Sandboxing Untrusted Code: Software-Based Fault Isolation (SFI)

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Motivation: Vulnerabilities in C

- Seen dangers of vulnerabilities:
  - injection of arbitrary code
  - return-to-libc (no code injection; malicious invocation of existing code)
- Vulnerabilities are bugs—application behavior not intended by programmer
- Bugs in C often because memory operations not safe
  - many ways to overwrite stored pointer, cause it to point to arbitrary memory

Motivation: Vulnerabilities in C

- Seen dangers of vulnerabilities:
  - injection of arbitrary code
  - return to libc (no code injection; malicious

Can we constrain behavior of application code to prevent bugs from corrupting memory, and thus allowing exploits?

- Bugs in C often because memory operations not safe
  - many ways to overwrite stored pointer, cause it to point to arbitrary memory

Motivation: Untrusted Extensions

- Users often wish to extend application with new functionality made available as a binary module, e.g.,
  - Flash player plugin for Firefox browser
  - Binary kernel module for new filesystem for Linux
- Key risk: code from untrusted source (e.g., web site), but will run in your application's address space
  - What if code overwrites your app's data?
  - Or calls functions in your app's code with ill intent? (e.g., calls disable_certificate_check())

Motivation: Untrusted Extensions

- Users often wish to extend application with new functionality made available as a binary module, e.g.,
  - Flash player plugin for Firefox browser

N.B. extension code may be malicious or may merely be buggy

web site), but will run in your application's address space

- What if code overwrites your app's data?
- Or calls functions in your app's code with ill intent? (e.g., calls disable_certificate_check())

Risks of Running Untrusted Code

- Overwrites trusted data or code
- Reads private data from trusted code’s memory
- Executes privileged instruction
- Calls trusted functions with bad arguments
- Jumps to middle of trusted function
- Contains vulnerabilities allowing others to do above

Allowed Operations for Untrusted Code

- Reads/writes own memory
- Executes own code
- Calls explicitly allowed functions in trusted code at correct entry points

Straw Man Solution: Isolation with Processes

- Run original app code in one process, untrusted extension in another; communicate between them by RPC
  - (Recall NFS over RPC, but between distinct hosts)
- Memory protection means extension cannot read/write memory of original app
- Not very transparent for programmer, if app and extension closely coupled
- Performance hit: context switches between processes
  - trap to kernel, copy arguments, save and restore registers, flush processor's TLB

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Can we do better?

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Today's Topic: Software-Based Fault Isolation

- Run untrusted binary extension in same process (address space) as trusted app code
- Place extension's code and data in sandbox:
  - Prevent extension's code from writing to app's memory outside sandbox
  - Prevent extension's code from transferring control to app's code outside sandbox
- Idea: add instructions before memory writes and jumps to inspect their targets and constrain their behavior

SFI Use Scenario

- Developer runs sandboxer on unsafe extension code, to produce safe, sandboxed version:
  - – adds instructions that sandbox unsafe instructions
  - – transformation done by compiler or by binary rewriter
- Before running untrusted binary code, user runs verifier on it:
  - – checks that safe instructions don’t access memory outside extension code’s data
  - – checks that sandboxing instructions in place before all unsafe instructions

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User need not trust sandboxer; only verifier

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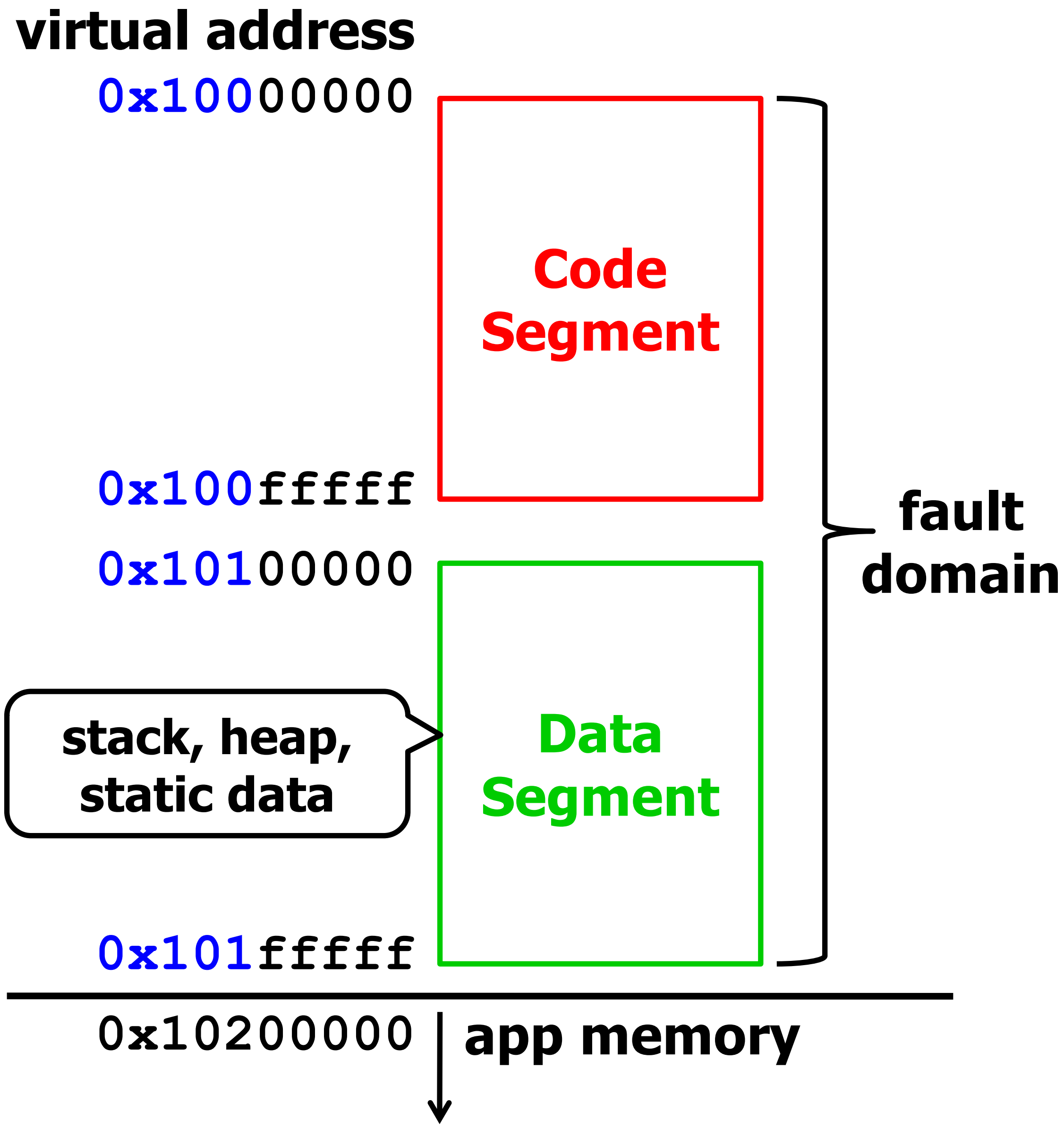
SFI Unit of Isolation: Fault Domain

- SFI confines untrusted code within a fault domain, in same address space (process) as trusted code
- Fault domain consists of:
  - – Unique ID (used for access control on syscalls)
  - – Code segment: virtual address range with same unique high-order bits, used to hold code
  - – Data segment: virtual address range with same unique high-order bits, used to hold data
- Segment ID: unique high-order bits for a segment

Fault Domain Example



- Segment IDs are 12 bits long in example
- Separate segments for code and data allow distinguishing addresses as falling in one or other

Sandboxing Memory

- Untrusted code should only be able to:
  - jump within its fault domain's code segment
  - write within its fault domain's data segment
- Sandboxer must ensure all jump, call, and memory store instructions comply with above
- Two types of memory addresses in instructions:
  - direct: complete address is specified statically in instruction
  - indirect: address is computed from register's value

Sandboxing Memory (2)

- For directly addressed memory instructions, sandboxer should only emit:
  - directly addressed jumps and calls whose targets fall in fault domain's code segment
    - e.g., `JUMP 0x10030000`
  - directly addressed stores whose targets fall in fault domain's data segment
    - e.g., `STORE 0x10120000, R1`
- Directly addressed jumps, calls, stores can be made safe statically

Sandboxing Indirectly Addressed Memory

- Indirectly addressed jumps, calls, stores harder to sandbox—full address depends on register whose value not known statically
  - e.g., **`STORE R0, R1`**
  - e.g., **`JR R3`**
- These are unsafe instructions that must be made safe at runtime

Sandboxing Indirectly Addressed Memory (2)

- Suppose unsafe instruction is

```
STORE R0, R1   ; write R1 to Mem[R0]
```

- Sandboxer rewrites code to:

```
MOV Ra, R0     ; copy R0 into Ra
SHR Rb, Ra, Rc ; Rb = Ra >> Rc, to get segment ID
CMP Rb, Rd     ; Rd holds correct data segment ID
BNE fault      ; wrong data segment ID
STORE Ra, R1   ; Ra in data segment, so do write
```

- Ra, Rc, and Rd are dedicated—may not be used by extension code

Sandboxing Indirectly Accessed Memory (3)

- Why does rewritten code use

```
STORE Ra, R1
```

- and not

```
STORE R0, R1
```

- After all, R0 has passed the check!
- Extension code may jump directly to STORE, bypassing check instructions!
- Because Ra, Rc, Rd are dedicated, Ra will always contain safe address inside data segment

Sandboxing Indirectly Accessed Memory (3)

- Why does rewritten code use

```
STORE Ra, R1
```

- and not

Remember: extension code may not set dedicated registers!

- Extension code may jump directly to STORE, bypassing check instructions!
- Because Ra, Rc, Rd are dedicated, Ra will always contain safe address inside data segment

Sandboxing Indirectly Accessed Memory (4)

- Costs of first sandboxing scheme for indirectly addressed memory:
  - adds 4 instructions before each indirect store
  - uses 6 registers, 5 of which must be dedicated (never available to extension)
    - example used 3 dedicated registers, but need 2 more for sandboxing unsafe code addresses
- Can we do better, and get away with fewer added instructions?
- Yes, if we give up being able to identify which instruction accessed outside sandbox!

Faster Sandboxing of Indirect Addresses

- Idea: don't check if target address is in segment; force it to be in segment
- So we transform `STORE R0, R1` into:

```
AND Ra, R0, Re ; clear segment ID bits in Ra
OR Ra, Ra, Rf  ; set segment ID to correct value
STORE Ra, R1   ; do write to safe target address
```

- Now segment ID bits in Ra will always be correct; can write anywhere in segment, but not outside it
- Cost: 2 added instructions, 5 dedicated registers

Faster Sandboxing of Indirect Jumps and Calls

- Very similar to data address sandboxing
- Transform `JR R0` as follows:

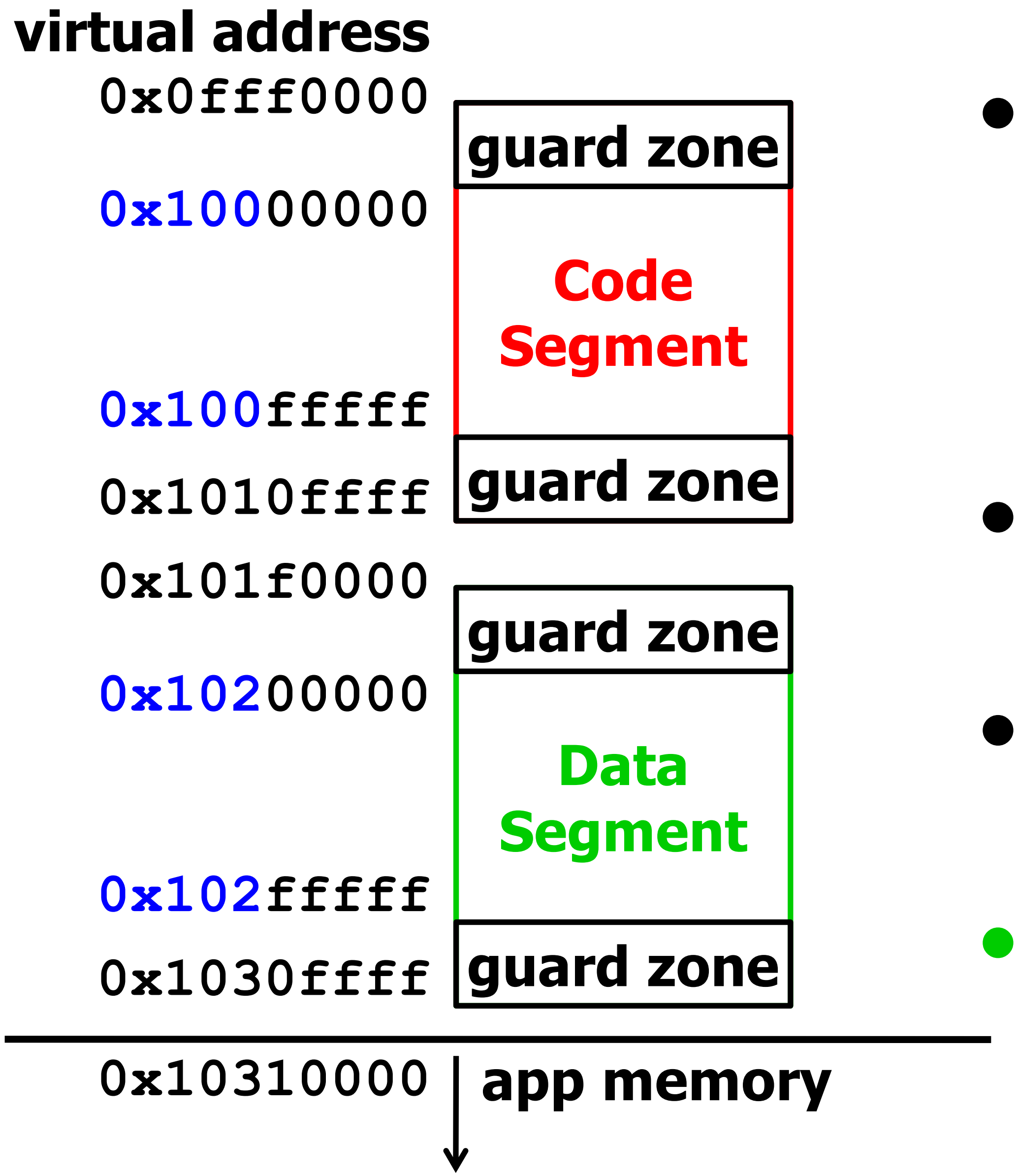
```
AND Rg, R0, Re ; clear segment ID bits in Rg
OR Rg, Rg, Rh  ; set segment ID to correct value
JR Rg          ; do jump to safe target address
```

- N.B. use of separate dedicated registers Rg for code target address, Rh for code segment ID
- Return from function similar, too (to sandbox return address)

Optimization: Guard Zones

- Some instructions use "register+offset" addressing: they use register as base, and supply offset for CPU to add to it
- To sandbox such an instruction, SFI would need to do additional ADD to compute base+offset
- Clever insight: offsets are of limited size, because of instruction encoding (+/- 64K on MIPS)
- So if base in correct segment, offset could stray no more than 64K outside that segment

Guard Zones (2)



- Surround each segment with 64K guard zone of unmapped pages
- Ignore offsets when sandboxing!
- Accesses to guard zones cause traps
- Saves one ADD for reg+offset instrs

Optimization: Stack Pointer

- Insight: stack pointer is read far more often than it’s written; used as base address for many reg+offset instructions
- SFI doesn’t sandbox uses of stack pointer as base address; instead sandboxes setting of stack pointer, so stack pointer always contains safe value
- Reduces number of instructions that pay sandboxing overhead

Verifier

- Upon receiving (supposedly) sandboxed binary, verifier must ensure all instructions safe
- For instructions that use direct addressing, easy to check statically that segment IDs in addresses are correct
- For those that use indirect addressing, verifier must ensure instruction preceded by full set of sandboxing instructions

Verifier (2)

- Verifier must ensure no privileged instructions in code
- Verifier must ensure PC-relative branches fall in code segment
- If sandboxed code fails any of these checks, verifier rejects it
- Otherwise, code is correctly sandboxed

Original SFI’s Limitations vs. x86

- MIPS instructions fixed-length; x86 instructions variable-length
  - Result: can jump into middle of x86 instruction!
  - e.g., binary for AND eax, 0x80CD is 25 CD 80 00 00
  - If adversary jumps to second byte, he executes the instruction CD 80, which traps to a system call on Linux!
  - **Jump to mid-instruction on x86 may even jump out of fault domain into app code!**
- x86 has very few registers (4 general-purpose ones), so cannot dedicate registers easily

SFI vs. Exploits

- Simple stack-smashing, injecting code in stack buffer?
  - can’t execute own injected code—can’t jump to data segment
- Return-to-libc?
  - can overwrite return address with one within fault domain’s code segment—so can do return-to-libc within extension
- Format string vulnerabilities?
  - same story as above

SFI vs. Exploits: Lessons

- SFI allows write (including buffer overrun, %n overwrite) to extension’s data
- SFI allows jumps anywhere in extension’s code segment
- …so attacker can exploit extension’s execution
- …and on x86, can probably cause jump out of fault domain

SFI vs. Exploits: Lessons

- SFI allows write (including buffer overrun, %n overwrite) to extension's data

To be fair, SFI wasn't designed for x86, and wasn't designed to prevent exploits, but rather to isolate untrusted extension from main application.

execution

- …and on x86, can probably cause jump out of fault domain

SFI Summary

- Confines writes and control transfers in extension’s data and code segments, respectively
- Can support direct calls to allowed functions in trusted (app) code
- Prevents execution of privileged instructions
- Any write or control transfer within extension’s memory is allowed
- Requires dedicated registers

Further Reading: Modern SFI Implementations

- Google's NativeClient project developed SFI implementations for x86-32, x86-64, and ARM (not examinable):
  - Yee et al., Native Client: A Sandbox for Portable, Untrusted x86 Native Code (Oakland 2009)
  - Sehr et al., Adapting Software Fault Isolation to Contemporary CPU Architectures (USENIX Security 2010)
- Goal: extend web browser with untrusted native binary code (e.g., browser plugins)
- Interesting design details for modern CPUs
- Now deprecated by Google; sandboxing for extending browser lives on in Web Assembly

CFI: Control-Flow Integrity

- Follow-on to original SFI; works on x86
- Idea: examine control flow graph (CFG) of program, which includes all functions and all transfers of control between them (e.g., calls of named functions, returns from them)
- Doesn’t require dedicated registers like SFI
- Finds all instruction boundaries
- Adds instructions to enforce that all jumps, branches, calls, returns transfer control to valid target found in CFG

CFI (2)

- Prevents return to injected code by overwriting return address:
  - transition to return address of injected code not in CFG
- Prevents return-to-libc attack:
  - enforces that return instruction in function f() can only transfer control to next instruction in some function that calls f()
- Further reading (not examinable): Abadi *et al.,* Control-Flow Integrity (CCS 2005)
- clang/LLVM compiler now includes a CFI implementation; easy way to play with CFI…