Real-World Buffer Overflow Protection for 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
  - End-to-End

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

```
char buf[1024];
strcpy(buf,input);//buffer overflow
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r1 ←r1 + 4
load  r2 ←M[r1]
store M[r3] ←r2
jmp M[retaddr]
```

T	Data
	r1:input+1020
	r2:0
	r3: buf+1024

	retaddr: safe

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T	Data
	r1: input+1024
	r2: bad
	r3: buf+1024

	retaddr: safe

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T	Data
(green)	r1: input+1024
(red)	r2: bad
(green)	r3: buf+1024
(red)	retaddr: bad

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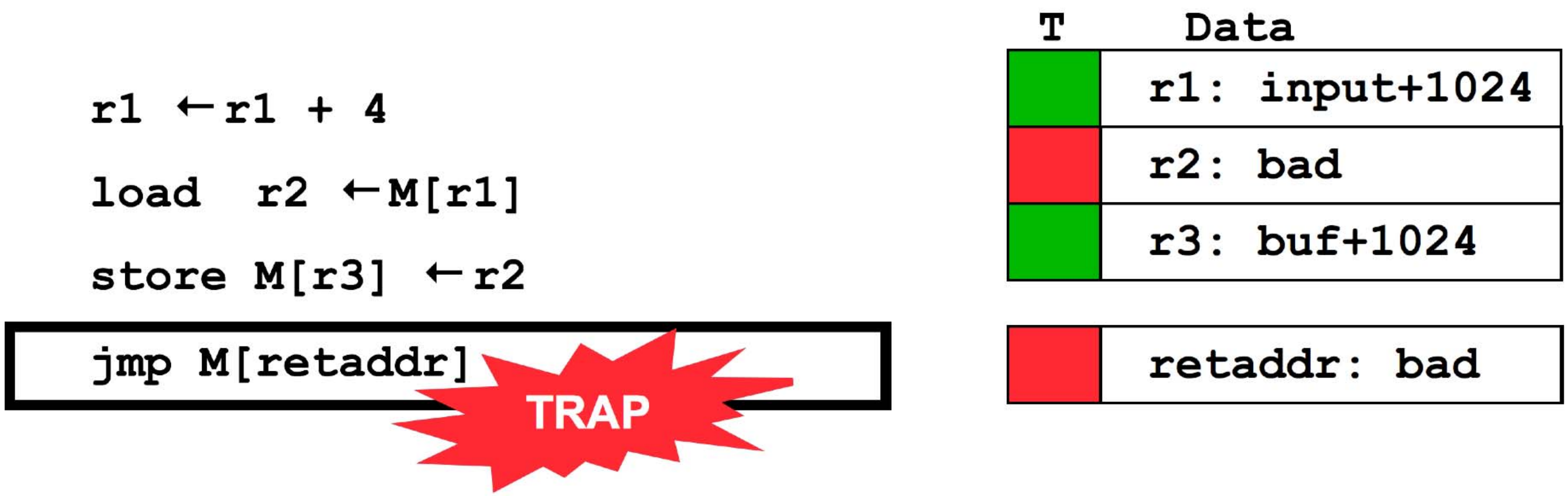


- ❑ Tainted pointer dereference ⇒security trap

Hardware DIFT Overview

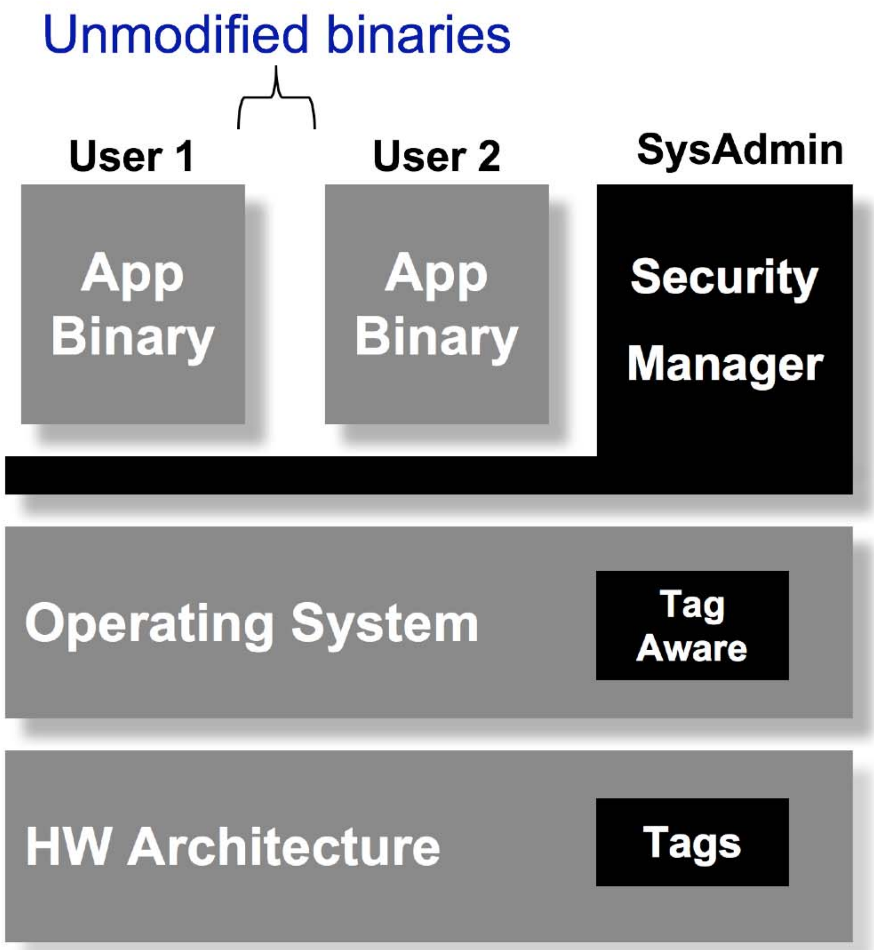
❑ The basic idea [Suh'04, Crandall'04, Chen'05, Dalton '07]

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

☑ Hardware Advantages

- Negligible runtime overhead
- Works with multithreaded and self-modifying binaries
- Apply tag policies to OS

Raksha Overview & Features [Dalton '07]



- 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

Check Policy Example: `load`

`load  r2 ← M[r1+offset]`

Check Enables

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]**)
   XOR mode: Tag(r2) ←Tag(**r1**) ^ Tag(**M[r1+offset]**)

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
- 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, …)

Outline

- ❑ Motivation & DIFT overview
- ❑ Preventing Buffer Overflows with DIFT
  - Previous Work
  - Novel DIFT buffer overflow prevention policy
- ❑ Evaluation
  - Security experiments
  - Lessons learned
- ❑ Conclusions

Naïve Buffer Overflow Detection

- Previous DIFT approaches recognize bounds checks
  - Must bounds check untrusted information to dereference
- 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
  - `*str++ = digits[val % 10]` (glibc)
  - `ent = hashtbl[x & TABLESZ - 1]` (GCC)
- Not all comparisons are bounds checks
  - `If (chunksize(sz) < FASTBIN_SZ)`
    - malloc() code caused false negative in traceroute exploit
- Bounds checks are not required for safety!
  - `return isdigit[(unsigned char)x]` (glibc)
    - 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

Preventing BOF with Pointer Identification

- New approach: prevent attackers from injecting pointers
  - Tainted information should not be directly dereferenced
  - Instead, use as offset combined with legitimate pointer

- Buffer overflow attacks rely on <u>injecting pointers</u>
  - Pointers are everywhere and security-critical
  - Code pointers (return address, function pointer, global offset table)
  - Data pointers (malloc heap chunks, filenames, permission structures)

- DIFT policy based on Pointer Injection
  - Track untrusted data (Taint bit) and legitimate pointers (Pointer bit)
    - Use two separate DIFT analyses
  - 2 tag bits per word – T bit, P-bit
  - Untrusted data may only be used an index to a legitimate pointer
    - Forbid any dereference with T-bit set and P-bit clear

New Policy for Taint Bit

- Goal: conservatively track untrusted information
  - Don’t try to clear taint by recognizing bounds checks
  - Only clear when reg/mem word overwritten by clean data
- Taint untrusted input
- OR Propagate on load, store, arithmetic, logical ops
- Check on code execution
  - Trap if code is tainted
- Check on load/store/jump address
  - Trap if address is tainted but does not have P-bit set

New Policy for Pointer Bit

- Goal: Identify all valid pointers at runtime

- Initialize P-bit for pointers to statically allocated mem at startup
  - More details on next slide on how to identify these

- Initialize P-bit for all pointers to dynamically allocated mem
  - Return value of mmap, shmat, brk syscalls

- Propagate P-bit during valid pointer ops
  - Load/Store Pointer
  - Pointer +,- Non Pointer
  - Pointer +,-, OR Pointer
    - Rare corner case in gcc, fprintf("%ld", pointer) …
  - Pointer AND non-pointer (only if pointer alignment)
  - Clear P-bit on all other operations

Identify Pointers at Startup

- Must set P-bit for all regs, memory with valid pointer at startup
  - Only regs with valid pointer are Stack Pointer, PC
- Scan Data and Code of all Objects (Executable and Libraries)
  - Set P-bit for potential valid pointers
- Object File Format (ELF, PE, etc) restricts references
  - Any reference to statically allocated mem must be relocatable
  - Only a few supported relocation entry formats…
  - Makes recognizing pointers in code/data practical

Identify Pointers cont'd

- Identifying Pointers in Data Segments
  - ELF, PE restrict data references to symbol + offset
    - Valid `int * y = &x + 12`
    - Invalid `int *y = &x >> 12`
  - Identify word of data as a pointer if
    - ObjectFile_Start <= word < ObjectFile_End

- Identifying Pointers in Code Segments
  - ELF SPARC restricts code references to sethi/or pairs
  - sethi instruction used to set upper 22 bits of register
  - Set P bit of sethi insn if constant within current obj file
  - At runtime, P-bit of sethi instructions propagates to dest

Protecting the Linux Operating System

- P-Bit, T-Bit initialization similar to userspace
  - OS has hardcoded pointer constants for heaps, I/O regions

- Problem: OS dereferences untrusted pointers!
  - System call arguments are untrusted
  - `ssize_t write(int fd, const void * buf, size_t count)`
  - Kernel must dereference `buf`, even though it is untrusted

- New security requirements
  - Must allow legitimate, safe user pointer dereferences
  - Must forbid user pointers into kernelspace
    - User/Kernel pointer dereference attack (compromises OS)

Protecting Linux cont'd

- Solution: __ex_table
  - Only user pointer dereferences cause MMU faults
  - __ex_table lists all instructions that may MMU fault
  - Similar data structures exist in Free/Net/OpenBSD, Solaris

- Preventing kernel memory corruption
  - Security exception if dereference tainted pointer
  - Exception handler permits tainted deref only if
    - PC is found in __ex_table
    - Load/store address is in userspace
  - Prevents buffer overflows *and* user/kernel pointer deref

- Found one local DoS bug with this technique
  - See paper for more details

Experiments

- Successfully running Gentoo on Raksha
  - Full FPGA-based prototype
  - Modern Linux distribution
  - Run gcc, OpenSSH, sendmail, Apache, etc.

- Protecting all of Userspace
  - Every program, every instruction
  - Policy enforced by trusted userspace monitor

- Protecting Kernel Space
  - Everything but first few instructions of trap handler
    - These instructions enable BOF tag policy
  - Protect bootup code, optimized handwritten assembly, context switching code, etc

Userspace Buffer Overflow Results

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

All applications are unmodified binaries

No false positives

Kernelspace Buffer Overflow Results

Module	Attack	Detection
Quotactl syscall	User/Kernel Pointer	User pointer to OS data
I2o driver	User/Kernel Pointer	User pointer to OS data
Sendmsg syscall	Stack, Heap Overflow	Tainted data pointer
Moxa driver	BSS Overflow	Tainted data pointer
Cm4040 driver	Heap Overflow	Tainted data pointer

Protection enabled for all of kernelspace

No false positives

Conclusions

- Bounds check recognition is fatally flawed
  - Diversity of operations is immense (e.g. % on SPARC)
  - Don't even need to bounds check in some corner cases
    - Cannot disambiguate these cases from attacks in practice

- New BOF policy – prevent pointer injection
  - Track tainted data *and* legitimate application pointers
  - Forbid dereference if T bit set and P-bit clear

- Result: protect code and data pointer with no false positives
  - Prevented attacks in userspace, kernelspace
  - Verified no false positives in user/kernel
    - Ran Apache, GCC, mysql, etc
    - Untrusted sources should never supply pointers

Further Information in the Paper

- Prototype implementation description
  - Full summary of check, propagate modes, etc
- Portability discussions
  - How to port T-bit, P-bit rules to x86
  - How to apply Linux kernel BOF rules to BSDs, Solaris
- Additional DIFT policies
  - Provide better coverage by using multiple policies
  - Red Zone Bounds Checking
  - Bounds Check Recognition for control pointers only
  - Format string protection

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