Raksha: A Flexible Architecture for Software Security

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Motivation

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

DIFT: Dynamic Information Flow Tracking

- DIFT <u>taints</u> data from untrusted sources
  - Extra tag bit per word marks if untrusted (e.g. net input)
- <u>Propagate</u> taint during program execution
  - Operations with tainted data produce tainted results
- <u>Check</u> for suspicious uses of tainted data
  - Tainted code execution
  - Tainted pointer dereference (code & data)
  - Tainted SQL command
- Potential: protecting unmodified binaries from low-level & high-level threats

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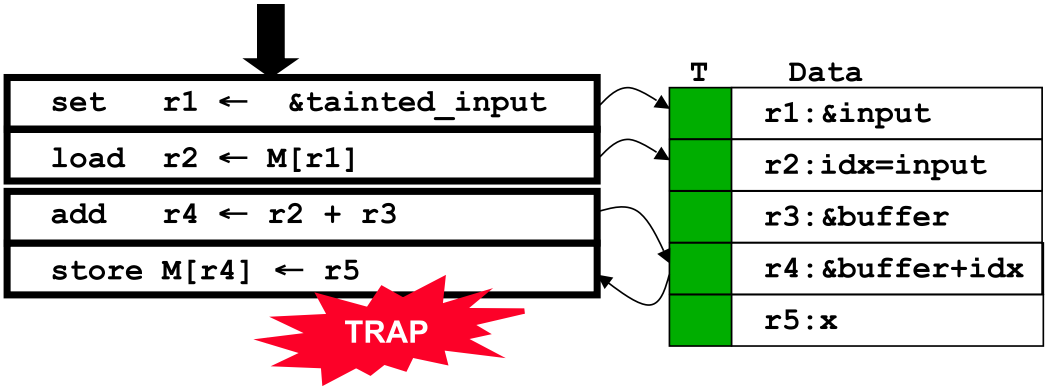
DIFT Example: Memory Corruption

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
```

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

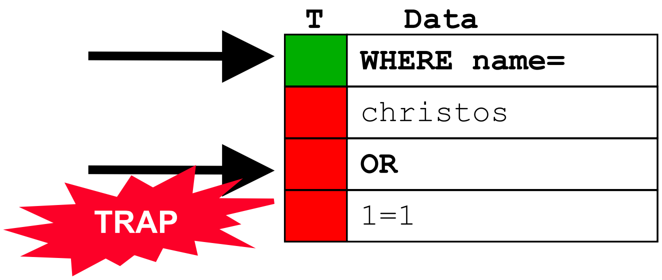
- Tainted pointer dereference ⇒ security trap

DIFT Example: SQL Injection

Username: christos’ OR ‘1’=‘1
Password:

Vulnerable SQL Code

SELECT * FROM *table*
WHERE *name*= ‘username’;
WHERE *name*= ‘christos’ OR ‘1’=‘1’ ;



T	Data
🟩	WHERE name=
🟥	christos
🟥	OR
🟥	1=1

☐ Tainted SQL command ⇒ security trap

DIFT in Software

☐ DIFT through code instrumentation [Newsome’05, Quin’06]
- Transparent through dynamic binary translation

☑ Software Advantages
- Runs on existing hardware
- Flexible security policies

☒ Software Disadvantages
- High overhead (≥3x)
- Does not work with threaded or self-modifying binaries
- Cannot protect OS
- Poor coverage: control-based, low-level attacks

The Case for HW Support for DIFT

☐ The basic idea [Suh'04, Crandall'04, Chen'05]

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

☑ Hardware Advantages

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

☒ Pitfalls to avoid

- Protect only against low-level attacks
- Fix security policies in HW
  - False positives & false negatives in real-world software
  - Cannot adapt to protect against future attacks
- Rely on OS mechanisms to handle security issues

Outline

☐ Motivation & DIFT overview

☐ The Raksha architecture for software security

- Technical approach
- Architectural features
- Full-system prototype

☐ Evaluation

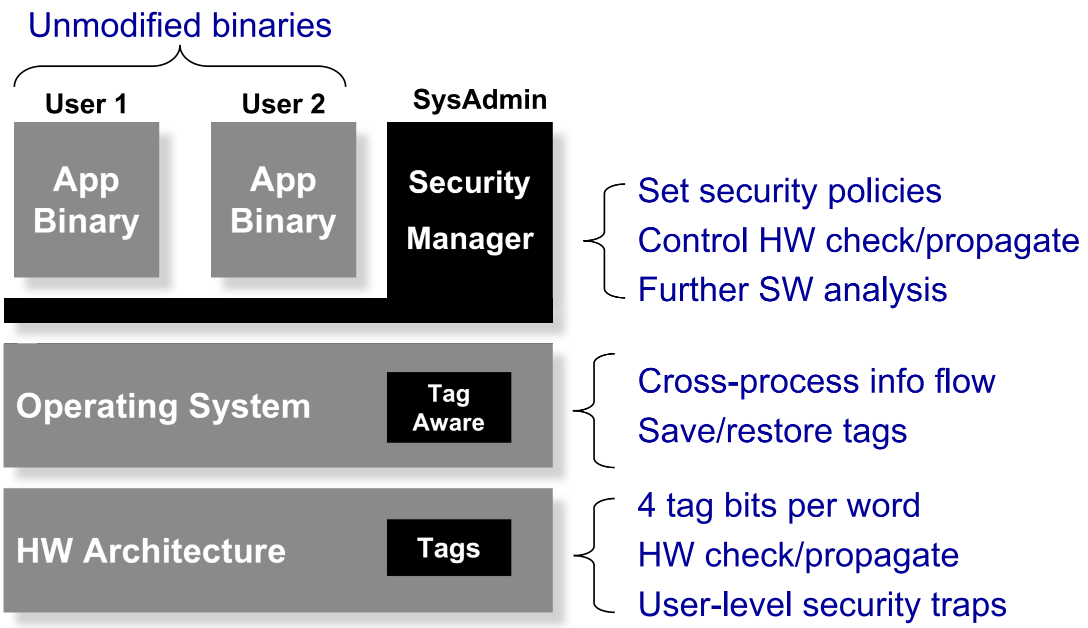
- Security experiments
- Lessons learned

☐ 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 Overview & Features



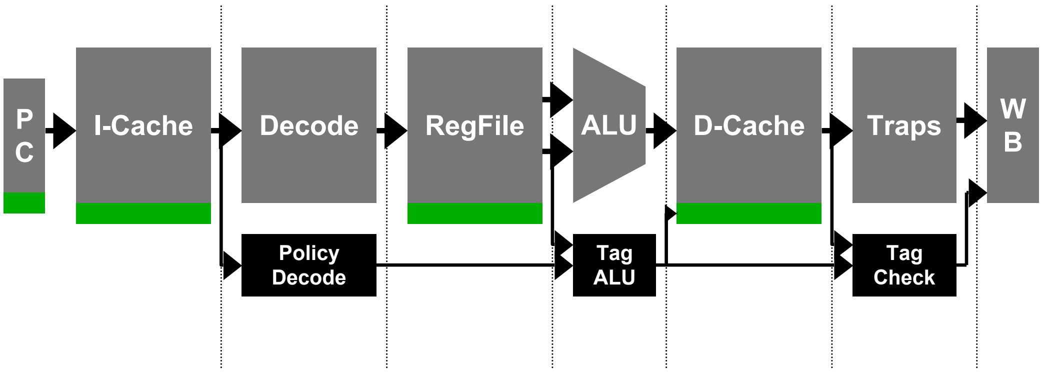
Unmodified binaries

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

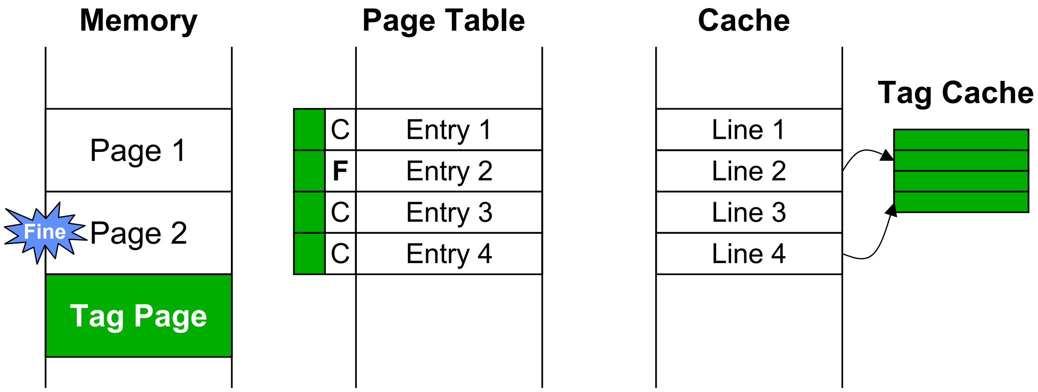
Raksha Architecture



- ❑ 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 Storage

- ❑ Simple approach: +4 bits/word in registers, caches, memory
  - 12.5% storage overhead
  - Used in our current prototype
- ❑ Multi-granularity tag storage scheme [Suh'04]
  - Exploit tag similarity to reduce storage overhead
  - Page-level tags ⇒ cache line-level tags ⇒ word-level tags



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
    - Same HW policies for both RISC & CISC ISAs

Propagate Policy Example: `load`

`load   r2 ← M[r1+offset]`

Propagate Enables

1. Propagate only from source register
   Tag(`r2`) ← Tag(`r1`)
2. Propagate only from source address
   Tag(`r2`) ← Tag(`M[r1+offset]`)
3. Propagate from both sources
   OR mode: Tag(`r2`) ← Tag(`r1`) **|** Tag(`M[r1+offset]`)
   AND mode: Tag(`r2`) ← Tag(`r1`) **&** Tag(`M[r1+offset]`)

Check Policy Example: `load`

`load   r2 ← M[r1+offset]`

Check Enables

1. Check source register tag

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

2. Check source address tag

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

Both enables may be set simultaneously

User-level Security Traps

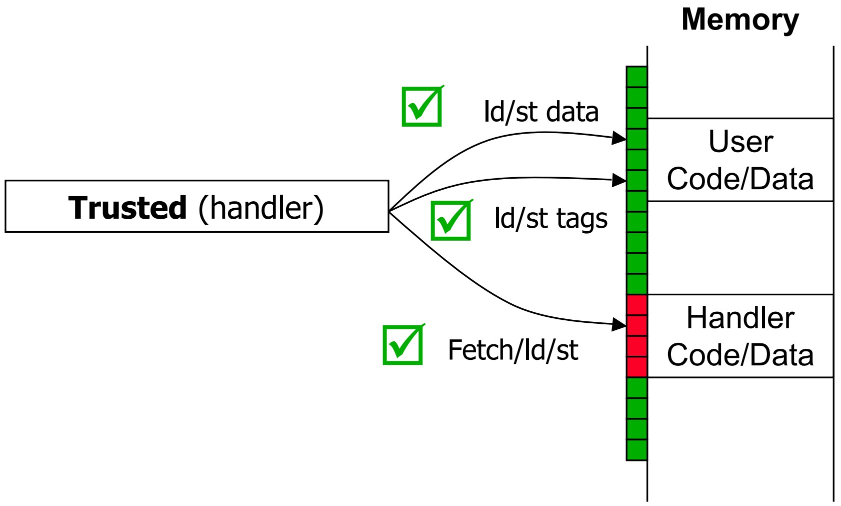
- ❑ Why user-level security traps?
  - Fast switch to SW ⇒ combine HW tainting with SW analysis
  - No switch to OS ⇒ DIFT applicable to most of OS code
- ❑ Requires new operating mode, orthogonal to user/kernel

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

- ❑ 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 only in trusted mode



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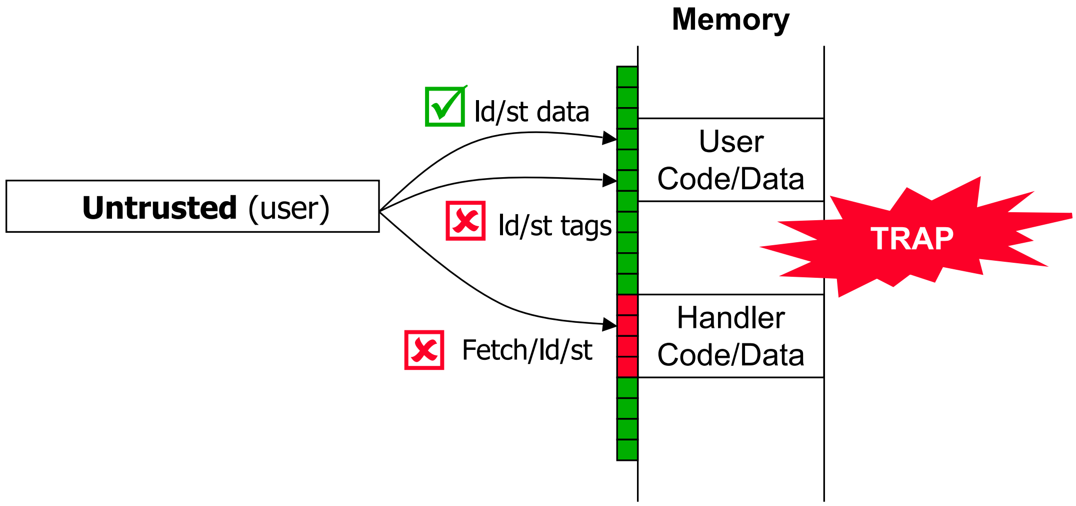
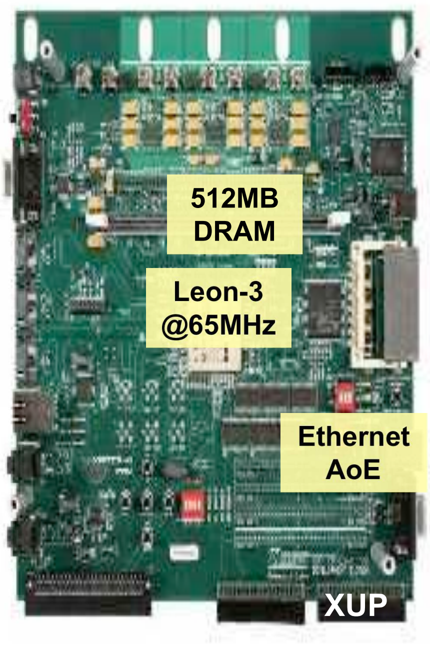


Raksha Prototype System

- 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
  - Mapped to FPGA board
- SW: Gentoo-based Linux distribution
  - Based on 2.6 kernel (modified to be tag aware)
  - ≥11,000 packages (GNU toolchain, apache …)
  - Set HW policies using preloaded shared libraries

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, …
  - High level protection => negligible overhead
  - Low level protection => depends on app
- Worst-case example from experiments
  - Most apps (gcc, mcf, …) very low overhead
  - Bzip2: +33% with Raksha 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 high-level 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

- Memory corruption (LL attacks)
  - Propagate on arithmetic, load/store, logical
  - Check on tainted pointer/PC use
  - Trap handler untaints data validated by user code
- String tainting (LL & HL attacks)
  - Propagate on arithmetic, load/store, logical
  - No checks
- System call interposition (HL attacks)
  - No propagation
  - Check on system call in untrusted mode
  - Trap handler invokes proper SW analysis (e.g. SQL parsing)
- 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's 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?
  - Available soon at http://raksha.stanford.edu
  - Raksha port to Xilinx XUP board
    - $300 for academics
    - $1500 for industry
  - Full RTL + Linux distribution

Tag Granularity

- ❑ Raksha HW maintains per word tag bits
  - 1 tag bit per word per policy
  - Sufficient for most security analyses

- ❑ What if SW wants byte or bit granularity for some data?
  - Maintain finer-grain tags in SW
  - Implement sandboxing policy for corresponding data
    - Switch to SW handler when data accessed
  - Handlers provides storage and functionality for fine-grain tags

- ❑ Acceptable performance if not common case…