Raksha: A Flexible Information Flow Architecture for Software Security

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Motivation

- Software security is in a crisis
- Ever increasing range of attacks
  - High-level, semantic attacks are now the main threat
    - SQL injection, cross-site scripting, directory traversal, …
  - Low-level, memory corruption attacks are still common
    - Buffer overflow, double free, format string, …
- Need an approach to software security that is
  - Robust & flexible
  - Practical & end-to-end
  - Fast

DIFT: Dynamic Information Flow Tracking

- DIFT taints data from untrusted sources
  - Extra tag bit per word marks if untrusted
- Propagate taint during program execution
  - Operations with tainted data produce tainted results
- Check for suspicious uses of tainted data
  - Tainted code execution
  - Tainted pointer dereference (code & data)
  - Tainted SQL command
- Potential: protection from low-level & high-level threats

DIFT Example: Memory Corruption

Vulnerable C Code

```
int idx = tainted_input;
buffer[idx] = x; // buffer overflow
```

```
set   r1 ← &tainted_input
load  r2 ← M[r1]
add   r4 ← r2 + r3
store M[r4] ← r5
```

TRAP

T	Data
	r1:&input
	r2:idx=input
	r3:&buffer
	r4:&buffer+idx
	r5:x

- Tainted pointer dereference ⇒ security trap

Software DIFT Systems

- ❑ DIFT through code instrumentation [Newsome'05, Quin'06]
  - Transparent through dynamic binary translation
- ☑ Advantages
  - Runs on existing hardware
  - Flexible security policies
- ☒ Disadvantages
  - High overhead (≥3x)
  - Does not work with threaded or self-modifying binaries
  - Cannot protect OS
- ❑ Coverage: control-based, low-level attacks

Hardware DIFT Systems

❑ DIFT through HW extensions [Suh'04, Crandall'04, Chen'05]

- Extend HW state to include taint bits
- Extend HW instructions to check & propagate taint bits

☑ Advantages

- Negligible runtime overhead
- Works with threaded and self-modifying binaries

☒ Disadvantages

- Inflexible security policies
- False positives & false negatives
- Cannot protect OS

❑ Coverage: control-based & data-based, low-level attacks

Outline

- ❑ Motivation & DIFT overview
- ❑ The Raksha architecture
  - Technical approach
  - Architectural features
  - Full-system prototype
- ❑ Evaluation
  - Security experiments
  - Lessons learned
- ❑ Conclusions

Raksha Philosophy

❑ Combine best of HW & SW

- HW: fast checks & propagation, works with any binary
- SW: flexible policies, high-level analysis & decisions

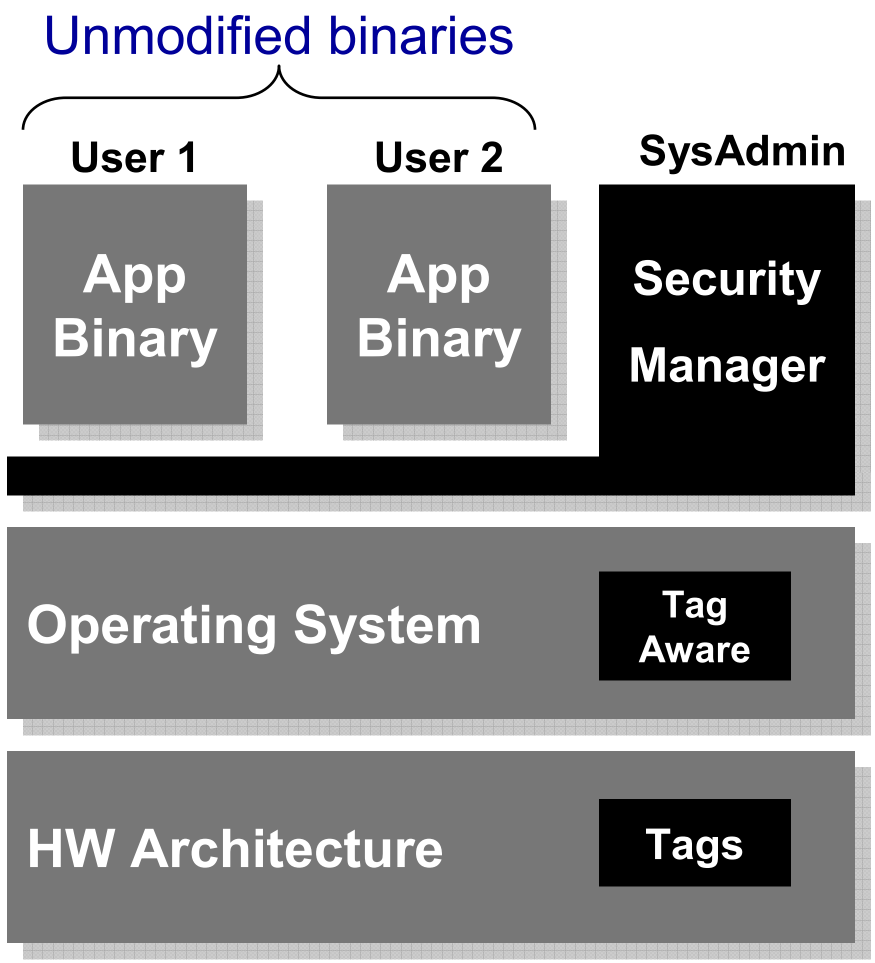
❑ Goals

- Protect against high-level & low-level attacks
- Protect against multiple concurrent attacks
- Protect OS code

❑ Comprehensive evaluation

- Run unmodified binaries on full-system prototype
- What works on a simulator, may not work in real life

Raksha Architecture & Features



Set security policies
Control HW check/propagate
Further SW analysis

Cross-process info flow
Save/restore tags

4 tag bits per word
HW check/propagate
User-level security traps

Setting HW Check/Propagate Policies

- A pair of policy registers per tag bit
  - Set by security manager (SW) when and as needed
- Policy granularity: operation type
  - Select input operands to check if tainted
  - Select input operands that propagate taint to output
  - Select the propagation mode (and, or)
- ISA instructions decomposed to ≥1 operations
  - Types: ALU, logical, branch, load/store, compare, FP, …
  - Makes policies independent of ISA packaging (RISC/CISC)

Check Policy Example: `load`

```
load  r2 ← M[r1+offset]
```

<u>Check Enables</u>

1. Check source register

   If Tag(**`r1`**)==1 then security_trap

2. Check source address

   If Tag(**`M[r1+offset]`**)==1 then security_trap

Both enables may be set simultaneously

Propagate Policy Example: `load`

`load  r2` ← **`M[r1+offset]`**

<u>**Propagate Enables**</u>

1. Propagate only from source register

   Tag(**`r2`**) ←Tag(**`r1`**)

2. Propagate only from source address

   Tag(**`r2`**) ← Tag(**`M[r1+offset]`**)

3. Propagate only from both sources

   OR mode: Tag(**`r2`**) ←Tag(**`r1`**) **|** Tag(**`M[r1+offset]`**)

   AND mode: Tag(**`r2`**) ←Tag(**`r1`**) **&** Tag(**`M[r1+offset]`**)

User-level Security Traps

- Why user-level security traps?
  - Fast switch to SW ⇒ combine HW tainting with SW analysis
  - No switch to OS ⇒ DIFT applicable to most of OS code

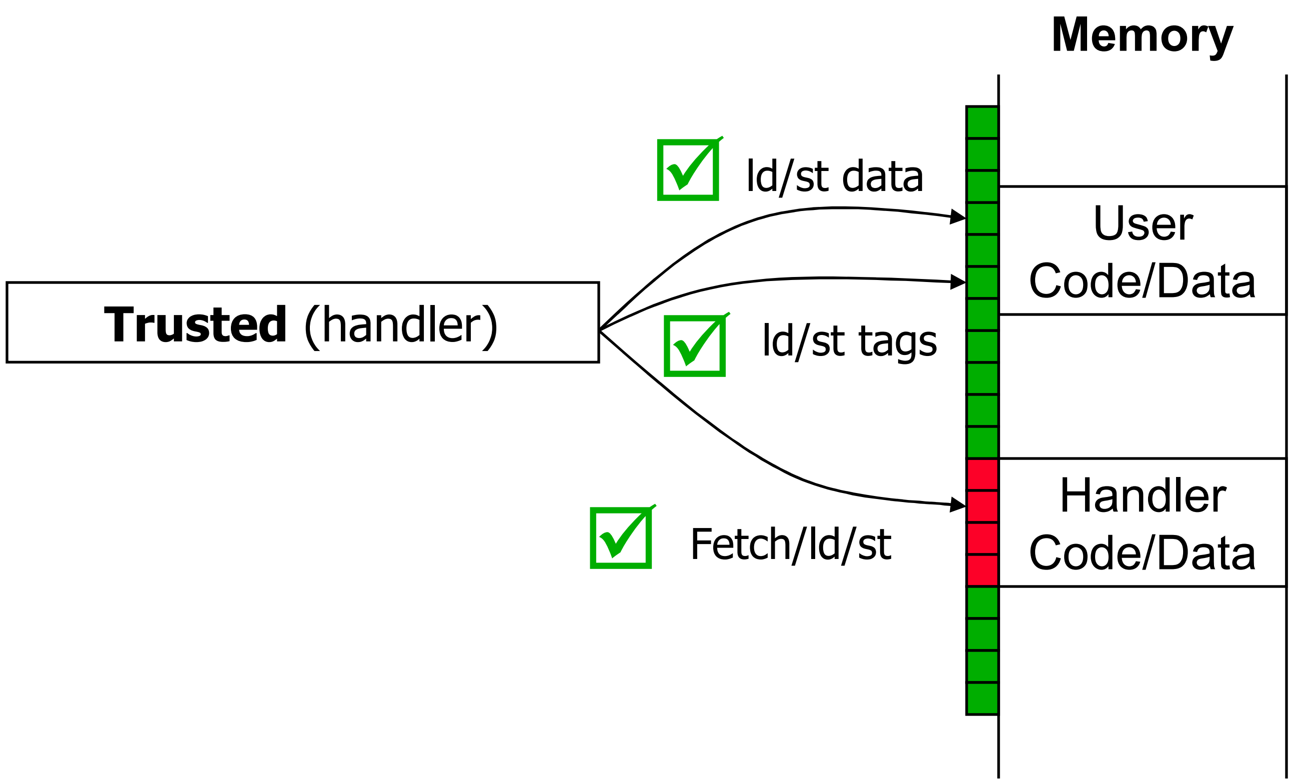
- Requires new operating mode, orthogonal to user/kernel

	Untrusted	Trusted
User	Limited instructions; limited address ranges; VM	
Kernel	Access to all instructions & address ranges; VM/PM	
	Tags are transparent	Direct access to tag bits & tag instructions

- On security trap
  - Switch to trusted mode & jump to predefined handler
  - Maintain user/kernel mode (no address space change)

Protecting the Trap Handler

- Can malicious user code overwrite handler?
  - Use one tag bit to support a sandboxing policy
  - Handler data & code accessible <u>only</u> in trusted mode



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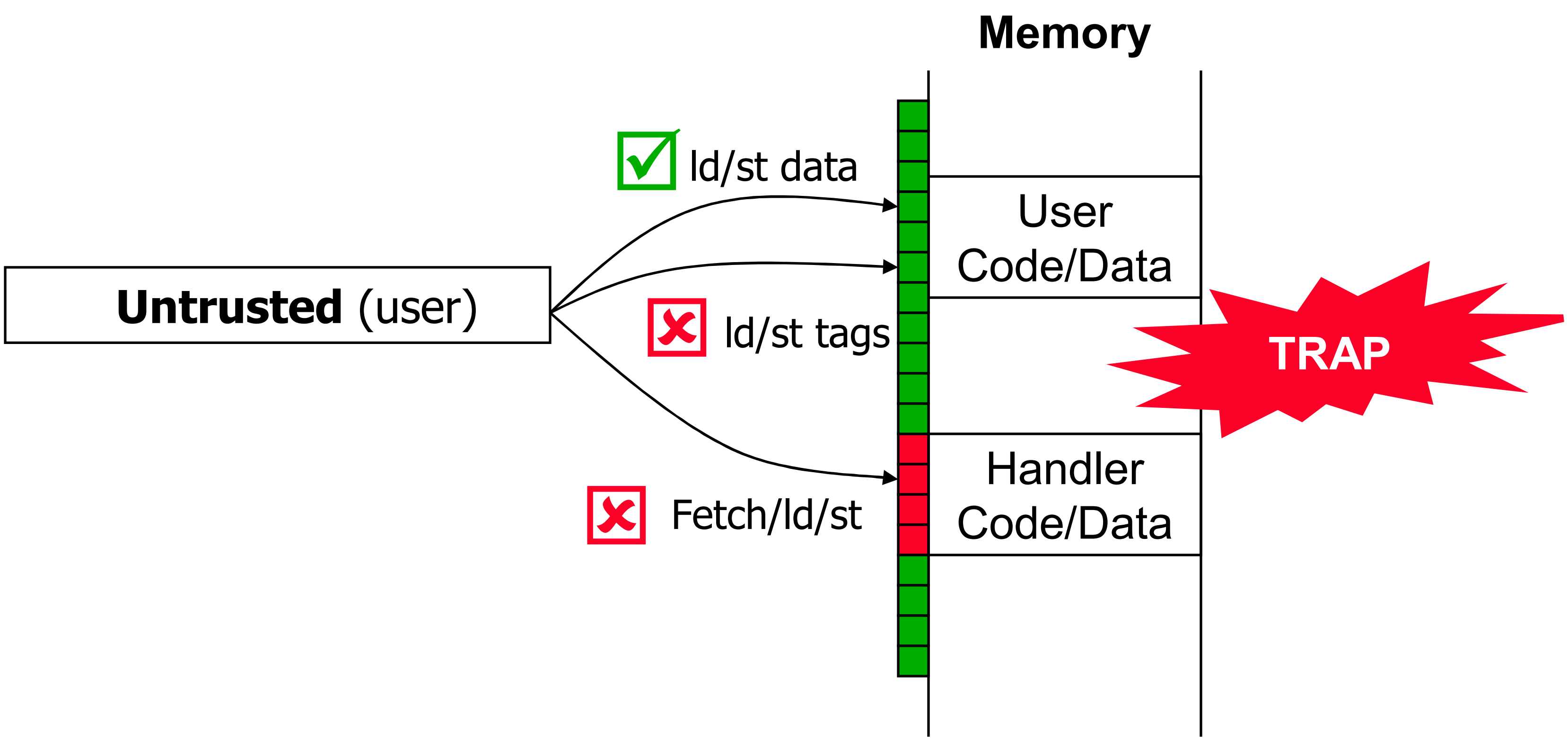
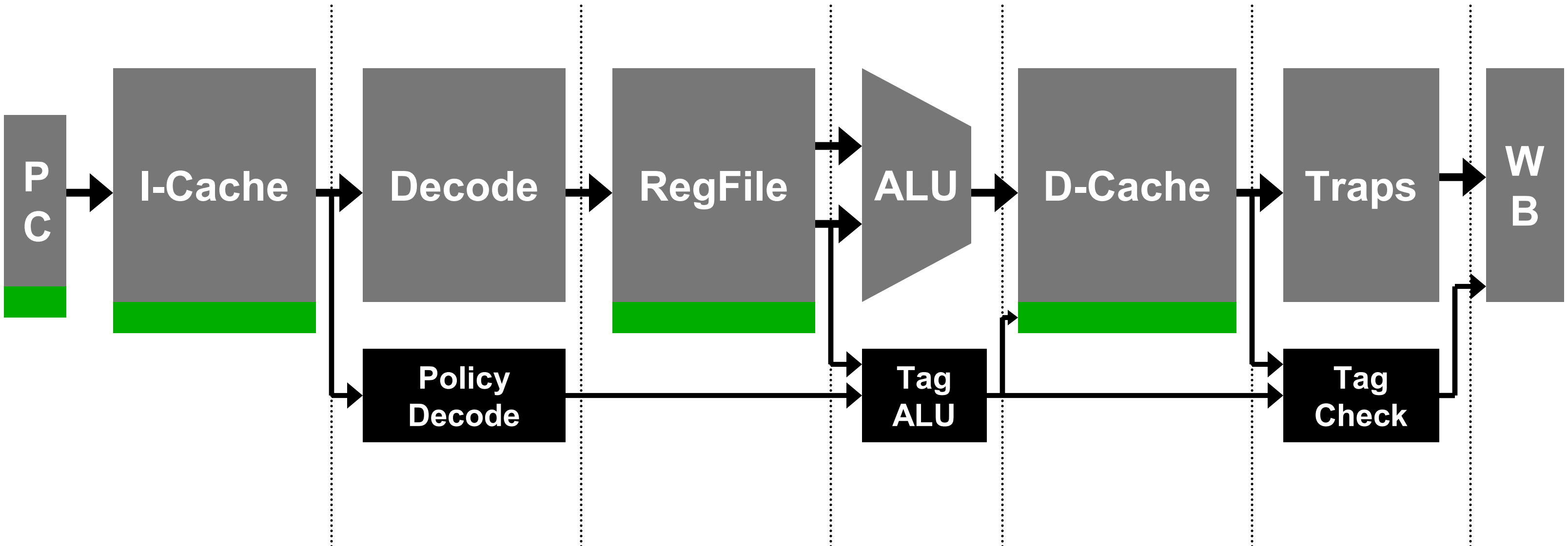


Raksha Prototype System

- Full-featured Linux system
  - On-line since October 2006…
- HW: modified Leon-3 processor
  - Open-source, Sparc V8 processor
  - Single-issue, in-order, 7-stage pipeline
  - Modified RTL for processor & system
  - First DIFT system on FPGA
- SW: custom Linux distribution
  - Based on 2.6 kernel (modified to be tag aware)
  - Set HW policies using preloaded shared libraries
  - ≥120 packages (GNU toolchain, apache, postgresql, …)

Processor Pipeline

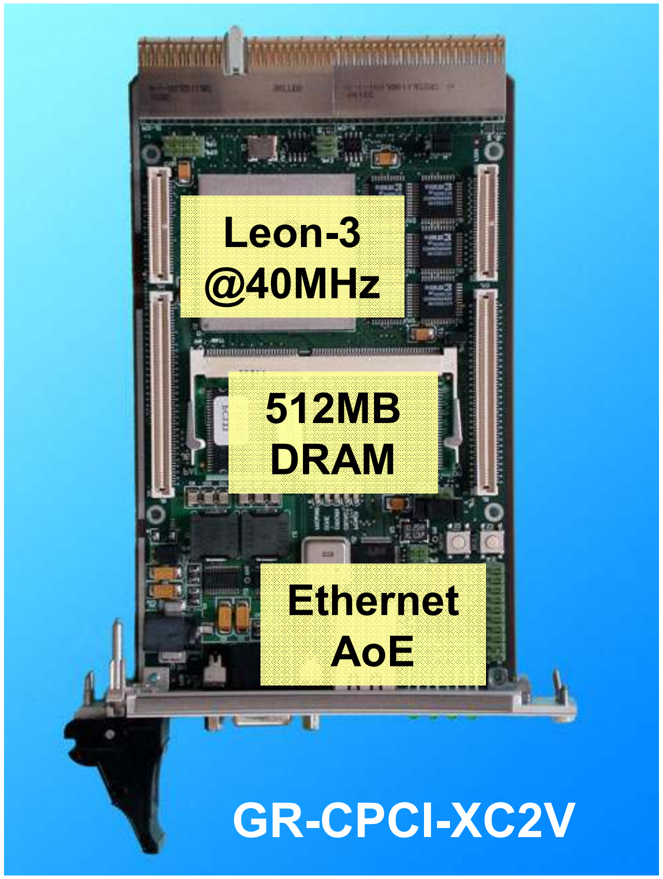


- Registers & memory extended with tag bits
- Tags flow through pipeline along with corresponding data
  - No changes in forwarding logic
  - No significant sources of clock frequency slowdown

Tag Granularity & Storage

- Tag granularity
  - HW maintains per word tag bits
  - What if SW wants byte or bit granularity for some data?
  - Maintain in SW using sandboxing & fast user-level traps
    - Acceptable performance if not common case…
- Tag storage
  - Initial HW $\Rightarrow$ +4 bits/word in registers, caches, memory
    - 12.5% storage overhead
  - Multi-granularity tag storage scheme [Suh'04]
    - Exploit tag similarity to reduce storage overhead
    - Page-level tags $\Rightarrow$ cache line-level tags $\Rightarrow$ word-level tags

Prototype Statistics



- Overhead over original
  - Logic: 7%
  - Storage: 12.5%
  - Clock frequency: none
- Application performance
  - Check/propagate tags ⇒ no slowdown
  - Overhead depends on SW analysis
    - Frequency of traps, SW complexity, …
- Worst-case example from experiments
  - Filtering low-level false positives/negatives
  - Bzip2: +33% with Raksha's user-level traps
  - Bzip2: +280% with OS traps

Security Experiments

Program	Lang.	Attack	Detected Vulnerability
traceroute	C	Double Free	Tainted data ptr
polymorph	C	Buffer Overflow	Tainted code ptr
Wu-FTPD	C	Format String	Tainted ‘%n’ in vfprintf string
gzip	C	Directory Traversal	Open tainted dir
Wabbit	PHP	Directory Traversal	Escape Apache root w. tainted ‘..’
OpenSSH	C	Command Injection	Execve tainted file
ProFTPD	C	SQL Injection	Tainted SQL command
htdig	C++	Cross-site Scripting	Tainted <script> tag
PhpSysInfo	PHP	Cross-site Scripting	Tainted <script> tag
Scry	PHP	Cross-site Scripting	Tainted <script> tag

- Unmodified Sparc binaries from real-world programs
  - Basic/net utilities, servers, web apps, search engine

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- Protection against low-level memory corruptions
  - Both control & non-control data attacks

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- 1st DIFT architecture to detect semantic attacks
  - Without the need to recompile applications

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- Protection is independent of programming language
  - Catch suspicious behavior, regardless of language choice

HW Policies for Security Experiments

- Concurrent protection using 4 policies

1. Memory corruption (LL attacks)
   - Propagate on arithmetic, load/store, logical
   - Check on tainted pointer/PC use
   - Trap handler untaints data validated by user code
2. String tainting (LL & HL attacks)
   - Propagate on arithmetic, load/store, logical
   - No checks
3. System call interposition (HL attacks)
   - No propagation
   - Check on system call in untrusted mode
   - Trap handler invokes proper SW analysis
4. Sandboxing policy (for trap handler protection)
   - Handler taints its code & data
   - Check on fetch/loads/stores in untrusted mode

Lessons Learned

- HW support for fine-grain tainting is crucial
  - For both high-level and low-level attacks
  - Provides fine-grain info to separate legal uses from attacks
- Lesson from high-level attacks
  - Check for attacks at system calls
  - Provides complete mediation, independent language/library
- Lessons from low-level attack
  - Fixed policies from previous DIFT systems are broken
    - False positives & negatives even within glibc
  - Problem: what constitutes validation of tainted data?
  - Need new SW analysis to couple with HW tainting
    - Raksha's flexibility and extensibility are crucial

Conclusions

- Raksha: flexible DIFT architecture for SW security
  - Protects against high-level & low-level attacks
  - Protects against multiple concurrent attacks
  - Protects OS code (future work)
- Raksha characteristics
  - Robust – applicable to high-level & low-level attacks
  - Flexible – programmable HW; extensible through SW
  - Practical – works with any binary
  - End-to-end – applicable to OS
  - Fast – HW tainting & fast security traps

Questions?

- Want to use Raksha?
  - Keep an eye on http://raksha.stanford.edu
  - Raksha port to Xilinx XUP board ($300 for academics)
  - Full RTL + Linux distribution
  - Expected release date in early July