Inline Reference Monitors: SFI, CFI, XFI, WIT, NaCl

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Reading Assignment

- Abadi et al. "Control-flow integrity" (CCS 2005).
- Akritidis et al. "Preventing memory error exploits with WIT" (Oakland 2008).
- Yee et al. "Native Client: a sandbox for portable, untrusted x86 native code" (Oakland 2009).

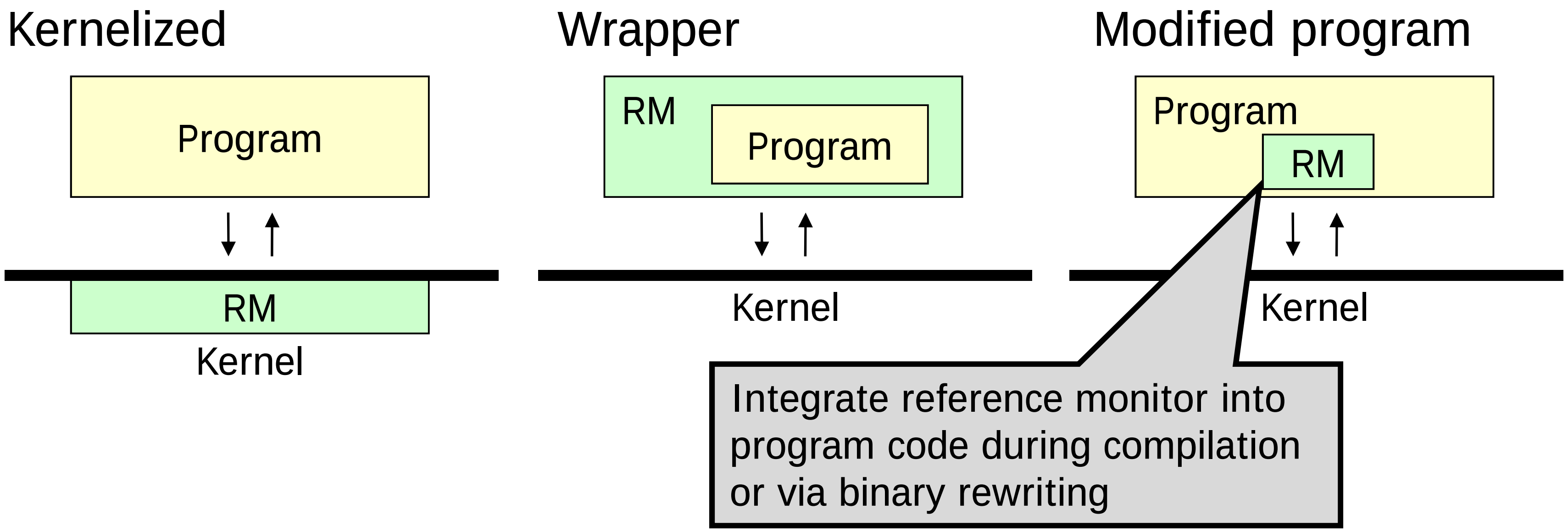
Reference Monitor

- Observes execution of the program/process
  - At what level? Possibilities: hardware, OS, network
- Halts or contain execution if the program is about to violate the security policy
  - What’s a “security policy”?
  - Which system events are relevant to the policy?
    - Instructions, memory accesses, system calls, network packets...
- Cannot be circumvented by the monitored process
- Most enforcement mechanisms we will see are example of reference monitors

Enforceable Security Policies

- Reference monitors can only enforce safety policies [Schneider '98]
  - Execution of a process is a sequence of states
  - Safety policy is a predicate on a prefix of the sequence
    - Policy must depend only on the past of a particular execution; once it becomes false, it's always false
- Not policies that require knowledge of the future
  - "If this server accepts a SYN packet, it will eventually send a response"
- Not policies that deal with all possible executions
  - "This program should never reveal a secret"

Reference Monitor Implementation



- Policies can depend on application semantics
- Enforcement doesn't require context switches in the kernel
- Lower performance overhead

What Makes a Process Safe?

- **Memory safety:** all memory accesses are "correct"
  - Respect array bounds, don't stomp on another process's memory, separation between code and data
- **Control-flow safety:** all control transfers are envisioned by the original program
  - No arbitrary jumps, no calls to library routines that the original program did not call
    - ... but wait until we see mimicry attacks
- **Type safety:** all function calls and operations have arguments of correct type

OS As A Reference Monitor

- Collection of running processes and files
  - Processes are associated with users
  - Files have access control lists (ACLs) saying which users can read/write/execute them
- OS enforces a variety of safety policies
  - File accesses are checked against file's ACL
  - Process cannot write into memory of another process
  - Some operations require superuser privileges
    - But may need to switch back and forth (e.g., setuid in Unix)
  - Enforce CPU sharing, disk quotas, etc.
- Same policy for all processes of the same user

Hardware Mechanisms: TLB

- TLB: Translation Lookaside Buffer
  - Maps virtual to physical addresses
  - Located next to the cache
  - Only supervisor process can manipulate TLB
    - But if OS is compromised, malicious code can abuse TLB to make itself invisible in virtual memory (Shadow Walker)
- TLB miss raises a page fault exception
  - Control is transferred to OS (in supervisor mode)
  - OS brings the missing page to the memory
- This is an expensive context switch

Steps in a System Call

[Morrisett]

User Process | **Kernel**

calls f=fopen("foo")

library executes "break"

trap

saves context, flushes TLB, etc.

checks UID against ACL, sets up IO buffers & file context, pushes ptr to context on user's stack, etc.

restores context, clears supervisor bit

calls fread(f,n,&buf)

library executes "break"

saves context, flushes TLB, etc.

checks f is a valid file context, does disk access into local buffer, copies results into user's buffer, etc.

restores context, clears supervisor bit

Time

Modern Hardware Meets Security

- Modern hardware: large number of registers, big memory pages
- Principle of least privilege $\Rightarrow$ each process should live in its own hardware address space
- ... but the performance cost of inter-process communication is increasing
  - Context switches are very expensive
  - Trapping into OS kernel requires flushing TLB and cache, computing jump destination, copying memory
- Conflict: isolation vs. cheap communication

Software Fault Isolation (SFI)

[Wahbe et al. SOSP '93]

- Processes live in the same hardware address space; software reference monitor isolates them
  - Each process is assigned a logical "fault domain"
  - Check all memory references and jumps to ensure they don't leave process's domain
- Tradeoff: checking vs. communication
  - Pay the cost of executing checks for each memory access and control transfer to save the cost of context switching when trapping into the kernel

Fault Domains

- Process's code and data in one memory segment
  - Identified by a unique pattern of upper bits
  - Code is separate from data (heap, stack, etc.)
  - Think of a fault domain as a "sandbox"
- Binary modified so that it cannot escape domain
  - Addresses masked so that all memory writes are to addresses within the segment
    - Coarse-grained memory safety (viz. array bounds checking)
  - Code inserted before each jump to ensure that the destination is within the segment
- Does this help much against buffer overflows?

Verifying Jumps and Stores

- If target address can be determined statically, mask it with the segment's upper bits
  - Crash, but won't stomp on another process's memory
- If address unknown until runtime, insert checking code before the instruction
- Ensure that code can't jump around the checks
  - Target address held in a dedicated register
  - Its value is changed only by inserted code, atomically, and only with a value from the data segment
- Mainly concerned with executing untrusted code

Simple SFI Example

- Fault domain = from 0x1200 to 0x12FF
- Original code: write x
- Naïve SFI:
  x := x & 00FF
  x := x | 1200
  write x
- Better SFI:
  tmp := x & 00FF
  tmp := tmp | 1200
  write tmp

convert x into an address that lies within the fault domain

...

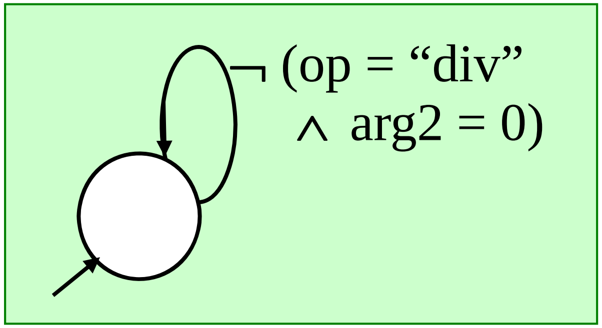
What if the code jumps right here?

Inline Reference Monitor

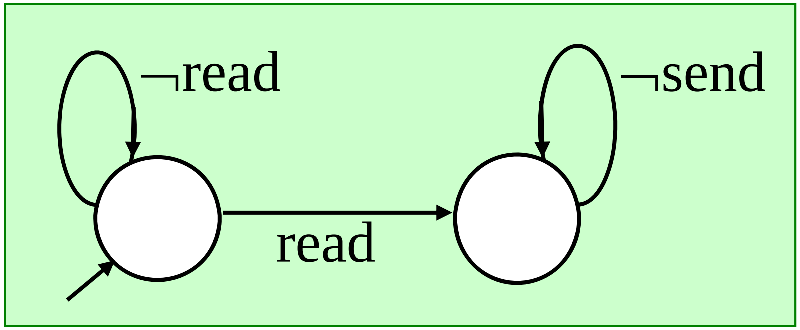
- Generalize SFI to more general safety policies than just memory safety
  - Policy specified in some formal language
  - Policy deal with application-level concepts: access to system resources, network events, etc.
    - "No process should send to the network after reading a file", "No process should open more than 3 windows", ...
- Policy checks are integrated into the binary code
  - Via binary rewriting or when compiling
- Inserted checks should be uncircumventable
  - Rely on SFI for basic memory safety

Policy Specification in SASI

[Cornell project]



No division by zero



No network send after file read

SASI policies are finite-state automata

- Can express any safety policy
- Easy to analyze, emulate, compile
- Written in SAL language (textual version of diagrams)

Policy Enforcement

- Checking before every instruction is an overkill
  - Check “No division by zero” only before DIV
- SASI uses partial evaluation
  - Insert policy checks before every instruction, then rely on static analysis to eliminate unnecessary checks
- There is a “semantic gap” between individual instructions and policy-level events
  - Applications use abstractions such as strings, types, files, function calls, etc.
  - Reference monitor must synthesize these abstractions from low-level assembly code

CFI: Control-Flow Integrity

[Abadi et al.]

- Main idea: pre-determine control flow graph (CFG) of an application
  - Static analysis of source code
  - Static binary analysis ← CFI
  - Execution profiling
  - Explicit specification of security policy
- Execution must follow the pre-determined control flow graph

CFI: Binary Instrumentation

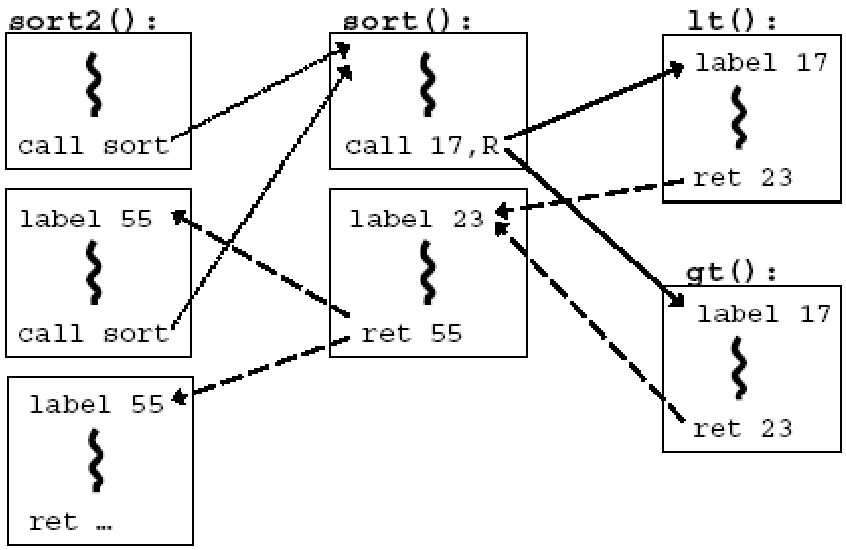
- Use binary rewriting to instrument code with runtime checks (similar to SFI)
- Inserted checks ensure that the execution always stays within the statically determined CFG
  - Whenever an instruction transfers control, destination must be valid according to the CFG
- Goal: prevent injection of arbitrary code and invalid control transfers (e.g., return-to-libc)
  - Secure even if the attacker has complete control over the thread’s address space

CFG Example

```
bool lt(int x, int y) {
    return x < y;
}

bool gt(int x, int y) {
    return x > y;
}

sort2(int a[], int b[], int len)
{
    sort( a, len, lt );
    sort( b, len, gt );
}
```



CFI: Control Flow Enforcement

- For each control transfer, determine statically its possible destination(s)
- Insert a unique bit pattern at every destination
  - Two destinations are equivalent if CFG contains edges to each from the same source
    - This is imprecise (why?)
  - Use same bit pattern for equivalent destinations
- Insert binary code that at runtime will check whether the bit pattern of the target instruction matches the pattern of possible destinations

CFI: Example of Instrumentation

Original code

Source Opcode bytes	Instructions		Destination Opcode bytes	Instructions	
FF E1	jmp ecx	; computed jump	8B 44 24 04	mov eax, [esp+4]	; dst

Instrumented code

```
B8 77 56 34 12    mov   eax, 12345677h    ; load ID-1         3E 0F 18 05    prefetchnta          ; label
40                inc   eax               ; add 1 for ID      78 56 34 12       [12345678h]       ;    ID
39 41 04          cmp   [ecx+4], eax      ; compare w/dst     8B 44 24 04    mov   eax, [esp+4]   ; dst
75 13             jne   error_label       ; if != fail        ...
FF E1             jmp   ecx               ; jump to label
```

Jump to the destination only if the tag is equal to “12345678”

Abuse an x86 assembly instruction to insert “12345678” tag into the binary

CFI: Preventing Circumvention

- Unique IDs
  - Bit patterns chosen as destination IDs must not appear anywhere else in the code memory except ID checks
- Non-writable code
  - Program should not modify code memory at runtime
    - What about run-time code generation and self-modification?
- Non-executable data
  - Program should not execute data as if it were code
- Enforcement: hardware support + prohibit system calls that change protection state + verification at load-time

Improving CFI Precision

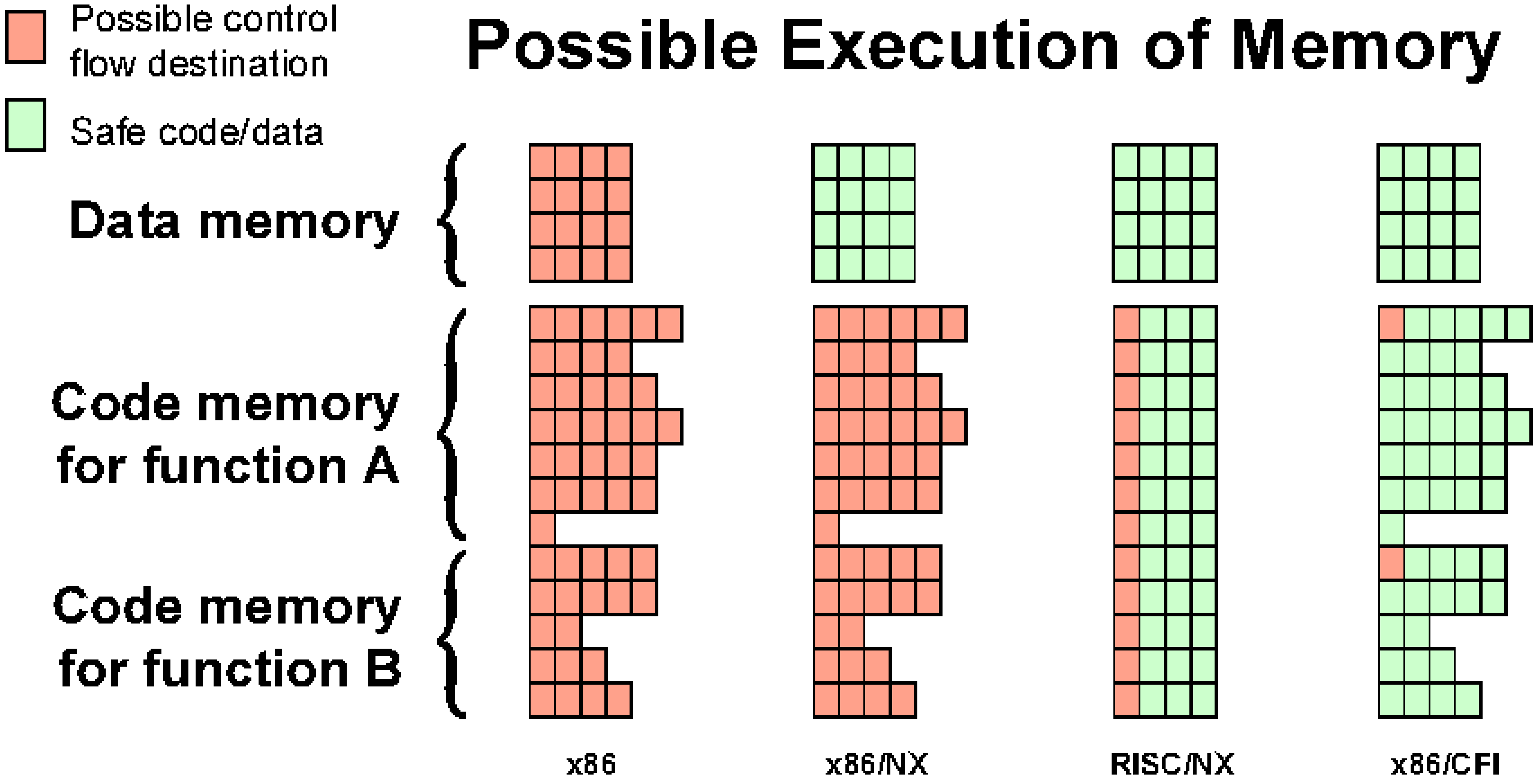
- Suppose a call from A goes to C, and a call from B goes to either C, or D (when can this happen?)
  - CFI will use the same tag for C and D, but this allows an “invalid” call from A to D
  - Possible solution: duplicate code or inline
  - Possible solution: multiple tags
- Function F is called first from A, then from B; what’s a valid destination for its return?
  - CFI will use the same tag for both call sites, but this allows F to return to B after being called from A
  - Solution: shadow call stack

CFI: Security Guarantees

- Effective against attacks based on illegitimate control-flow transfer
  - Stack-based buffer overflow, return-to-libc exploits, pointer subterfuge
- Does <u>not</u> protect against attacks that do not violate the program’s original CFG
  - Incorrect arguments to system calls
  - Substitution of file names
  - Other data-only attacks

Possible Execution of Memory

[Erlingsson]



Next Step: XFI

[Erlingsson et al. OSDI '06]

- Inline reference monitor added via binary rewriting
  - Can be applied to some legacy code
- Uses CFI as a building block to prevent circumvention
- Supports fine-grained access control policies for memory regions
  - More than simple memory safety (cf. SFI)
- Relies in part on load-time verification
  - Similar to "proof-carrying code"

Two Stacks

- XFI maintains a separate "scoped stack" with return addresses and some local variables
  - Keeps track of function calls, returns and exceptions
- Secure storage area for function-local information
  - Cannot be overflown, accessed via a computed reference or pointer, etc.
  - Stack integrity ensured by software guards
  - Presence of guards is determined by static verification when program is loaded
- Separate "allocation stack" for arrays and local variables whose address can be passed around

XFI: Memory Access Control

- Module has access to its own memory
  - With restrictions (e.g., shouldn't be able to corrupt its own scoped stack)
- Host can also grant access to other contiguous memory regions
  - Fine-grained: can restrict access to a single byte
  - Access to constant addresses and scoped stack verified statically
  - Inline memory guards verify other accesses at runtime
    - Fast inline verification for a certain address range; if fails, call special routines that check access control data structures

XFI: Preventing Circumvention

- Integrity of the XFI protection environment
  - Basic control-flow integrity
  - “Scoped stack” prevents out-of-order execution paths even if they match control-flow graph
  - Dangerous instructions are never executed or their execution is restricted
    - For example, privileged instructions that change protection state, modify x86 flags, etc.
- Therefore, XFI modules can even run in kernel

WIT: Write Integrity Testing

[Akritidis et al.]

- Combines static analysis ...
  - For each memory write, compute the set of memory locations that may be the destination of the write
  - For each indirect control transfer, compute the set of addresses that may be the destination of the transfer
  - “Color table” assigns matching colors to instruction (write or jump) and all statically valid destinations
    - Is this sound? Complete?
- ... with dynamic enforcement
  - Code is instrumented with runtime checks to verify that destination of write or jump has the right color

WIT: Write Safety Analysis

- Start with off-the-shelf points-to analysis
  - Gives a conservative set of possible values for each ptr
- A memory write instruction is “safe” if...
  - It has no explicit destination operand, or destination operand is a temporary, local or global variable
    - Such instructions either modify registers, or a constant number of bytes starting at a constant offset from the frame pointer or the data segment (example?)
  - ... or writes through a pointer that is always in bounds
    - How do we know statically that a pointer is always in bounds?
- Safe instructions require no runtime checks
- Can also infer safe destinations (how?)

WIT: Runtime Checks

- Statically, assign a distinct color to each <u>un</u>safe write instruction and all of its possible destinations
  - What if some destination can be written by two different instructions? Any security implications?
- Add a runtime check that destination color matches the statically assigned color
  - What attack is this intended to prevent?
- Same for indirect (computed) control transfers
  - Except for indirect jumps to library functions (done through pointers which are protected by write safety)
  - How is this different from CFI? Hint: think RET address

WIT: Additional Protections

- Change layout of stack frames to segregate safe and unsafe local variables
- Surround unsafe objects by guards/canaries
  - What attack is this intended to prevent? How?
- Wrappers for malloc()/calloc() and free()
  - malloc() assigns color to newly allocated memory
  - free() is complicated
    - Has the same (statically computed) color as the freed object
    - At runtime, treated as an unsafe write to this object
    - Reset color of object to 0 – what attack does this prevent?
    - Several other subtle details and checks – read the paper!

WIT: Handling Libraries

- Basic WIT doesn't work for libraries (why?)
- Instead, assign the same, standard color to all unsafe objects allocated by library functions and surround them by guards
  - Different from the colors of safe objects and guards
  - Prevents buffer overflows
  - What attack does this <u>not</u> prevent?
- Wrappers for memory copying functions
  - For example, memcpy() and strcpy()
  - Receive color of the destination as an extra argument, check at runtime that it matches static color

Native Client

[Yee et al. - Google]

- Goal: download an x86 binary and run it "safely"
  - Much better performance than JavaScript, Java, etc.
- ActiveX: verify signature, then unrestricted
  - Critically depends on user's understanding of trust
- .NET controls: IL bytecode + verification
- Native Client: sandbox for untrusted x86 code
  - Restricted subset of x86 assembly
  - SFI-like sandbox ensures memory safety
  - Restricted system interface
  - (Close to) native performance

NaCl Sandbox

- Code is restricted to a subset of x86 assembly
  - Enables reliable disassembly and efficient validation
  - No unsafe instructions
    - syscall, int, ret, memory-dependent jmp and call, privileged instructions, modifications of segment state ...
- No loads or stores outside dedicated segment
  - Address space constrained to 0 mod 32 segment
  - Similar to SFI
- Control-flow integrity

Constraints for NaCl Binaries

C1	Once loaded into the memory, the binary is not writable, enforced by OS-level protection mechanisms during execution.
C2	The binary is statically linked at a start address of zero, with the first byte of text at 64K.
C3	All indirect control transfers use a `nacljmp` pseudo-instruction (defined below).
C4	The binary is padded up to the nearest page with at least one `hlt` instruction (0xf4).
C5	The binary contains no instructions or pseudo-instructions overlapping a 32-byte boundary.
C6	All *valid* instruction addresses are reachable by a fall-through disassembly that starts at the load (base) address.
C7	All direct control transfers target valid instructions.

Control-Flow Integrity in NaCl

- For each direct branch, statically compute target and verify that it's a valid instruction
  - Must be reachable by fall-through disassembly
- Indirect branches must be encoded as

```
and  %eax, 0xffffffe0
jmp  *%eax
```

  - Guarantees that target is 32-byte aligned
  - Works because of restriction to the zero-based segment
  - Very efficient enforcement of control-flow integrity
- No RET
  - Sandboxing sequence, then indirect jump

Interacting with Host Machine

- Trusted runtime environment for thread creation, memory management, other system services
- Untrusted $\rightarrow$ trusted control transfer: trampolines
  - Start at 0 mod 32 addresses (why?) in the first 64K of the NaCl module address space
    - First 4K are read- and write-protected (why?)
  - Reset registers, restore thread stack (outside module's address space), invoke trusted service handlers
- Trusted $\rightarrow$ untrusted control transfer: springboard
  - Start at non-0 mod 32 addresses (why?)
  - Can jump to any untrusted address, start threads

Other Aspects of NaCl Sandbox

- No hardware exceptions or external interrupts
  - Because segment register is used for isolation, stack appears invalid to the OS $\Rightarrow$ no way to handle
- No network access via OS, only via JavaScript in browser
  - No system calls such as connect() and accept()
  - JavaScript networking is subject to same-origin policy
- IMC: inter-module communication service
  - Special IPC socket-like abstraction
  - Accessible from JavaScript via DOM object, can be passed around and used to establish shared memory