Exploit Defenses: ASLR, W⊕X, TaintCheck

Brad Karp
UCL Computer Science

CS GZ03 / M030
3rd December 2014

Host-Based Exploit Defenses

- Firewalls: defenses against worms in-network
  - Can see lots of traffic at one monitoring point
  - Can filter traffic for many vulnerable hosts
  - Limited information available: only packet fields, payload contents
- Today: identifying and defending against exploits (and so against worms) on hosts
  - Much more information: see effect of network request on running process's execution!
  - Potentially more accurate
  - Requires changes to host software
  - Performance concern; don't want to slow busy server

Outline

- W$\oplus$X page protections
  - and limitations
- Address Space Layout Randomization
  - and limitations
- TaintCheck
  - and limitations

Goals for Host-Based Exploit Defenses

- Works on executables
  - …and so for legacy code
  - Source code often not available
- Prevents broadest possible range of exploits
- Low/no false positives, false negatives
- Minimal performance reduction
  - Server operator won’t want to sacrifice performance
  - Attacker may recognize server protected if performance slows—and not send malicious request!

W⊕X Page Protections

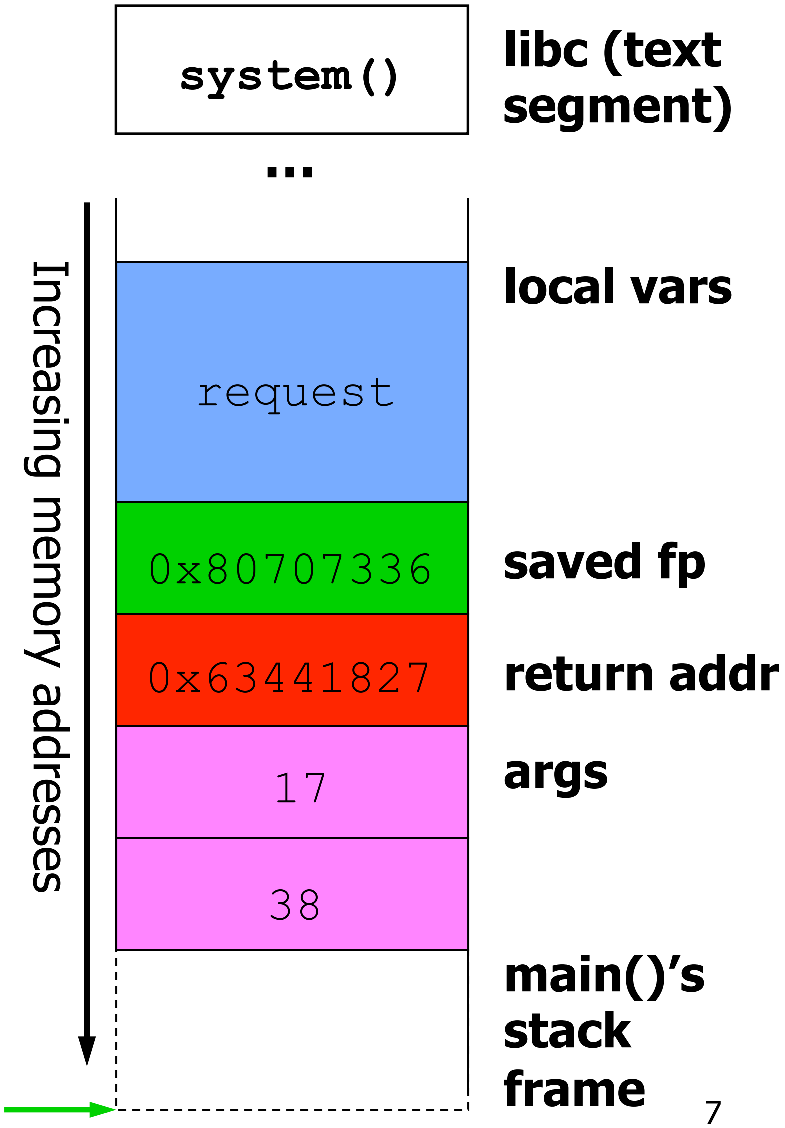
- Recall from OS: CPU implements page protection in hardware
  - For each 4K memory page, permission bits specified in page table entry in kernel: read, write
- Central problem in many exploits:
  - Code supplied by user in input data
  - Execution transferred to user's input data
- **Idea: don't let CPU execute instructions stored in data pages**
  - i.e., each page should either be writable or executable, but not both: W⊕X
  - Text pages: X, not W
  - Data (stack, heap) pages: W, not X

W⊕X Details

- Originally no X bit in Intel CPUs; just R and W, all R pages implicitly X
- AMD and Intel introduced “NX” bit (no execute); available on today’s processors (in PAE mode)
  - Not a new idea; present in, e.g., DEC Alpha
  - Used by Linux PaX and Windows XP SP2
- Linux PaX implements W⊕X for x86 processors without NX bit hardware
  - Based on segment limit registers
  - Halves address space available to each process
  - Minor performance reduction
- W⊕X breaks just-in-time (JIT) code generation in legacy applications!

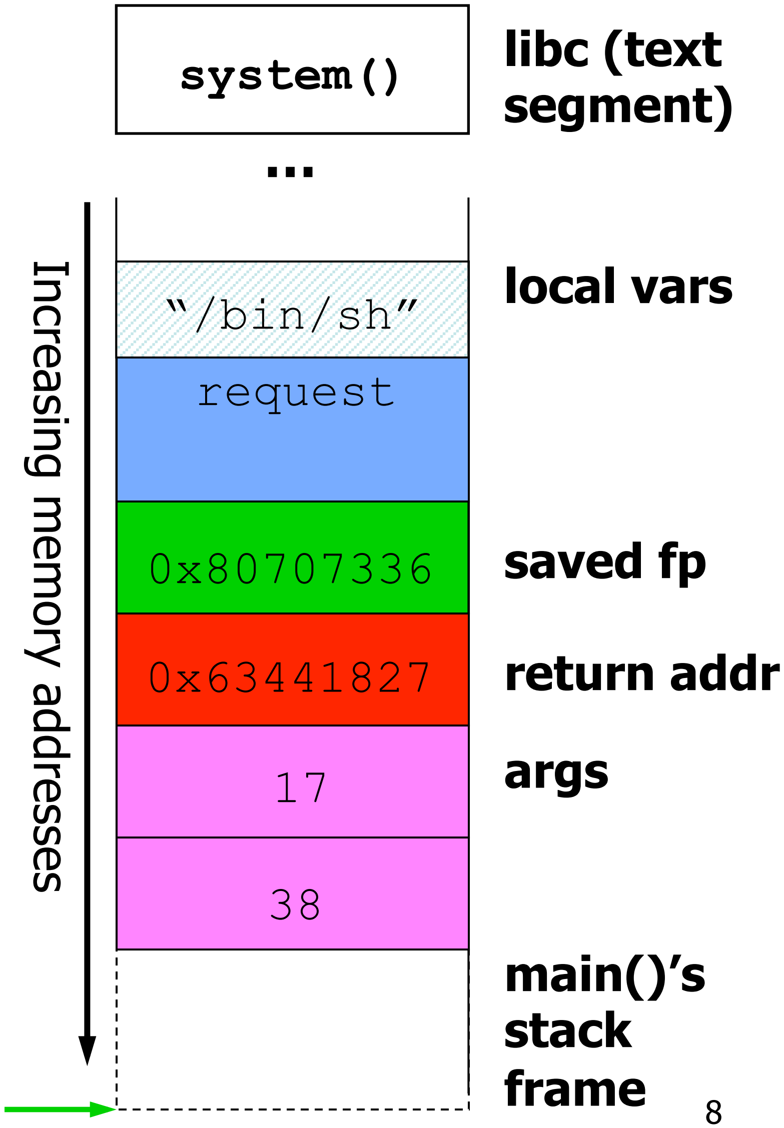
W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



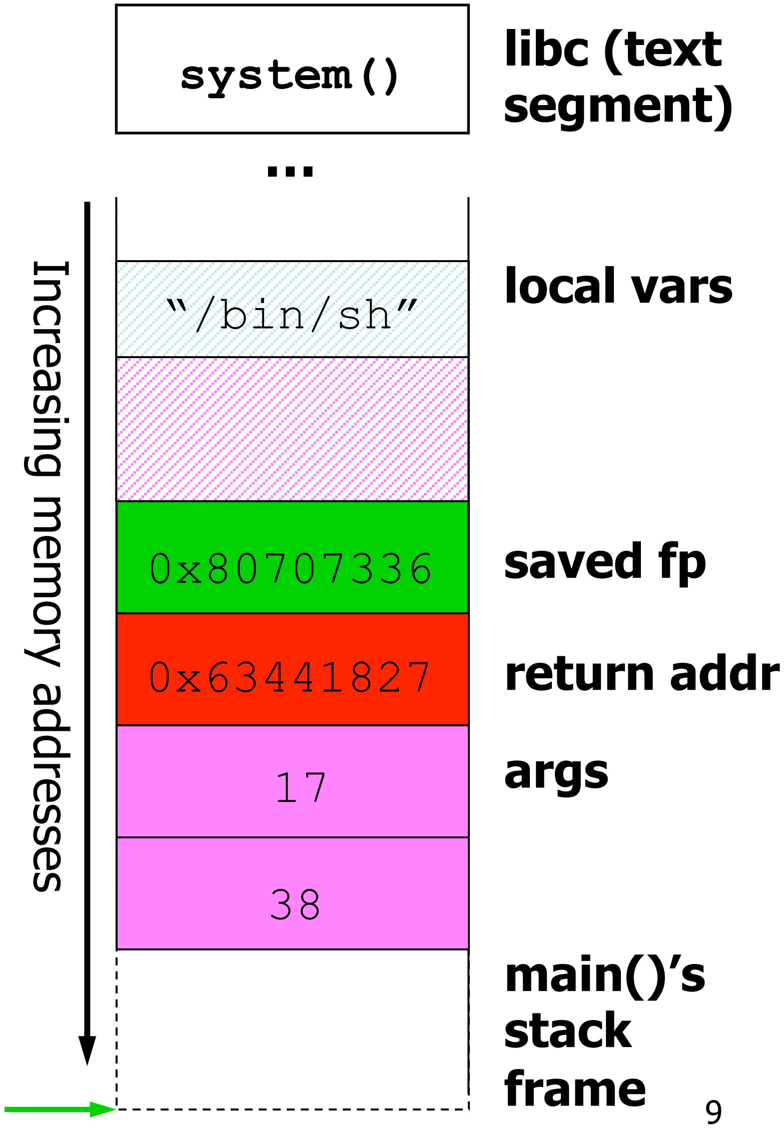
W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



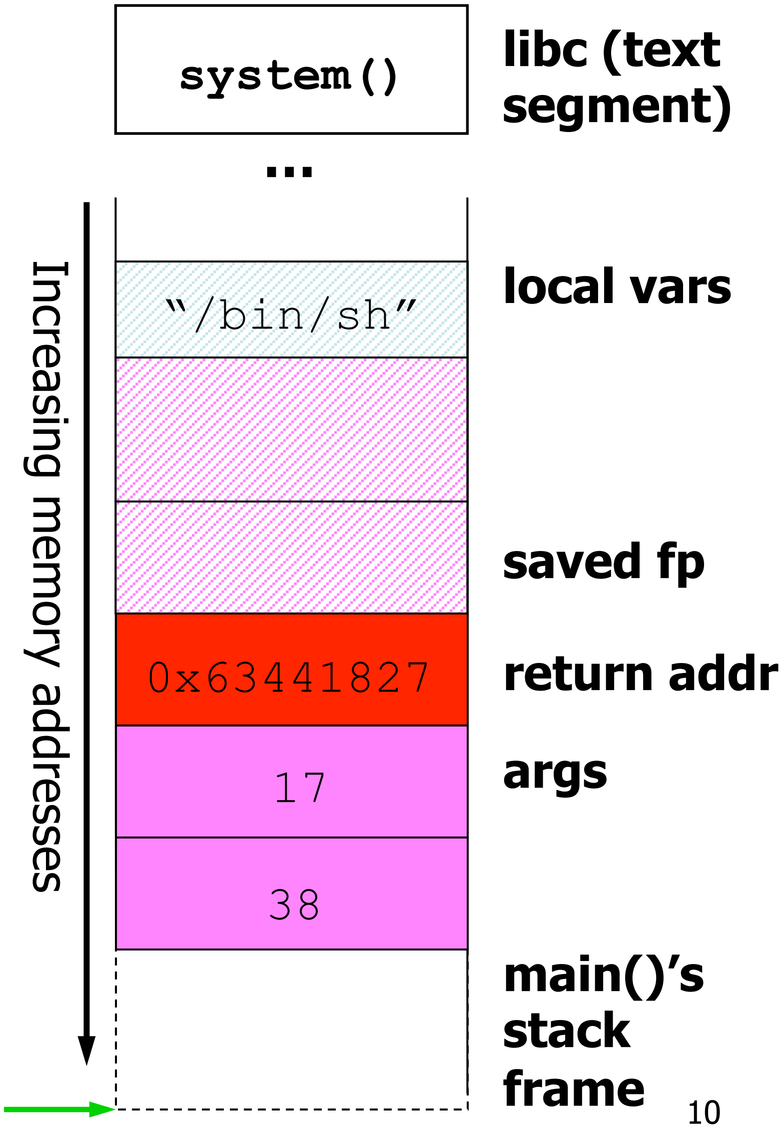
W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



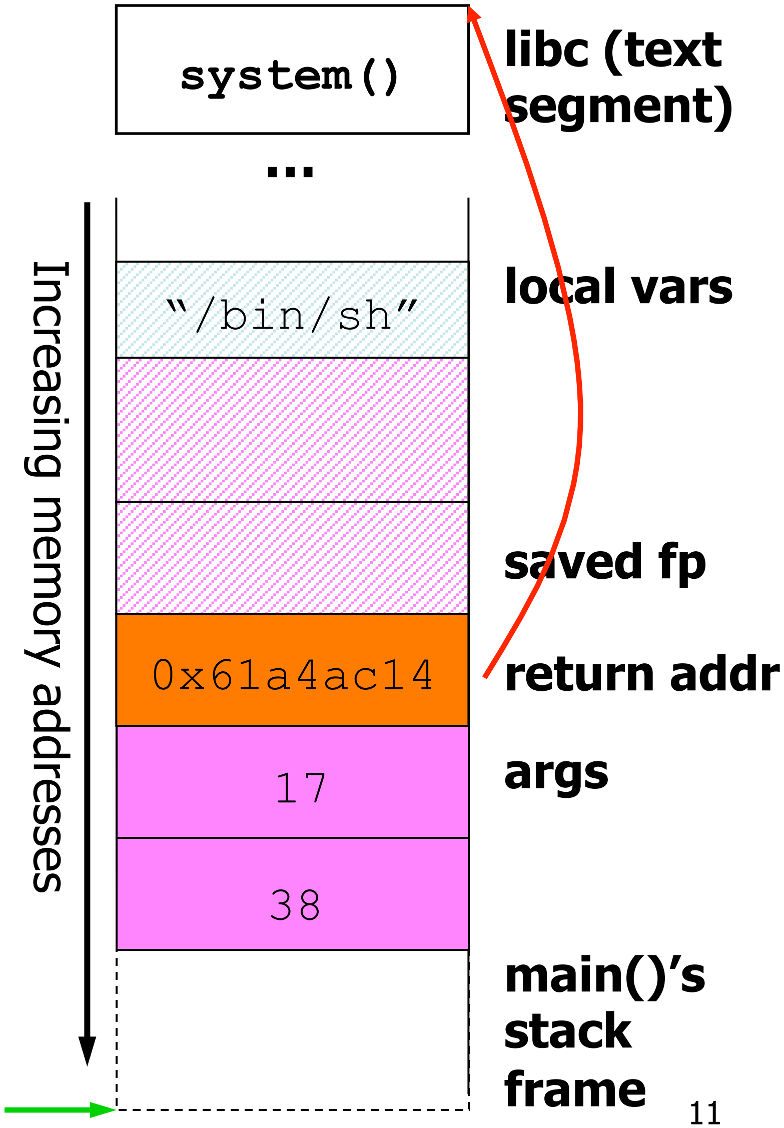
W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



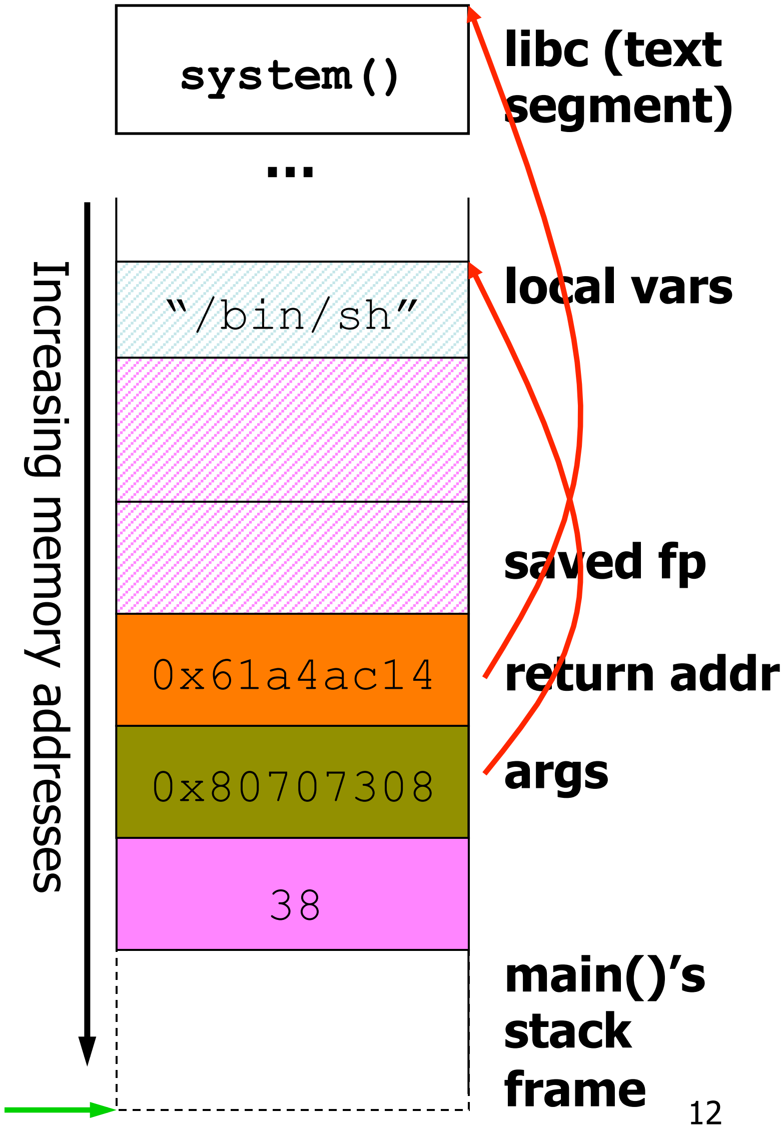
W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



W⊕X Hole: Return-to-libc Attacks

- Instead of putting shellcode on stack, can put args there, overwrite return address with pointer to well known library function
  - e.g., `system("/bin/sh");`
- Return-to-libc attack



Address Space Layout Randomization (ASLR)

- Central observation: attacker must predict addresses
  - e.g., shellcode buffer address, libc function address, string argument address
- Idea: randomize addresses in process
  - With high probability, attacker will guess wrong
  - Jump to unmapped memory: crash
  - Jump to invalid instruction stream: crash
- Useful as efficient exploit detector
  - Memory faults or illegal instructions suggest exploit

ASLR Implementation: PaX for Linux

- Linux process contains three memory regions:
  - Executable: text, init data, uninit data
  - Mapped: heap, dynamic (shared) libraries, thread stacks, shared memory
  - Stack: user stack
- ASLR adds random offset to each area when process created
  - Efficient; easily supported by virtual memory hardware
  - 16, 16, 24 bits randomness, respectively
- Mapped offset limited to 16 bits
  - bits 28-31 cannot be changed; would interfere with big mmap()s
  - bits 0-11 cannot be randomized; would make mmap()ed pages not be page-aligned

Derandomization Attack on ASLR [Shacham, Boneh et al.]

- 16 bits not that big; try to guess random offset added to mapped area
- Once know random offset, can predict addresses of shared libraries
  - thus libc function addresses
  - …so can mount return-to-libc attack
- Two phases:
  - brute-force random offset to mapped area
  - compute "derandomized" address of syscall(), use in return-to-libc attack

Derandomization Attack Details

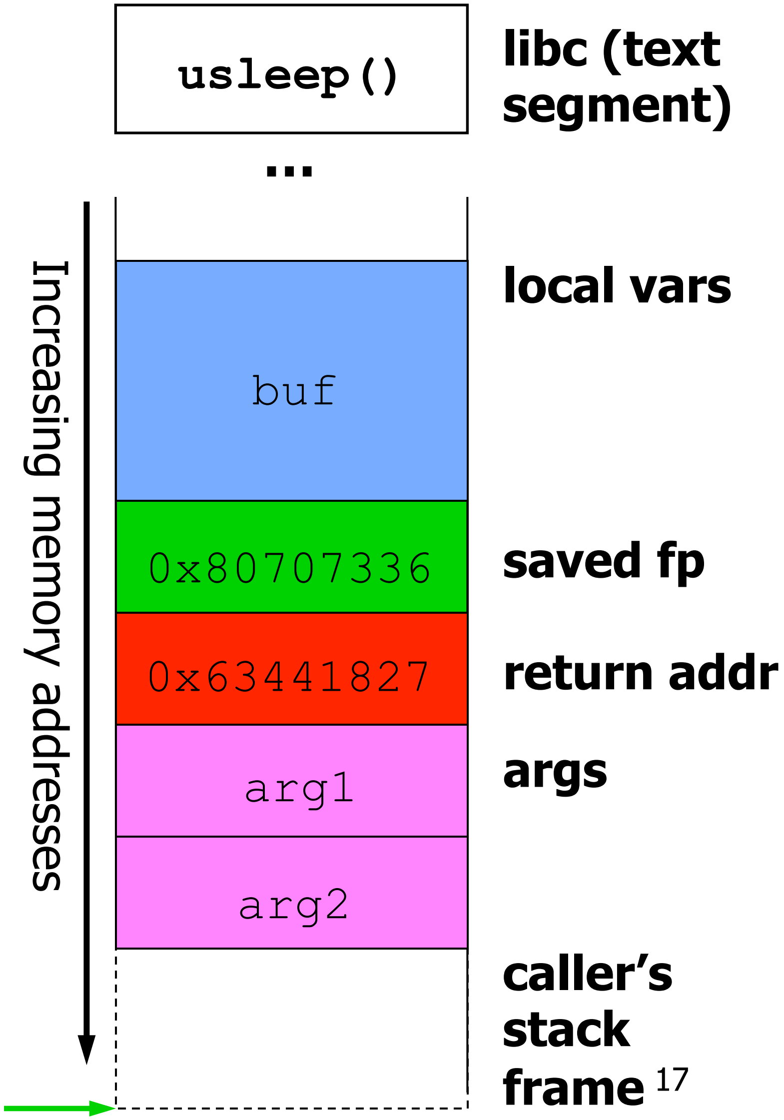
- Target: "classic" stack buffer overflow placed in Apache web server

```
char buf[64];
…
strcpy(buf, input);
```

- Plan:
  - Try to return to usleep(), guessing random offset for mapped area each time
  - If guess wrong, target process crashes, closes connection immediately; parent forks new child (with same random offset)
  - If guess right, target process delays in usleep(), then crashes and closes connection immediately

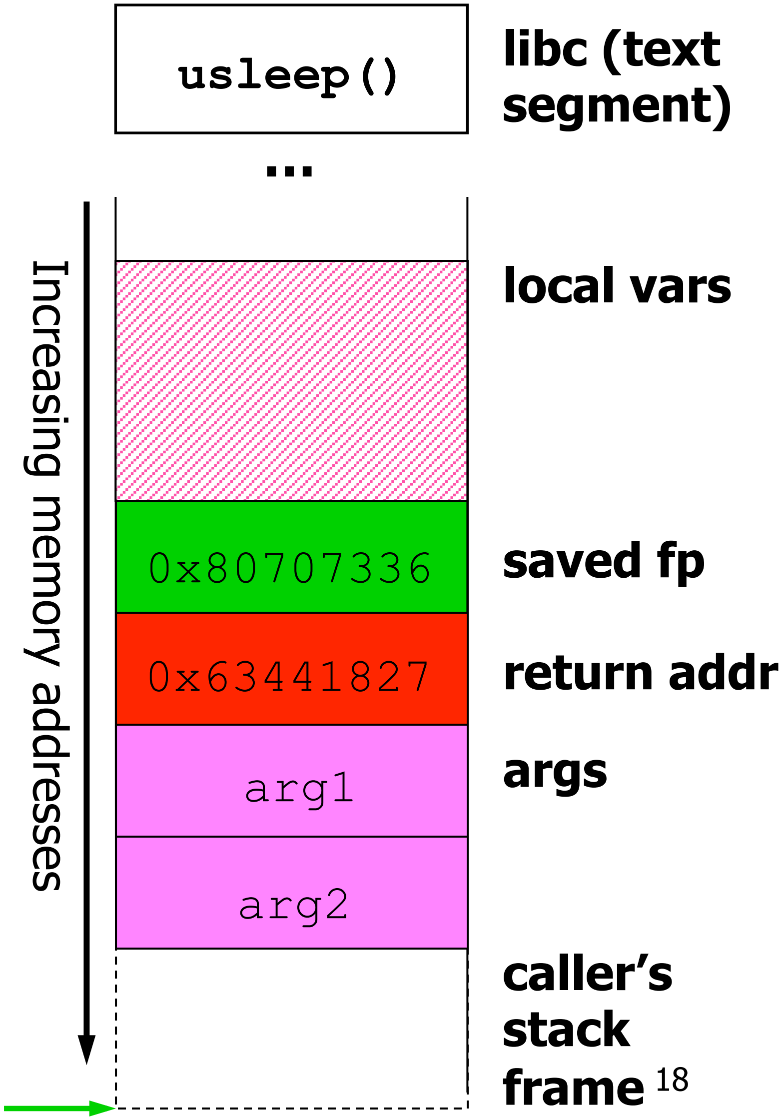
Derandomization Attack: Phase 1

- Know offset of `usleep()` within libc, know base of mapped area (w/o randomization)
- Each return address guess:
  - base + `usleep()` offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, `usleep()` sees return address `0xdeadbeef`, arg 16,843,009 usec (16 sec); sleep, crash



Derandomization Attack: Phase 1

- Know offset of **`usleep()`** within libc, know base of mapped area (w/o randomization)
- Each return address guess:
  - base + **`usleep()`** offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, **`usleep()`** sees return address **`0xdeadbeef`**, arg 16,843,009 usec (16 sec); sleep, crash



`usleep()`

libc (text segment)

...

Increasing memory addresses

local vars

`0x80707336`

saved fp

`0x63441827`

return addr

`arg1`

`arg2`

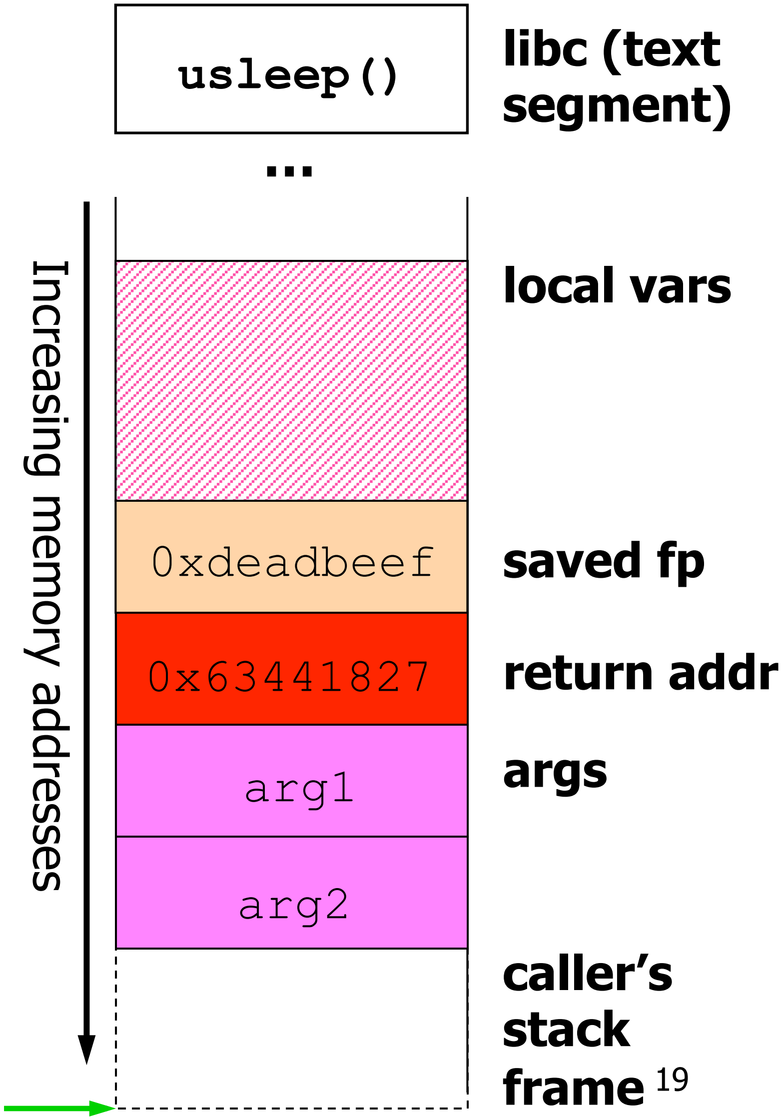
args

caller's stack frame

Derandomization Attack: Phase 1

- Know offset of **`usleep()`** within libc, know base of mapped area (w/o randomization)
- Each return address guess:

  base + **`usleep()`** offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, **`usleep()`** sees return address **`0xdeadbeef`**, arg 16,843,009 usec (16 sec); sleep, crash



`usleep()` — **libc (text segment)**

...

Increasing memory addresses

local vars

`0xdeadbeef` — **saved fp**

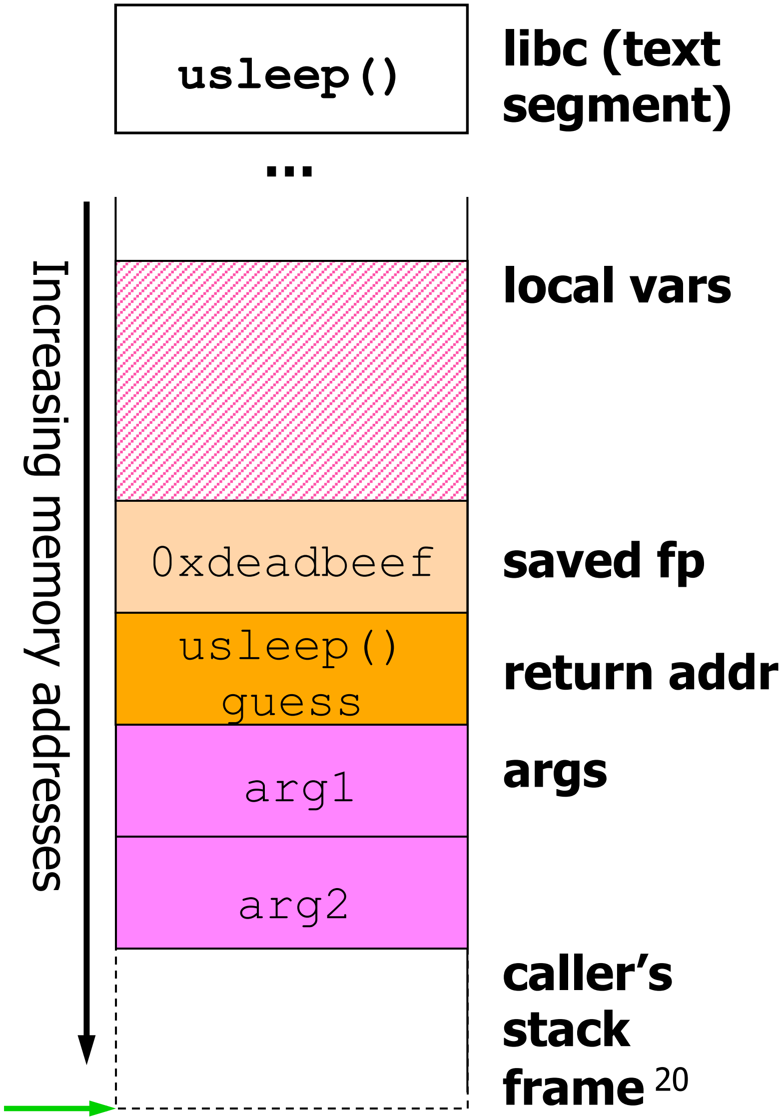
`0x63441827` — **return addr**

`arg1`, `arg2` — **args**

caller's stack frame

Derandomization Attack: Phase 1

- Know offset of **`usleep()`** within libc, know base of mapped area (w/o randomization)
- Each return address guess:
  - base + **`usleep()`** offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, **`usleep()`** sees return address **`0xdeadbeef`**, arg 16,843,009 usec (16 sec); sleep, crash



`usleep()`

libc (text segment)

...

local vars

`0xdeadbeef`

saved fp

`usleep()` `guess`

return addr

`arg1`

`arg2`

args

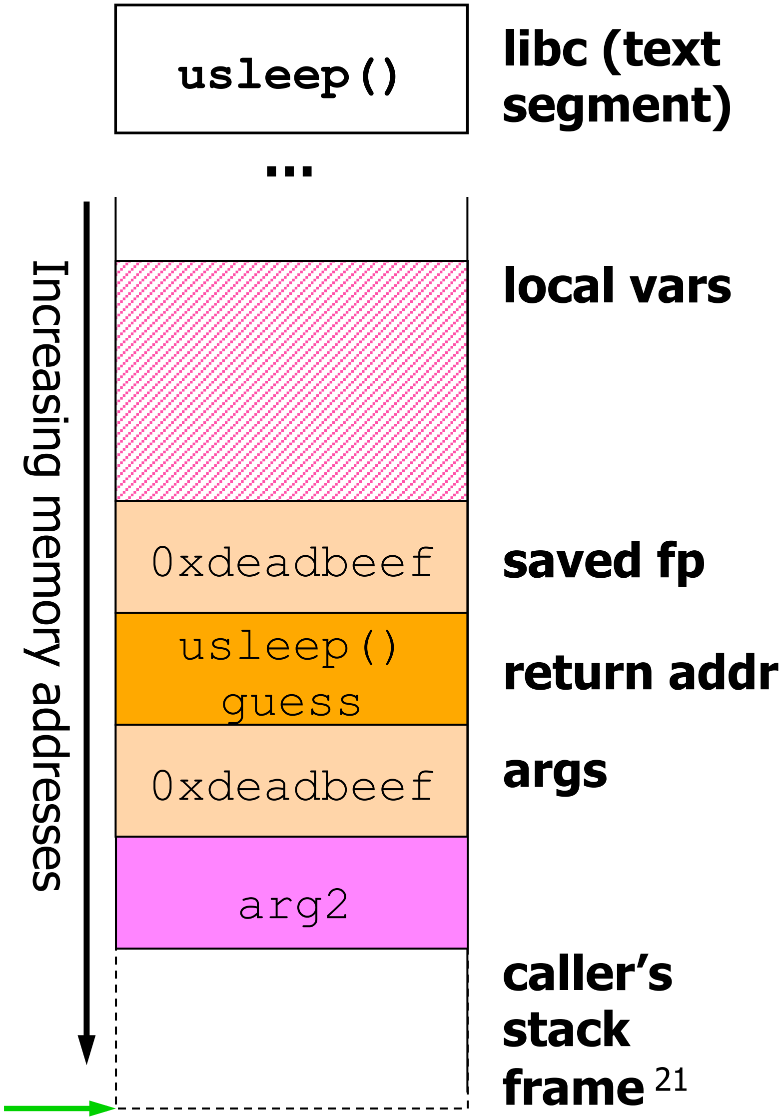
caller's stack frame

Increasing memory addresses

Derandomization Attack: Phase 1

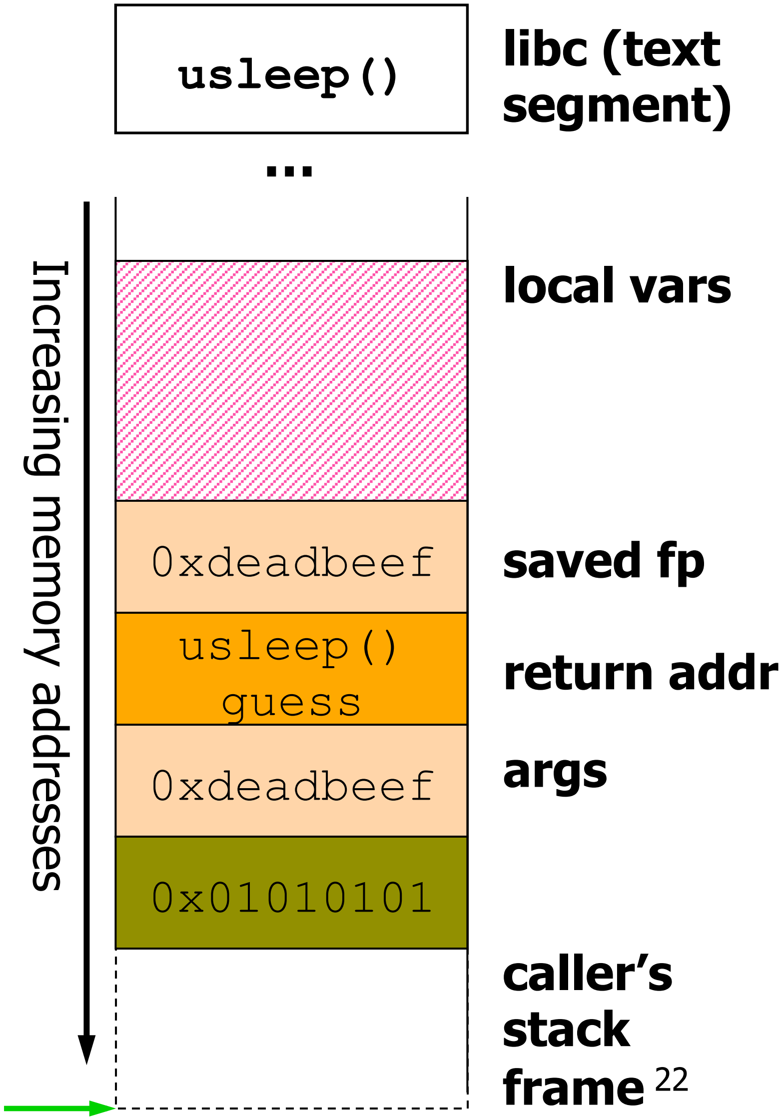
- Know offset of **`usleep()`** within libc, know base of mapped area (w/o randomization)
- Each return address guess:

  base + **`usleep()`** offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, **`usleep()`** sees return address **`0xdeadbeef`**, arg 16,843,009 usec (16 sec); sleep, crash



Derandomization Attack: Phase 1

- Know offset of `usleep()` within libc, know base of mapped area (w/o randomization)
- Each return address guess:
  - base + `usleep()` offset + guess in [0, 64K]
- If guess wrong, crash
- If guess right, `usleep()` sees return address `0xdeadbeef`, arg 16,843,009 usec (16 sec); sleep, crash



`usleep()` libc (text segment)

...

Increasing memory addresses

local vars

`0xdeadbeef` saved fp

`usleep()` guess return addr

`0xdeadbeef` args

`0x01010101`

caller's stack frame

Derandomization Attack: Phase 2

- Now know random offset of mapped area
- Compute exact address of system() libc function:

  address = base + system() offset in libc + guessed random offset
- Perform return-to-libc attack using system(), as in earlier example; "/bin/sh" in buf[] on stack
- Turns out caller's frame contains pointer to buf[]!
- So overwrite stack past buf[] with several copies of address of any ret instruction found in libc, followed by address of system()
  - Repeatedly pops stack until returns to system(), with pointer to buf[] on top of stack (argument position)
  - Details in paper, top of p. 8

Derandomization Attack: Performance

- Many trials of phase 1 necessary to learn random offset of mapped area on server
- For 1.8 GHz AMD Athlon server, attacked by 2.4 GHz Pentium 4 client:
  - 216 seconds on average to complete both phases
  - 200 bytes of traffic per probe; 12.8 MB data from client worst-case, 6.4 MB data in expectation

Can ASLR Be Made More Robust?

- 64-bit CPU architectures
  - Probably 40 bits of random offset; much harder to brute-force without attracting attention; so some help with new hardware
- Re-randomize address space after every crash (probe)
  - For single randomization at startup, expected number of probes: 2^{n-1}
  - For re-randomized n-bit random offset, expected number of probes: 2^n
  - Only twice as many probes needed as in attack when randomizing once at start!
  - Not promising…

TaintCheck: Detecting Exploits by Analyzing Server Execution

- Approach: instrument program to monitor its own execution, detect when exploit occurs
- Goals:
  - Work on binaries (no source code required)
  - Low false positives/false negatives
  - Detect wide range of exploits (new varieties all the time; point solutions unconvincing)
  - Help humans understand how exploit worked, after the fact; how did data flow from malicious input to point of exploit?

TaintCheck:
Basic Execution Monitoring Idea

- Many exploits use data supplied by user (or derived from data supplied by user) to subvert control flow of program
  - Need to modify jump, call instruction target addresses, or function return addresses
- During execution, before any control transfer instruction, validate target address not derived from user-supplied data
  - If it is, exploit detected; raise alarm
  - If it isn’t, continue execution normally

Tainting User Input and Data Derived from It

- User is the source of exploits; don’t trust data from him
- Mark all data from user (received from network, or from input files) as tainted
- Propagate taint during execution
  - Results of operations on tainted data should be tainted
  - Copies of tainted data should be tainted
- Clear taint when tainted data overwritten with untainted data
- How do we get a precompiled program executable to behave this way?

Valgrind: Modifying Executables at Runtime

- Run executable under Valgrind system
- Give Valgrind instructions on how to instrument executable
  - literally, what instructions or function calls to search for, and what instructions to add to them
- Valgrind's processing loop:
  - Fetch next basic block of program (dictated by IP/PC)
  - Translate code into UCode, Valgrind's instruction set
  - Add instrumentation code to Valgrind UCode
  - Translate code back to x86; cache for reuse
  - Execute instrumented x86 basic block
  - Repeat…

Adding Instrumentation: Tracking Tainted Data

- After I/O system calls:
  - If reading from socket, mark target buffer contents as tainted
- After all memory load instructions:
  - If source memory tainted, mark register tainted
  - If source memory untainted, mark register untainted
- After all memory store instructions:
  - If source register tainted, mark memory tainted
  - If source register untainted, mark memory untainted
- After all arithmetic instructions:
  - If any operand tainted, mark result tainted
  - If no operands tainted, mark result untainted

Adding Instrumentation: Detecting Invalid Uses of Tainted Data

- Before all control transfer instructions, add code:
  - If register or memory location holding target function pointer is tainted, raise alarm
  - Means derived from user input; should never happen!
- Needed before each jump, call, ret

Tracking Taint: Shadow Memory

- For every byte of memory, keep shadow memory that tracks taint status
- Simple interface:
  - Is-Tainted(addr) -> {T | F}
  - Taint(addr, len), Untaint(addr, len)
- Two modes of operation
  - Fast: single bit for each byte of memory
  - Detailed: 4-byte pointer to Taint data structure, containing details of system call, stack, value; written at time of tainting
  - Detailed mode useful for analysis of exploits
- Implementation greatly affects performance
  - Space vs. time tradeoff: packed vs. unpacked

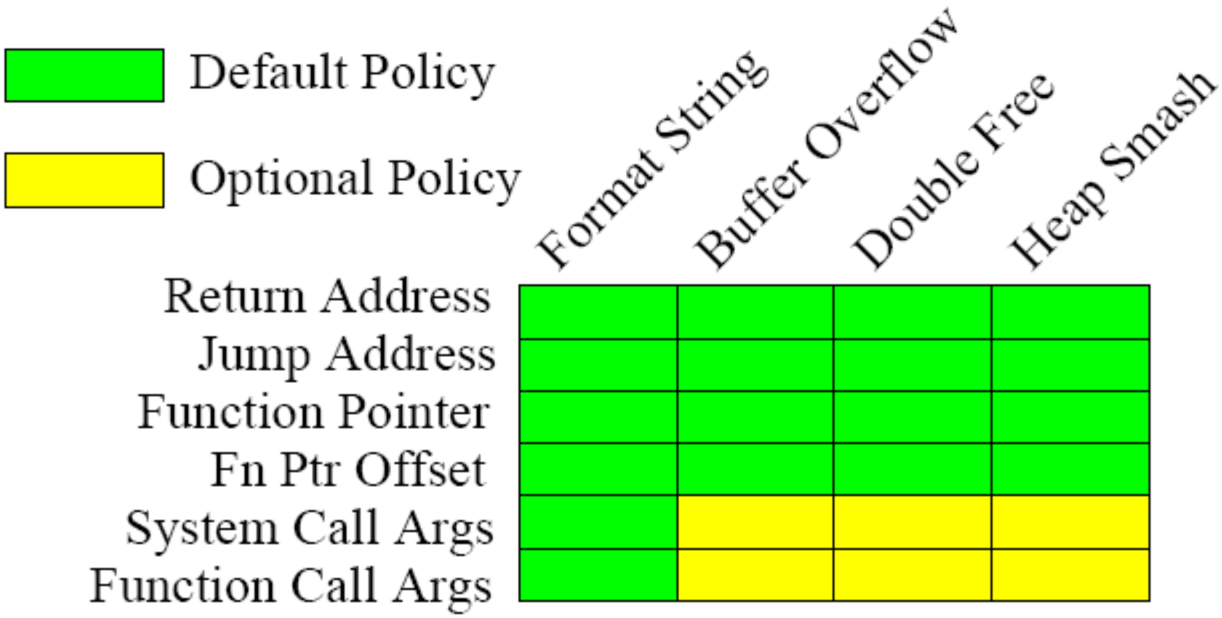
Corner Case: Implicit Flows

- Suppose x tainted, then execute:

```
if (x == 0)
    y = 0;
else
    y = 1;
```

- TaintCheck doesn't taint processor condition flags
  - Would often result in inappropriate propagation of taint; false positives
- But x clearly influences value of y, and y could later influence other values
- Result: false negatives are possible
  - e.g., image compression bit-twiddling code?

Exploit Detection Coverage



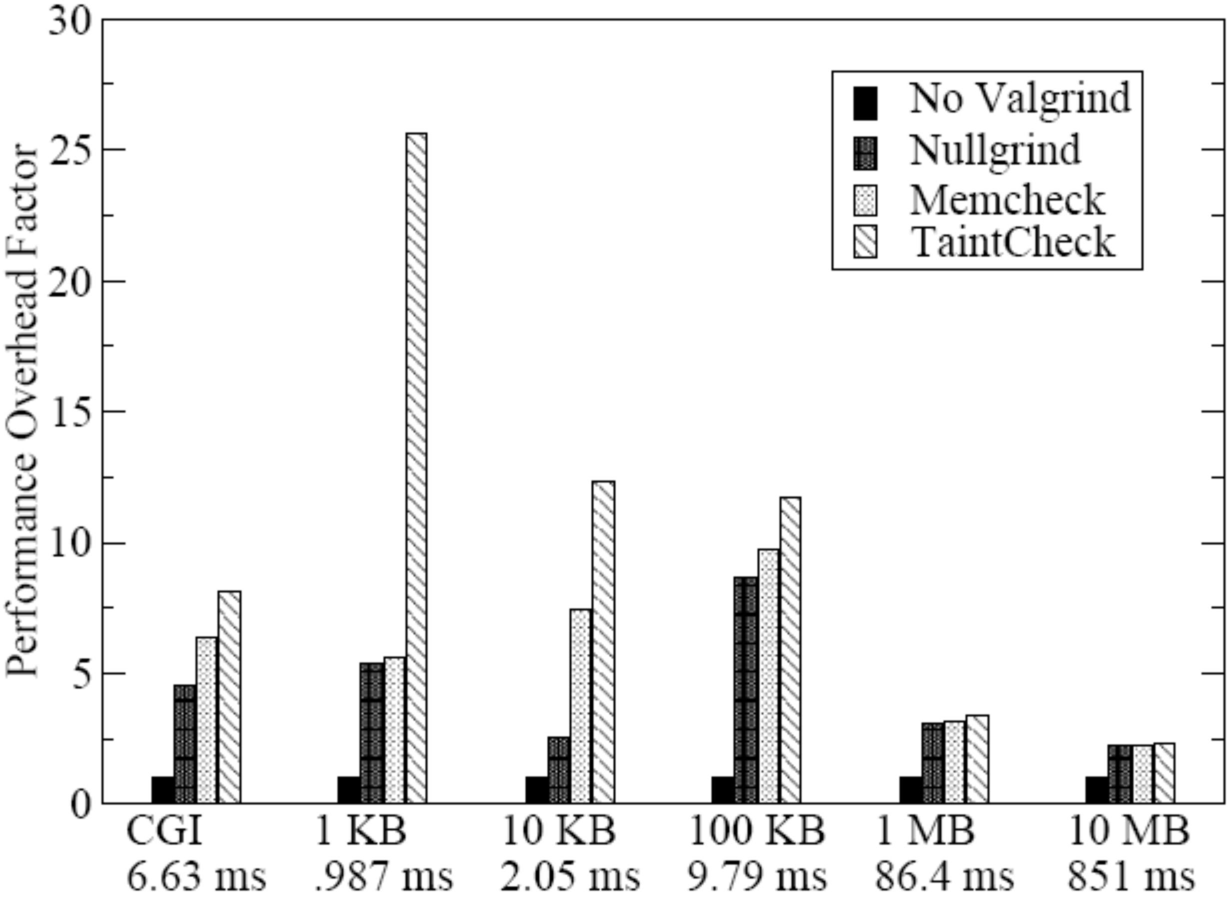
🟩 Default Policy

🟨 Optional Policy

	Format String	Buffer Overflow	Double Free	Heap Smash
Return Address	🟩	🟩	🟩	🟩
Jump Address	🟩	🟩	🟩	🟩
Function Pointer	🟩	🟩	🟩	🟩
Fn Ptr Offset	🟩	🟩	🟩	🟩
System Call Args	🟩	🟨	🟨	🟨
Function Call Args	🟩	🟨	🟨	🟨

- TaintCheck can also instrument function and system calls
- e.g., check printf()-like library calls for tainted format string args
- Built system successfully detects many overwrite exploits (return address, function pointer, format string, GOT entry)

TaintCheck's Performance: Monitoring Apache



- Lots of extra instructions…
- Exec time not really right metric; throughput better metric

TaintCheck: Modes of Use (1)

- Identify worm payloads
  - Can be configured to store trace of tainted data flow from all inputs
  - When exploit detected, can walk back to identify input that led to exploit
  - Could pass worm payloads to signature generation system, like Autograph
    - Much more accurate than port-scanner heuristic!
- Prevent exploit of server
  - Halt execution upon exploit detection

TaintCheck: Modes of Use (2)

- Probably too slow for production servers
  - 25X server farm size increase for Amazon?
- Could possibly deploy on a few servers: sample traffic
  - Would slow detection of new worm, though; only sampling some inputs
  - Adversary may possibly be able to detect monitored servers by their slow response time; avoid sending them exploit payload