Real-World Buffer Overflow Protection in User & Kernel Space

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Motivation

- Buffer overflows remain a critical security threat
- Deployed solutions are insufficient
  - Provide limited protection (NX bit)
  - Require recompilation (Stackguard, /GS)
  - Break backwards compatibility (ASLR)
- Need an approach to software security that is
  - Robust - no false positives on real-world code
  - Practical - works on unmodified binaries
  - Safe - few false negatives
  - 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: Buffer Overflow

Vulnerable C Code

```
int buf[8];
for (i = 0; i < len; i++)
    buf[i] = u;
return;
```

```
load  r2 ← M[u]
store M[buf+0] ← r2
…
store M[buf+7] ← r2
store M[ra] ← r2
jmp
```

TRAP

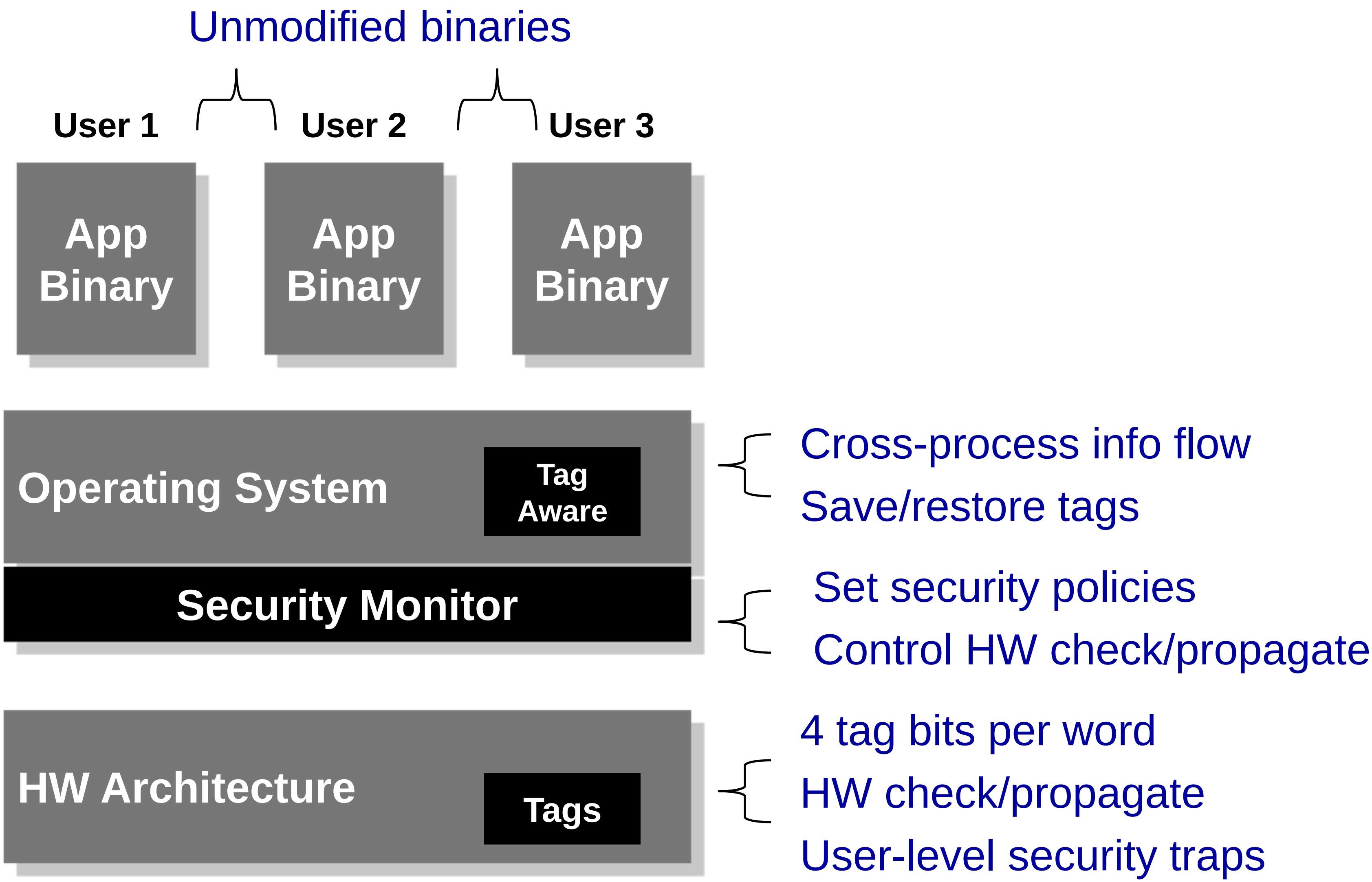
T	Data
(red)	u: &evil
(green)	buf[0]: &evil
(green)	buf[7]: &evil
(green)	ra: &evil

- Tainted pointer dereference ⇒ security trap

Hardware DIFT Overview

- 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
    - Software DIFT overheads range from 3-37x
  - Works with multithreaded and self-modifying binaries
  - Apply tag policies to OS

Raksha Overview & Features



Outline

- ❑ Motivation & DIFT overview
- ❑ Preventing buffer overflows with DIFT
  - Previous work
  - Novel BOF prevention policy
- ❑ Evaluation
  - Prototype
  - Security experiments
  - Lessons learned
- ❑ Conclusions

Naïve Buffer Overflow Detection

- Previous DIFT approaches recognize bounds checks
  - Must bounds check untrusted info before dereference
    - Example: `if (u < len) print buf[u];`
- Taint untrusted input
- OR Propagate taint on load,store,arithmetic,logical ops
- Clear taint on bounds checks
  - Comparisons against untainted info
- Check for tainted code, load/store/jump addresses
  - Forbid tainted pointer deref, code execution

Problems with Naïve Approach

- Not all bounds checks are comparisons
  - Example : `*str++ = digits[val % 10]`
  - GCC, glibc, gzip…
- Not all comparisons are bounds checks
  - Example: `if (sz < fastbin_size) insert_fastbin(chunk);`
  - Resulted in false negative during traceroute/malloc exploit
- Bounds checks are not required for safety!
  - Example: `return isdigit[(unsigned char)x]`
    - isdigit array is 256 entries! Don't need any bounds check
    - But stripped binary doesn't tell us array sizes….

End result: unacceptable false positives in real code

Building a Better Security Model for BOF

- Buffer overflow attacks rely on injecting **pointers**
  - Code pointers
    - Return address, Global Offset Table (GOT), function ptr
  - Data pointers [Chen 05]
    - Filenames, permission/access control structures, etc

- Why pointers?
  - They're everywhere!
    - Every stack frame (local pointers, frame pointer, ret addr)
    - Every free heap object (glibc)
    - Global Offset Table, constructors, destructors, …
  - Security-critical
    - Control pointers - arbitrary code execution
    - Data Pointers – subvert logic using tainted data structures

Preventing Pointer Injection with DIFT

- Buffer overflows exploits overwrite **pointers**
  - But should **never** receive pointer from network!
  - Tainted data used as pointer **index**, never as pointer **address**

- New DIFT BOF Policy
  - Tainted data cannot be dereferenced directly
  - Must be combined with application pointer to be safe
  - Pointer bit – tag legitimate application pointers
  - Taint bit – tag untrusted data

- But how do we identify legitimate application pointers?

New BOF Policy – Taint bit

- Goal: conservatively track untrusted information
  - Do **not** try to clear taint by recognizing bounds checks
  - Only clear taint when reg/mem word overwritten

- Taint untrusted input
- OR Propagate on load, store, arithmetic, logical ops
- Check for tainted code
- Check if code/data ptr is tainted and **not** a valid ptr
  - Security exception if Taint bit set & Pointer bit clear

New BOF Policy – Pointer bit

- Propagate Pointer bit during valid pointer ops
  - Load/Store Pointer
  - Pointer +,-,OR,AND Non-Pointer
  - Pointer +,- Pointer
    - Encountered in real-world, byte of pointer used as array index
- Clear P-bit on all other operations
  - Multiply, logical negation, etc
- Check for untrusted pointer dereferences
  - Security exception if T-bit set, P-bit clear

Identifying Userspace Pointers

- Initialize P-bit for all local variable references
  - Set P-Bit for stack pointer
- Initialize P-bit for all dynamically allocated memory references
  - Set P-bit for return value of mmap, brk syscalls
- Initialize P-Bit for static/global variable references
  - Scan all executable, library objects for these references
    - Scan both code, data regions
    - Set P-bit for potential any potential valid pointers
  - ABI (ELF, PE) restricts such references
    - Must be valid relocation entry type

BOF Protection in Kernel Space

- OS dereferences untrusted pointers!
  - System call arguments come from untrusted userspace
  - Example: `int unlink(const char * pathname)`
- Why is this safe?
  - All user pointers must be checked by `access_ok()`
  - Ensures user pointer is in userspace, not kernelspace
- What instructions may access userspace?
  - Any instruction accessing userspace may cause MMU fault
  - All modern Unix OSes build tables of these instructions!
    - Any MMU fault not found in the table is an OS bug
- Safe untrusted pointer dereference in Linux:
  - Tainted pointer must point to userspace
  - PC must be in MMU fault list

Raksha Prototype System

- Full-featured Linux system
- 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 (65Mhz workstation)
- SW: ported Gentoo Linux distribution
  - Based on 2.6 kernel (modified to be tag aware)
  - Kernel preloads security manager into each process
  - Over 14,000 packages in repository (GNU toolchain, apache, sendmail, …)

Experiments (Userspace)

- Successfully running Gentoo **without false positives**
  - Every program, even init, has BOF protection enabled
  - Run gcc, OpenSSH, sendmail, etc.
- Prevented attacks on real-world applications

Program	**Attack**	**Detection**
Polymorph	Stack overflow	Tainted code ptr
Atphttpd	Stack overflow	Tainted code ptr
Sendmail	BSS overflow	Tainted data ptr
Traceroute	Double free	Tainted data ptr
Nullhttpd	Heap overflow	Tainted data ptr

All userspace programs are unmodified binaries

Experiments (Kernelspace)

- Protect entire Linux kernel from BOF
  - **First** comprehensive kernel buffer overflow protection
  - Even protect assembly code, device drivers, ctx switch
- Only observed one potential false positive
  - **Caused by previously undiscovered security hole!**
- Prevented real-world attacks on Linux kernel

Subsystem	Vulnerability
quota system call	User/Kernel pointer deref
i2o driver ioctl	User/Kernel pointer deref
moxa driver	BSS overflow
cm4040 driver	Heap overflow
sendmsg system call	Stack, Heap overflow

Comprehensive BOF protection

- Can some BOF vulnerabilities still be exploited?
  - Yes, if BOF doesn't rely on pointer corruption
    - Authentication flag, user IDs, array/pointer offsets…
  - Rare, but possible – depends on application data structure layout, etc

- Combine multiple BOF protection policies for safety!
  - Attacker must evade **all** active policies to succeed
    - But must ensure **all** policies have no real-world false positives…
  - Policy #1: Bounds check BOF protection for control pointer only
    - Bounds check false positives only observed for **data** pointers
    - Prevents control pointer array offset overwites
  - Policy #2: Red Zone bounds checking for heap
    - Tag begin/end of each heap object with Sandbox bit
    - Raise error if user attempts to load/store to sandbox'd address
    - Detects heap buffer overflows

- Use Raksha to run all policies concurrently (w/ Pointer BOF)
  - No false positives – tested in userspace <u>and</u> kernelspace
  - Verified new policies stop control pointer overwrites, heap overflows (resp.)

Conclusions

- Pointer-based BOF protection is **practical**
  - Prevents real-world buffer overflows – code/data pointer
    - No source code access, debugging info, etc required
  - No observed false positives
    - Tested GCC, Apache, OpenSSH, etc
- Protection can even be extended to OS
  - Full OS - FS, MM, device drivers, context switch, etc
  - Only potential false positive was a real security hole
- Compose multiple policies for best protection
  - Only miss an attack if it can evade **all** active policies

Questions?

- Want to use Raksha?
  - Go to http://raksha.stanford.edu
  - Raksha port to Xilinx XUP board
    - $300 for academics
    - $1500 for industry
  - Full RTL + Linux distribution coming soon

Bonus round: Why not bounds checking?

- Compatibility
  - C was never meant to be bounds checked
    - Ex: optimized glibc() memchr() reads out of bounds
    - Context sensitive- Apache ap_alloc => malloc=>brk
  - Inline assembly, Multithreading
  - Dynamically loaded plugins, dynamically gen'd code
  - Closed-source libraries, objects in other languages
- Cost – recompiling is expensive
  - **Global** recompilation of all system libs is not happening
  - Just ask MS to recompile MFC…
- Performance
  - Overheads must be low (single digit) to drive adoption