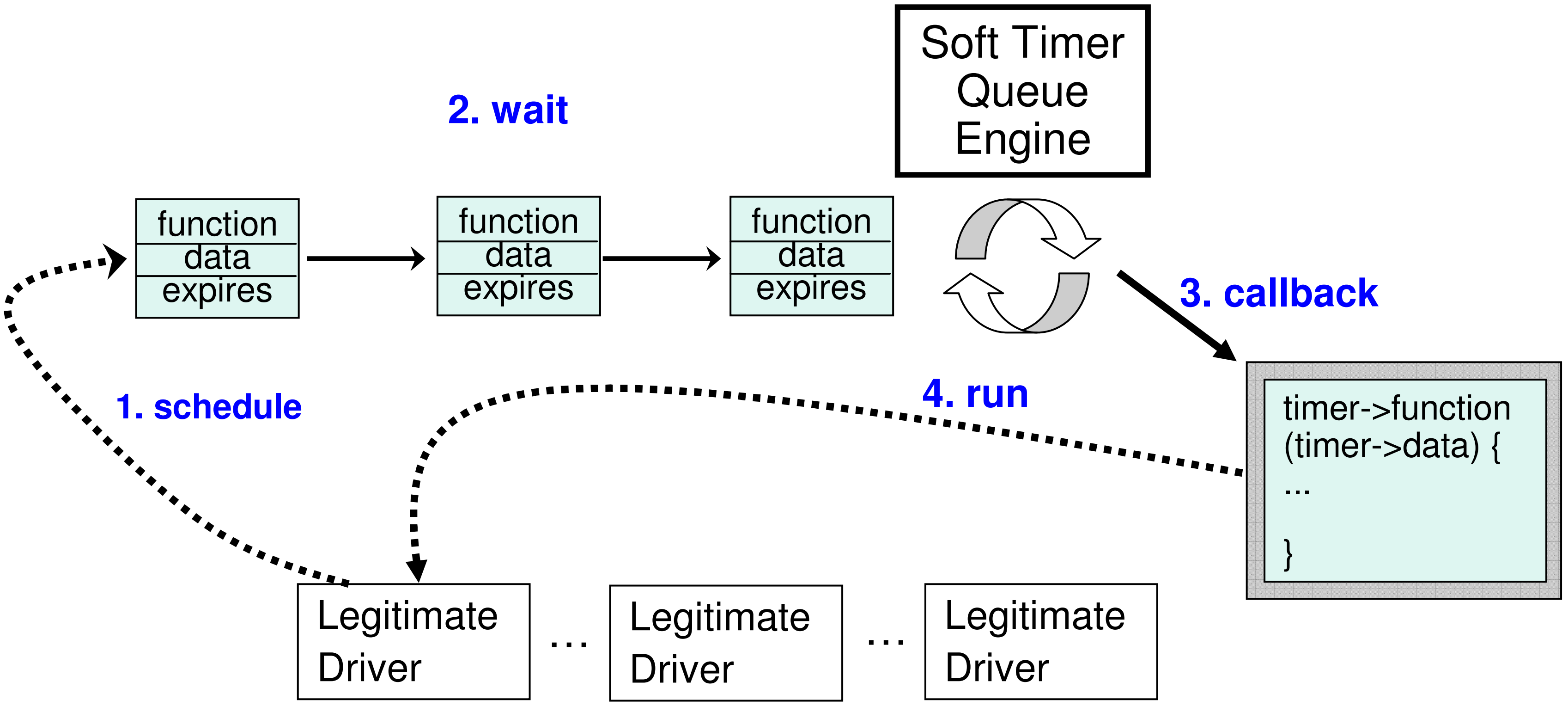
- Transient control flow attacks
  – Soft-timer-driven attacks

The Soft-timer Queue

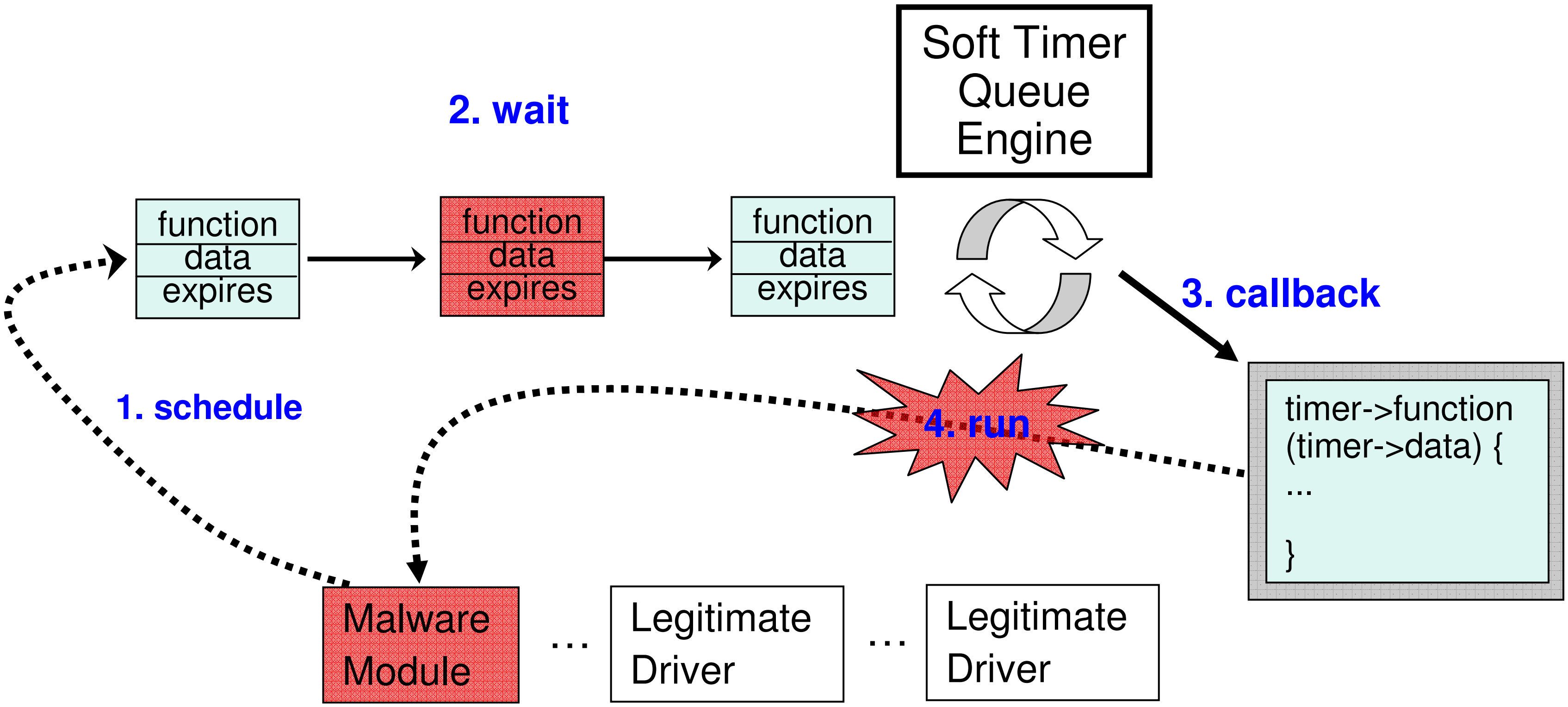
- A dynamic schedulable queue in the kernel
- Can be used to inject transient control flows



Soft-timer-driven Control Flow Attacks



Soft-timer-driven Control Flow Attacks



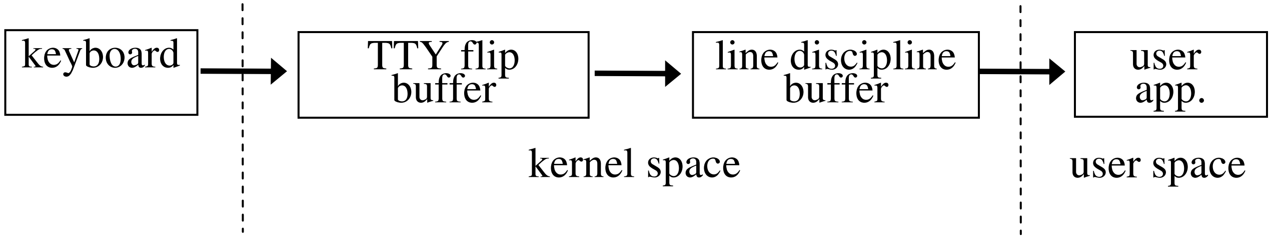
Proof of Concept Malware

- How do they work?
  - Request the first STIR to interpose on the kernel control flow at break-in
  - Execute when the first STIR expires (a callback)
  - Before giving up control, request the next STIR
  - Wait for the next callback to happen

- What can they do?
  - Collect confidential information (stealthy key logger)
  - Mount a DoS attack (stealthy cycle stealer)
  - Schedule a hidden process (alter-scheduler)

STIR: Soft-Timer Interrupt Request

The Stealthy Key Logger



- Runs in Linux kernel 2.6.16
- Periodically reads the TTY line discipline buffer in the kernel, which can keep a history of up to 2,048 keystrokes
- Timer period is 1 second

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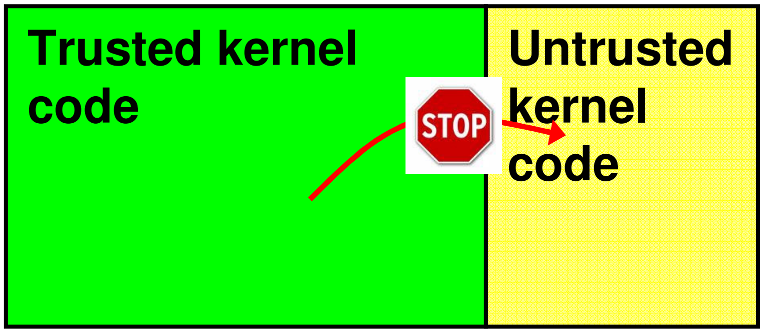
Defending Soft-timer-driven Attacks

- Main idea: a soft-timer callback function and its callees (functions it calls) should always target the trusted code of the kernel during the execution of the callback function.
- By preserving such invariants, we can defeat soft-timer-driven attacks.



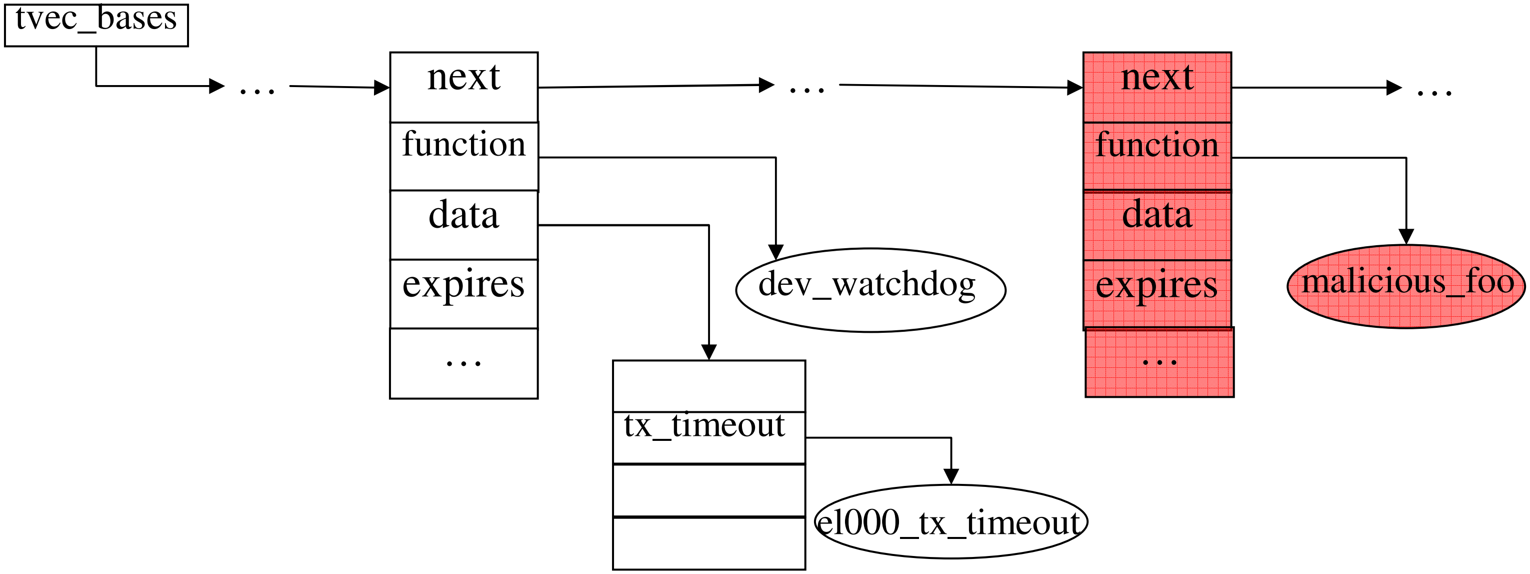
Q:

How can we draw the line between trusted and untrusted parts of the kernel?

A:

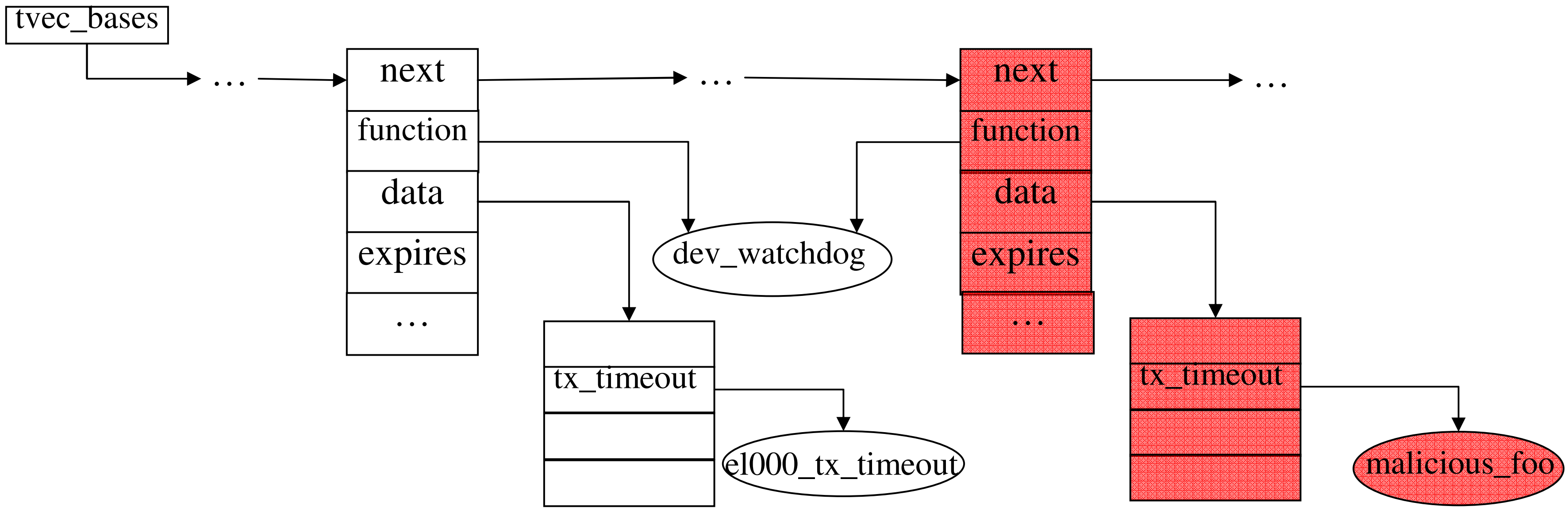
Validate the targets of indirect control transfers. E.g., what can timer–>function legally point to?

Basic Defense Strategy



- Check the callback function against a white list of legitimate callback functions

More Comprehensive Defense Strategy

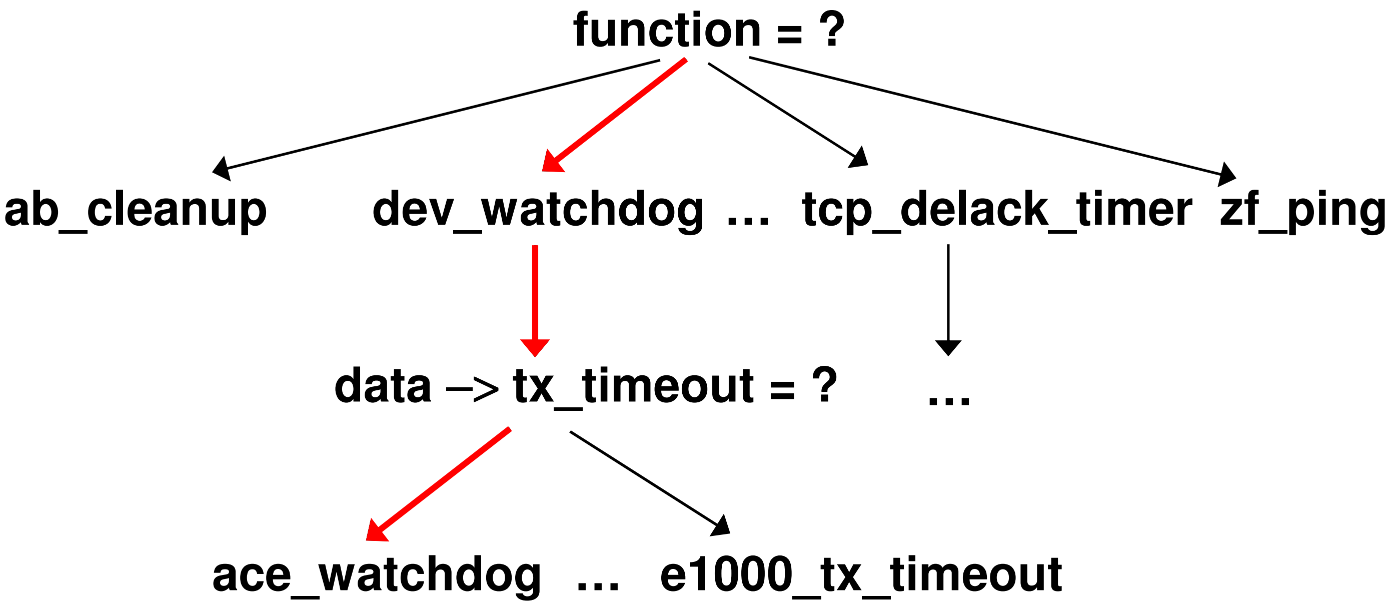


- Check the callback function as well as the data pointer
- Smarter malware may supply a legitimate callback function but a malicious data pointer (similar to the “jump-to-libc” style attacks).

High-Level View of the Defense

Input: function, data

Output: yes/no



How do we build and use this whitelist tree ?

STIR Summary Signatures

- summary_signature := <function, assertion>
- assertion := *true* | dpred AND asserti…
- dpred := de… …nctionlist)
- functionlist := function | function OR …

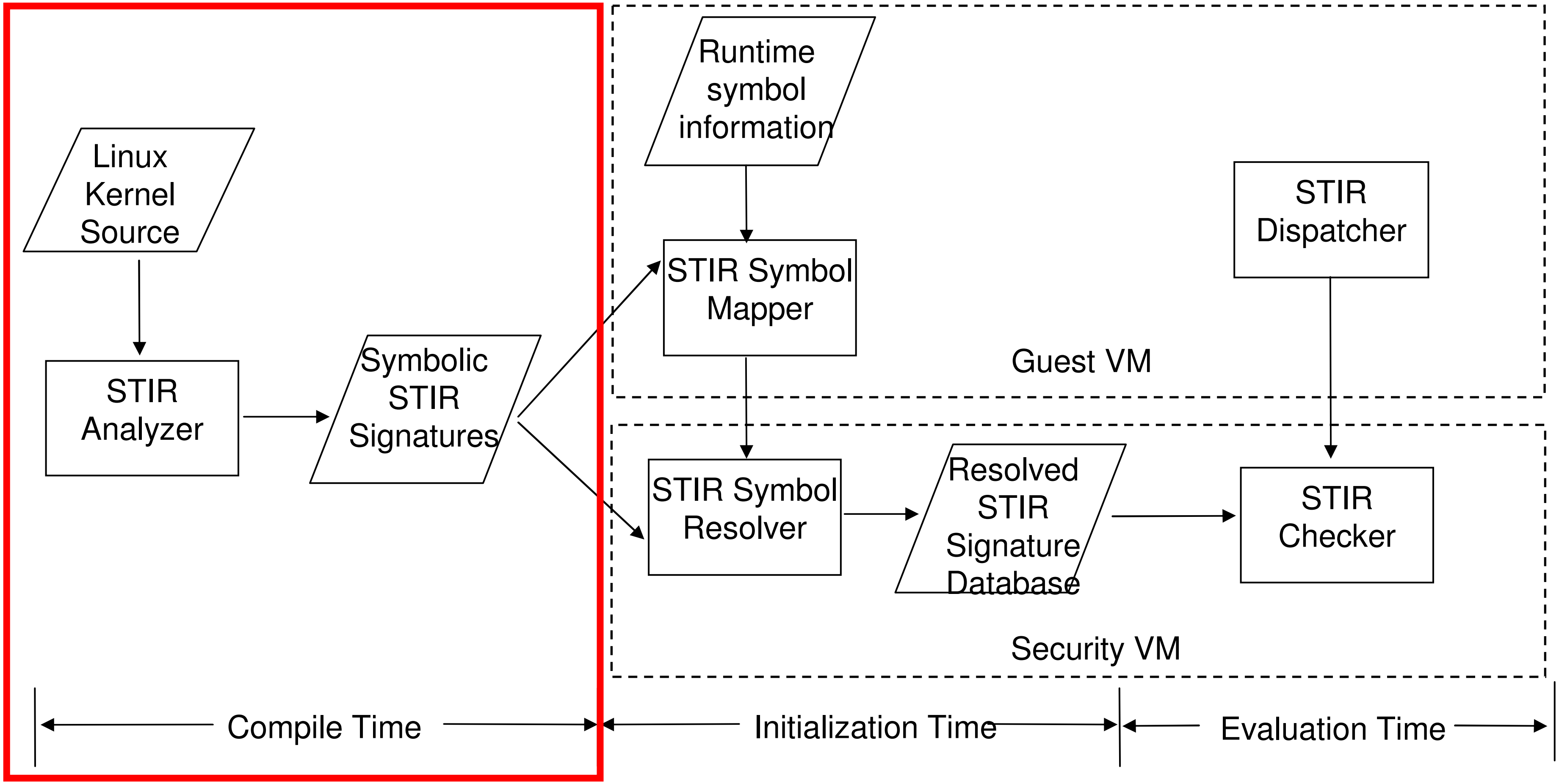
Constraint on the function pointer

Constraint on the data attribute

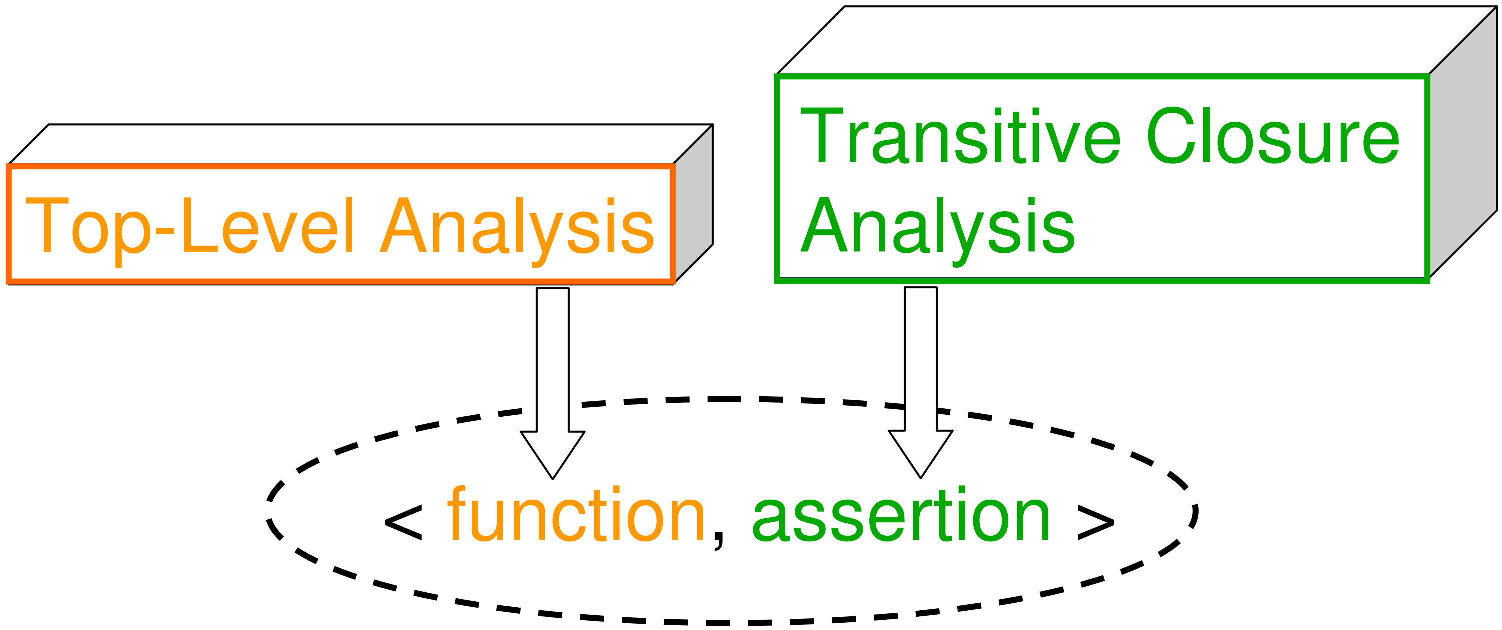
- Example summary signature:

  < dev_watchdog, data->tx_timeout **equals** (e1000_tx_timeout OR xircom_tx_timeout) >

Processing STIR Summary Signatures



Static Analysis Overview



STIR summary signature

Top-Level Analysis

```
/* Linux kernel 2.6.16/net/sched/sch_generic.c */

static void dev_watchdog_init(struct net_device *dev)
{
        init_timer(&dev->watchdog_timer);
        dev->watchdog_timer.data = (unsigned long)dev;
        dev->watchdog_timer.function = dev_watchdog;
}
```

- Traverse each assignment statement (lval = rval) in the kernel, if lval ends with a field named **function** within a structure of type **timer_list**, then rval is recognized as a soft timer callback function

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Transitive Closure Analysis

```
static void
dev_watchdog(unsigned long arg)

{

 struct net_device *dev = (struct
net_device *)arg;

if (dev->qdisc != &noop_qdisc) {

…

   printk(KERN_INFO "…%s…\n",
dev->name);

   dev->tx_timeout(dev);

…

}
```

- Objective: To identify the constraints on the “data” attribute of a legitimate STIR

Transitive Closure Analysis

tainted_vars:

{arg}

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tainted_vars:

{arg}

{arg, dev}

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Transitive Closure Analysis

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…

   printk(KERN_INFO “…%s…\n",
dev->name);

   dev->tx_timeout(dev);

…

}
```

tainted_vars:

{arg, dev}

Question 1:

dev->tx_timeout = ?

Answer:

Find all legitimate functions that can be assigned to the "tx_timeout" field of a structure of type "net_device"

→top-level analysis

Transitive Closure Analysis

```
static void
dev_watchdog(unsigned long arg)

{

 struct net_device *dev = (struct
net_device *)arg;

if (dev->qdisc != &noop_qdisc) {

…

  printk(KERN_INFO "…%s…\n",
dev->name);

  dev->tx_timeout(dev);

…

}
```

Question 2:

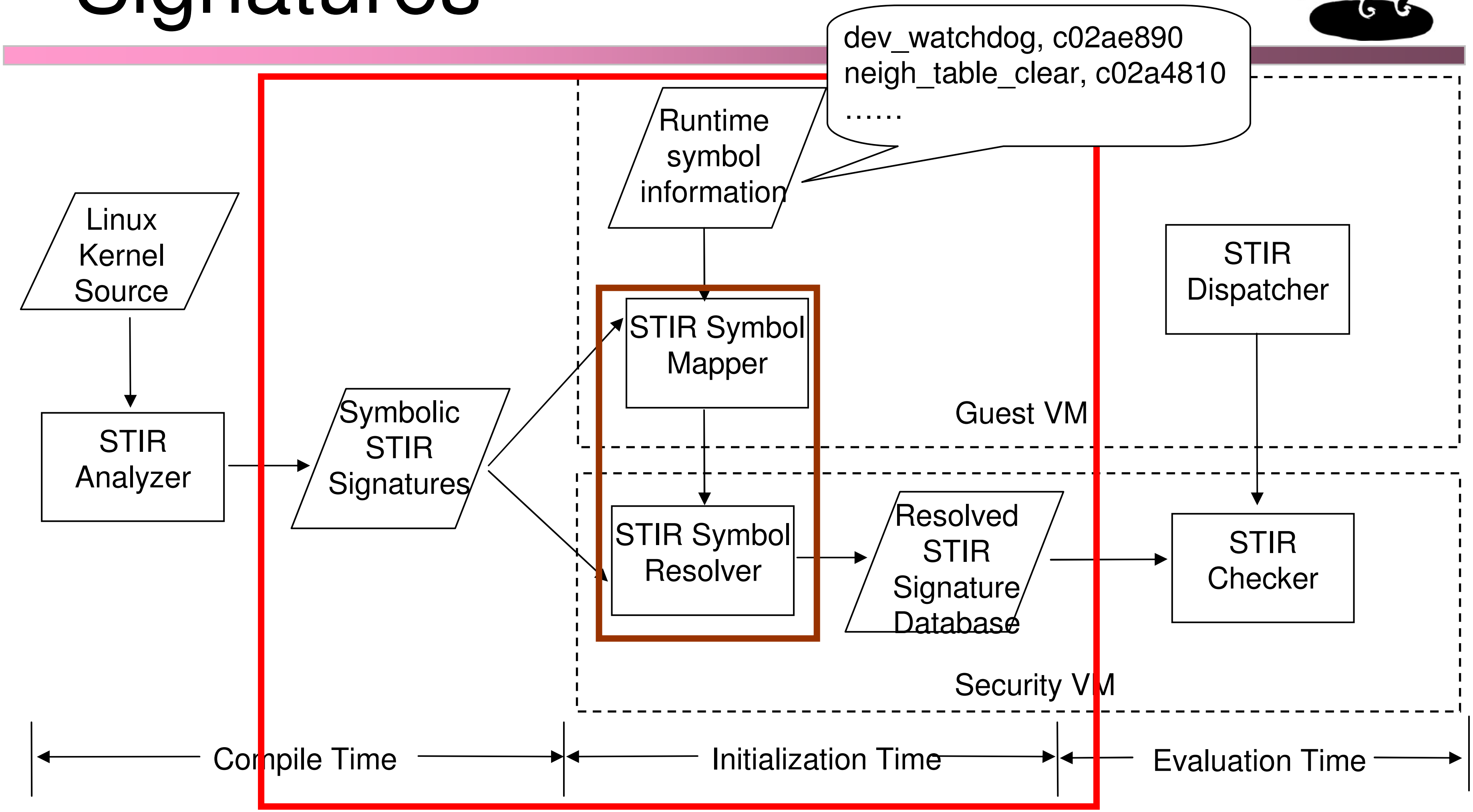
How is the control flow of dev->tx_timeout influenced by dev?

Answer:

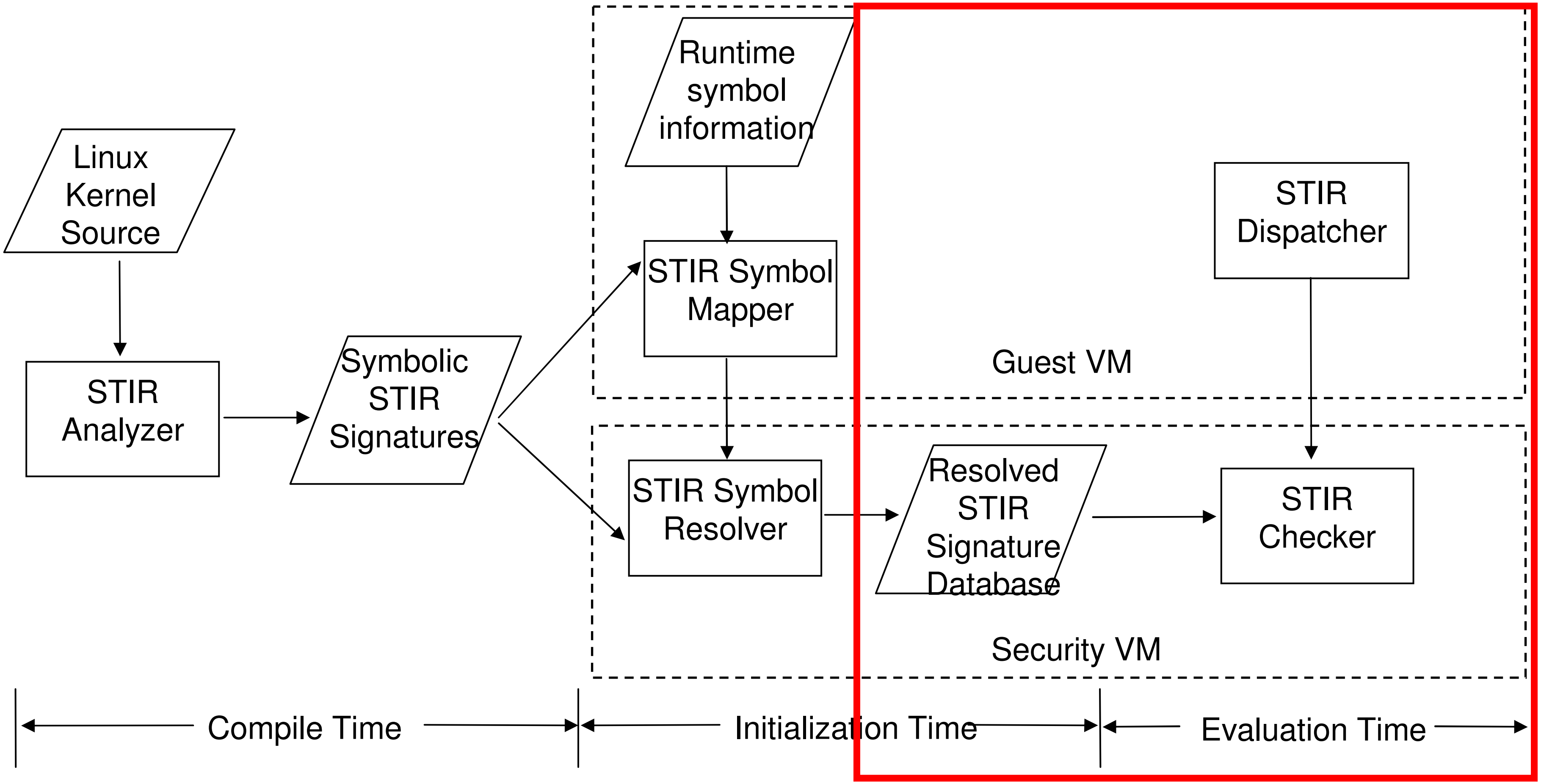
Perform a transitive closure analysis on the target function.

```
static void ariadne_tx_timeout(struct
net_device *dev)
{
   volatile struct Am79C960 *lance =
(struct Am79C960*)dev->base_addr;
 …
}
```

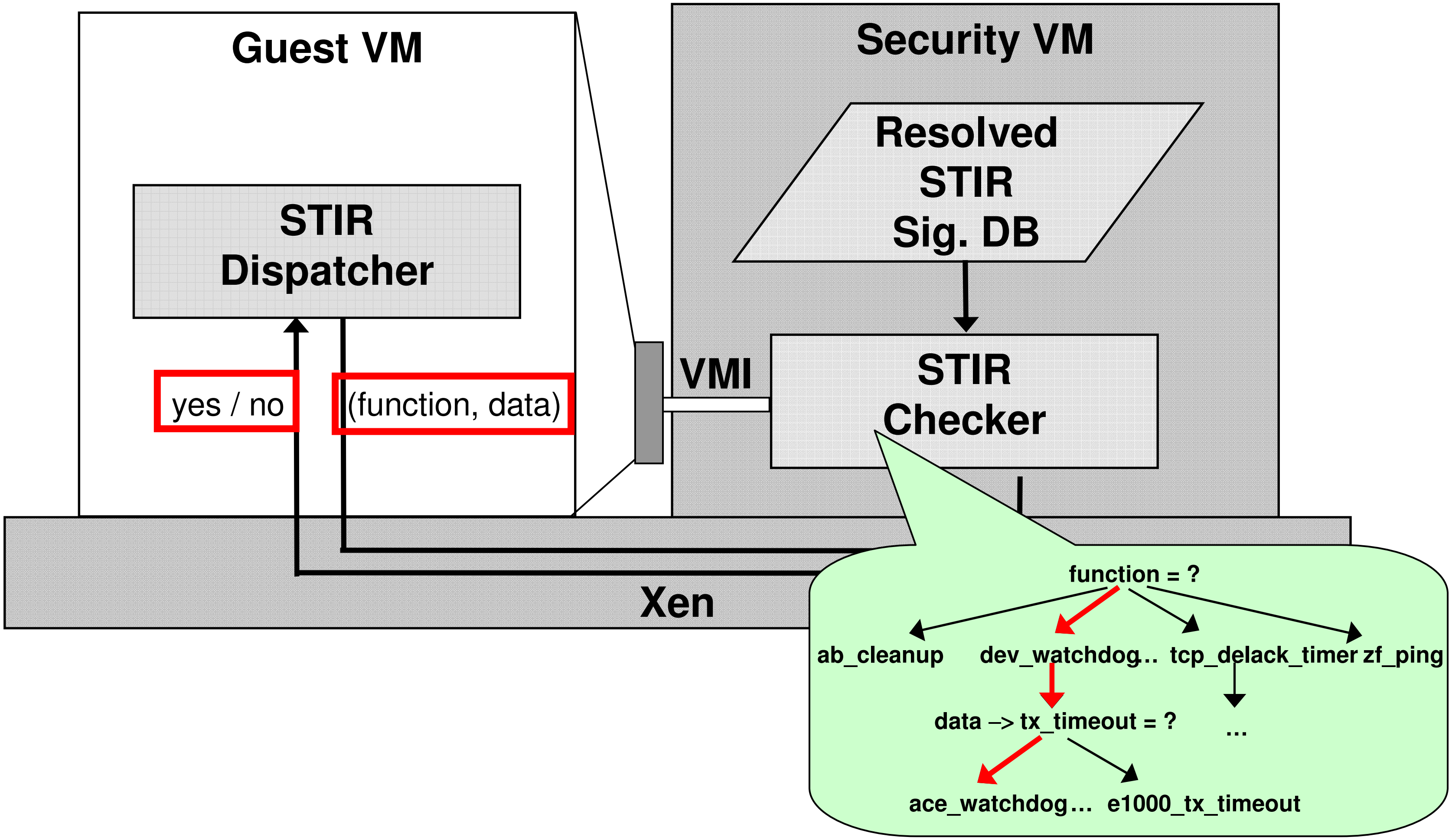
Processing STIR Summary Signatures



Checking STIRs



STIR Checking Architecture



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Implementation of the STIR Analyzer

- Based on CIL (C Intermediate Language)
- Comprised of several analysis modules
  - A top-level analyzer
  - A transitive closure analyzer
  - A type analyzer
  - Shell scripts to compose the modules

Implementation of the STIR Checking

- On top of Xen 3.0.4
- Used the VT (virtualization technology) support of an Intel CPU
- Based on the Lares architecture

Evaluation: Security Assumptions

- The VMM and the Security VM are part of the TCB (Trusted Computing Base).
- The legitimate kernel code in the guest VM's memory can not be tampered with.
- The source code of the kernel and all kernel extensions are available for static analysis.
- The guest system can be booted into a known good state (e.g., secure boot).

Evaluation: Static Analysis Results

- We found 365 top-level callback functions in 3,688 kernel source files analyzed.
- The majority of these STIR callback functions do not derive function pointers from the input parameter.
- 32 of them need transitive closure analysis.

Evaluation: Effectiveness of Defense

- Attack experiments: can detect the sample malware.
- Can have no false negatives because it mediates every STIR execution and prevents the execution of all unknown, illegitimate STIRs.
- Can have no false positives because all potential legitimate STIRs are captured in the summary signature database.

Evaluation: Execution Time Overhead

	cat	ccrypt	gzip	cp	make
Original (seconds)	20.85	3.30	5.92	43.95	217.95
STIR-aware (seconds)	20.96	3.30	6.01	46.61	218.58
Overhead	0.52%	0%	1.52%	6.05%	0.29%
Callbacks/Sec	46.9	46.3	47.3	61.4	81.6

cat - read and display the content of 8,000 small files (with size ranging from 5K to 7.5K bytes).

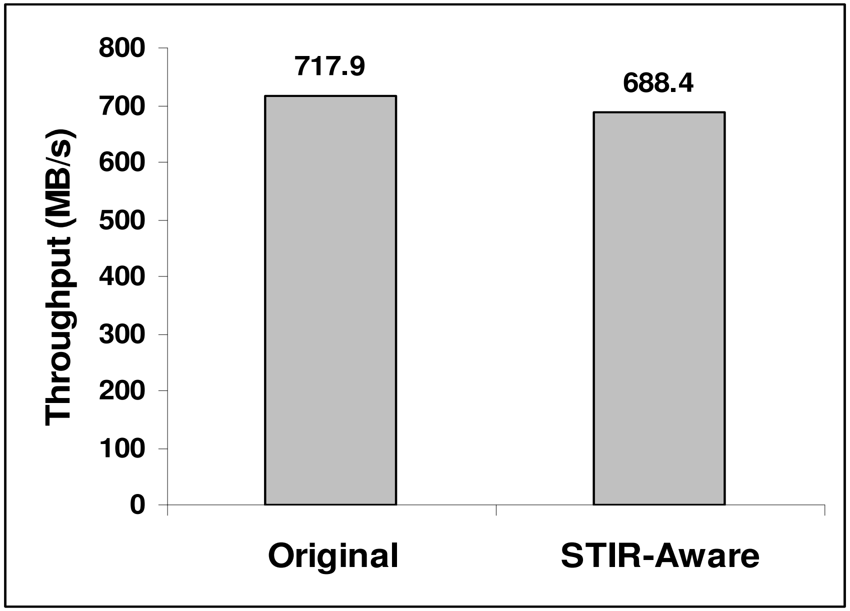
ccrypt - encrypt a text stream of 64M bytes.

gzip - compress a text file of 64M bytes using the --best option.

cp - recursively copy a Linux kernel source tree.

make - perform a full build of the Apache HTTP server (version 2.2.2) from source.

Evaluation: Network Throughput Overhead



Performance drop: 4.1%

Callback frequency: 287/second

- We used the Iperf-2.0.2 benchmark.
- The security VM ran the Iperf server and the guest VM ran the Iperf client.
- The experiment was run for 60 seconds, using 64KB buffers and 10 concurrent connections.

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Related Work

- Focused on code changes
  - Tripwire (a file system integrity checker)
  - IMA (TCG-based, load-time kernel and application integrity checker)
  - Copilot (coprocessor-based, run-time kernel integrity checker)
  - Pioneer (purely software-based run-time integrity checker)
- Focused on data changes
  - SBCFI (state-based control flow integrity), a sampling-based checker targeting persistent kernel control flow attacks
  - CFI (control flow integrity), checking the dynamic execution flow of a program against a statically computed control flow graph

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Conclusions

- The Soft-timer mechanism of a modern kernel provides a novel hiding technique for the malware.
- We develop a white list approach for defending against such malware.
- We use static analysis to derive the white list.
- We use virtualization to implement the defense.