

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

Brad Karp
UCL Computer Science



CS GZ03 / M030
9th December 2013

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

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

Can we do better?

- **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

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

SFI Use Scenario

- Developer runs **sandboxer** on unsafe extension code, to produce safe, sandboxed version:
 - adds instructions that sandbox unsafe instructions

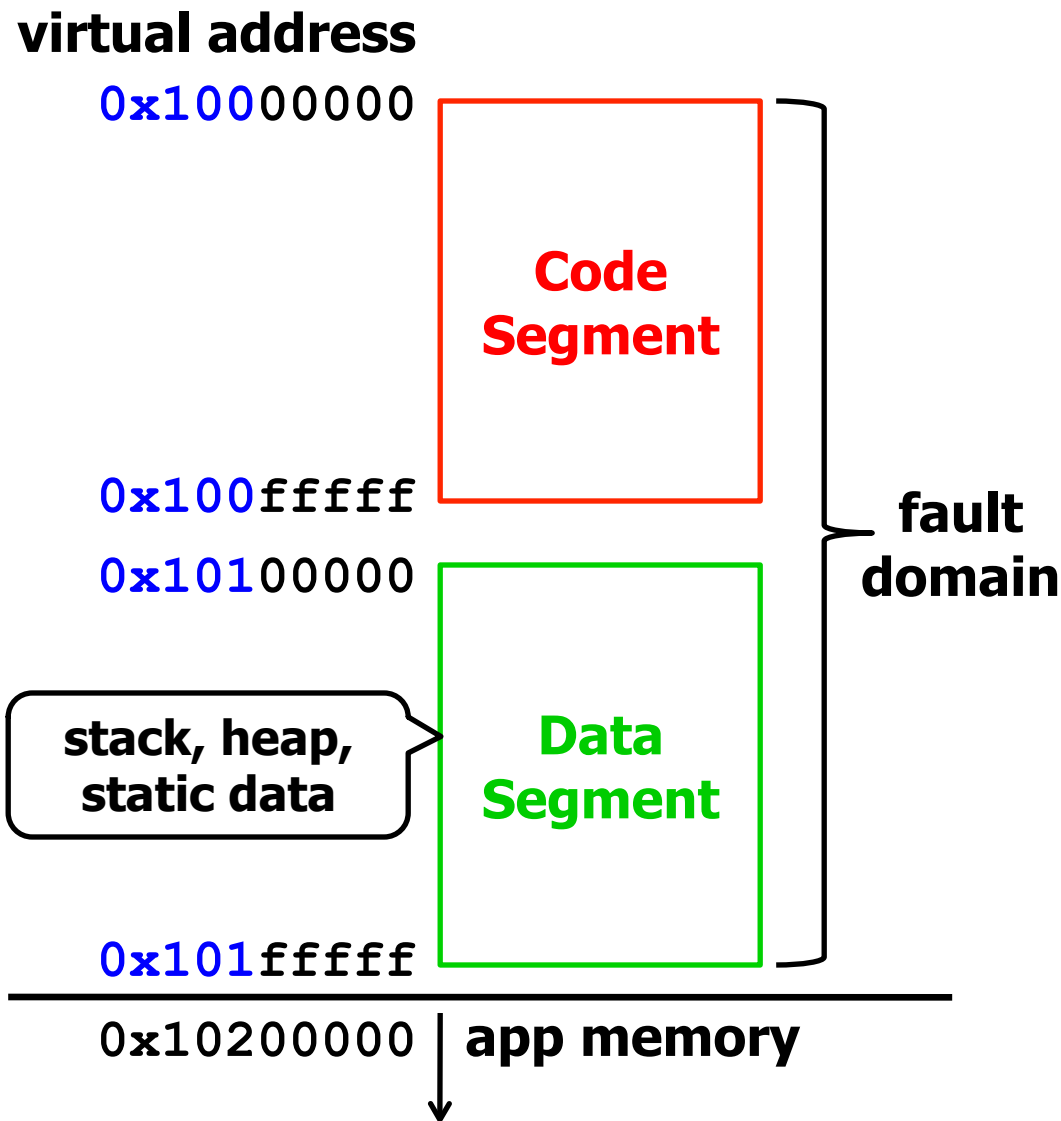
User need not trust sandboxer; only verifier

- 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

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

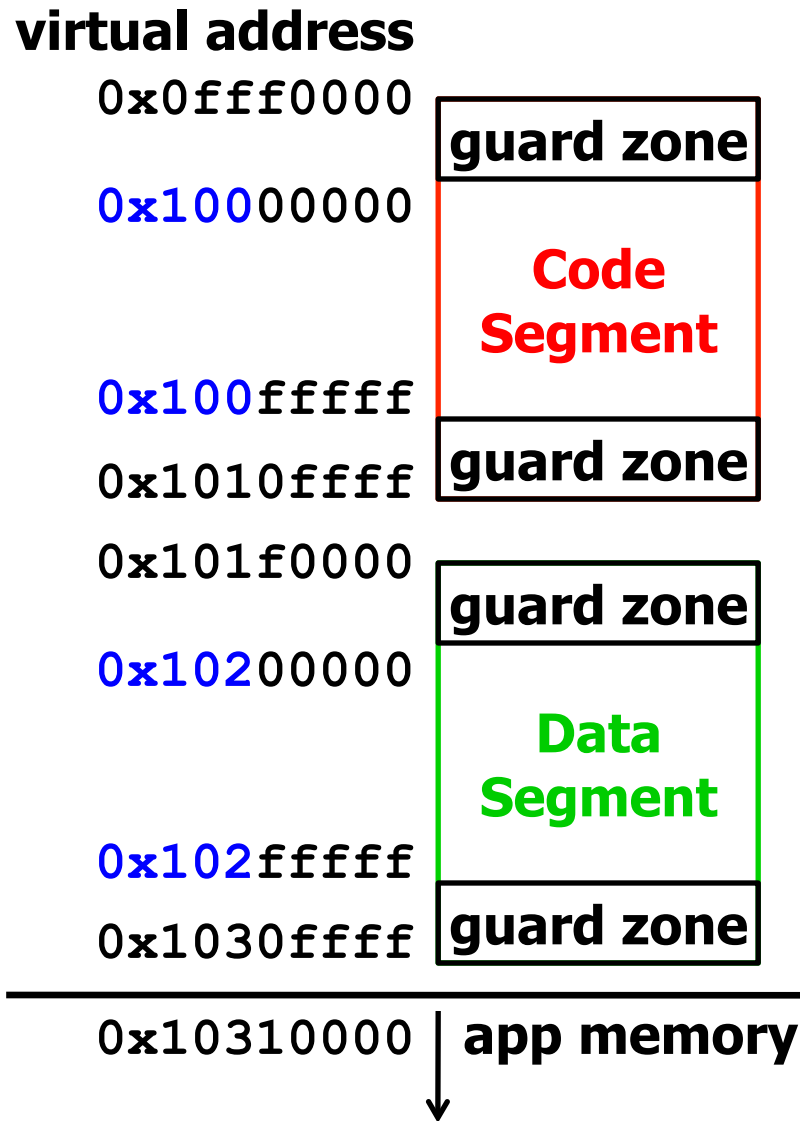
Faster Sandboxing of Indirect Jumps and Calls

- 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**

SFI Limitations on 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

CFI: Control-Flow Integrity

- Follow-on to 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