Securing Untrusted Code

Untrusted Code

- **May be untrustworthy**
  - Intended to be benign, but may be full of vulnerabilities
  - These vulnerabilities may be exploited by attackers (or other malicious processes) to run malicious code
- **Or, may directly be malicious: may use**
  - Obfuscation
    - Code obfuscation
    - Anti-analysis techniques
    - Use of vulnerabilities to hide behavior
  - (Behavioral) evasion
    - Actively subvert enforcement mechanisms
- **Security is still defined in terms of policies**
  - But enforcement mechanisms need to be stronger in order to defeat a strong adversary.

Reference Monitors

- **Security policies can be enforced by reference monitors (RM)**
  - Key requirements
    - Complete mediation
    - (If interaction with user is needed) Trusted path
- **With benign code, we typically assume that it won’t actively evade enforcement mechanisms**
  - We can *possibly* maintain security even if there are ways to subvert the checks made by the RM

Types of Reference Monitors

- **External RM**
  - RM resides outside the address space of untrusted process
  - Relies on memory protection
    - Protect RM’s data from untrusted code
    - Limit access to RM’s code
- **Inline RM**
  - Policy enforcement code runs within the address space of the untrusted process
  - Cannot rely on traditional hardware-based memory protection

External Reference Monitors

- System-call based RMs
- Linux Security Modules (LSM)
- AppArmor

System-call based RMs

- **OSes already implement RMs to enforce OS security policies**
  - Most aspects of policy are configured (e.g., file permissions), while the RM mainly includes mechanisms to enforce these policies
- **But these are typically not flexible enough or customizable**
- **More powerful and flexible policies may be realized using a customized RM**
- **System-calls provide a natural interface at which such a customized RM can reside and mediate requests.**

Why monitor system calls?

- **Complete mediation: All security-relevant actions of processes are administered through this interface**
- **Performance: Associated with a context-switch --- can be exploited to protect RM without extra overheads**
- **Granularity**
  - Finer granularity than typical access control primitives
  - But coarse enough to be tractable: a few hundred system calls
- **Expressiveness**
  - Clearly defined, semantically meaningful, well-understood and well-documented interface (except for some OSes like Windows)
  - Orthogonal (each system call provides a function that is independent of other system calls --- functions that rarely, if ever, overlap)
  - Can control operations for which OS access controls are ineffective, e.g., loading modules
    - A large number of security-critical operations are traditionally lumped into "administrative privilege"
- **Portability: System call policies can be easily ported across similar OSes, e.g., various flavors of UNIX**

Some drawbacks of system calls

- **Interface is designed for functionality**
  - Several syscalls may be equivalent for security purposes, but we a syscall policy needs to treat them separately
- **Not all relevant operations are visible**
  - For instance, syscall policies cannot control name-to-file translations
- **Race conditions**
  - Pathname based policies are prone to race conditions
  - More generally, there may be TOCTTOU races relating to system call arguments
    - Unless the argument data is first copied into RM, checked, and then this checked copy is used by the system call
      - Adds more complexity
  - The window for exploiting TOCTTOU attacks can be increased by using a large sequence of symbolic links in the name

System call interposition approaches

- **User-level interception**
  - RM resides within a process
    - Library interposition
      - RM resides in the same address space
      - Advantages
        - high performance
        - Potential for intercepting higher level (semantically richer) operations
      - Drawbacks: RM is unprotected, so appropriate only for benign code
    - Kernel-supported interposition, with RM residing in another process
      - Advantages: Secure for untrusted code
      - Drawback: High overheads due to context switches
      - Example: ptrace interface on Linux
- **Kernel interception**
  - The RM resides in the kernel
  - Advantages: high performance, secure for untrusted code
  - Drawbacks:
    - difficult to program
    - requires root privilege
    - Rootkit defense measures pose compatibility issues

Linux Security Module Framework

- **Motivated by the drawbacks of syscall monitors**
- **Defines a number of “hooks” within Linux kernel**
  - Includes all points where security checks need to be done
  - RMs can register to be invoked at these hooks
  - SELinux, as well as Linux capabilities are implemented using such RMs
- **Drawbacks**
  - The framework has significant complexity --- while it simplifies some things, the increased complexity makes other things hard.
  - Requires a lot of effort to identify the things that need checking, and where all the hooks need to be placed
  - Very closely tied to the implementation details of an OS --- not easily ported to other OSes.

Inline Reference Monitoring

- Foundations
  - Software Fault Isolation (SFI)
  - Control-flow Integrity (CFI)
- Case Study
  - Google Native Client (NaCl)

Inline Reference Monitors (IRMs)

- **Provide finer granularity**
  - “Variable x is always greater than y”
  - Provides much more expressive power
- **Very efficient**
  - Does not require a context switch
- **Key challenge:**
  - Protecting IRM from hostile code

Securing RMs in the same address space

- **Protect RM data that is used in enforcing policy**
  - Software-based fault isolation (SFI)
- **Protect RM checks from being bypassed**
  - Control-flow integrity (CFI)
- **Note**
  - For vulnerability defenses (e.g., Stackguard), we implement the checks using an IRM
  - But we don’t worry so much about these properties since we are dealing with benign (and not malicious) code

Software Fault Isolation (SFI)

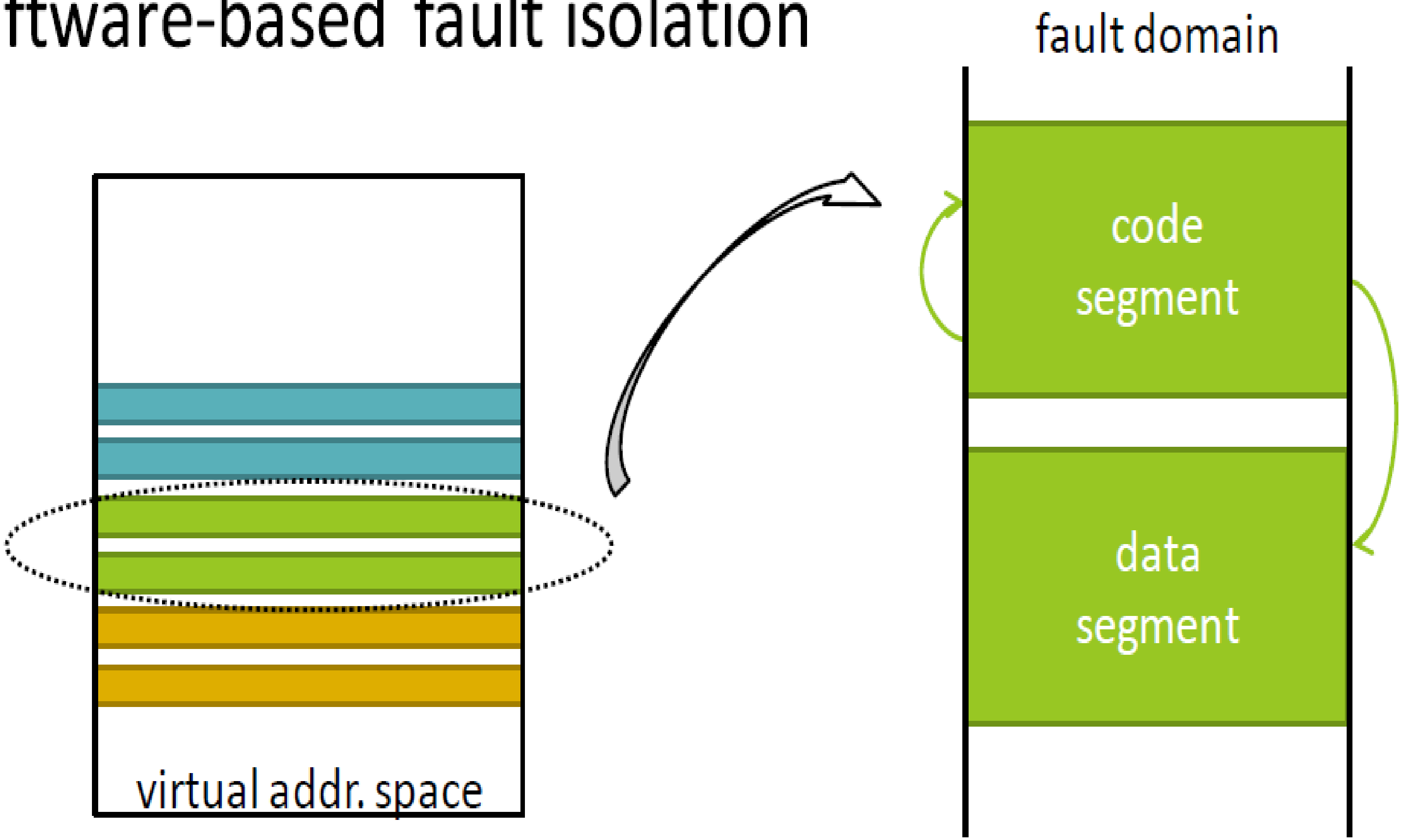
Background

- **Fault Isolation**
  - What is fault isolation?
    - when "something bad" happens, the negative consequences are limited in scope.
  - Why is it needed?
    - Untrusted plug-ins makes applications unreliable
    - Third-party modules make the OS unreliable
- **Hardware based Fault Isolation**
  - Isolated Address Space
  - RPC interfaces for cross boundary communication

SFI [Wahbe et al 1994]

- **Motivation**
  - Hardware-assisted context-switches are expensive
    - TLB flushing; some caches may require flushing as well
- **Key idea**
  - Insert inline checks to verify memory address bounds for
    - Data accesses
    - Indirect control-flow transfers (CFT)
      - Direct CFTs can be statically checked
- **Challenges**
  - Efficiency
    - each memory access has the overhead of checking
  - Security
    - Preventing circumvention or subversion of checks

software-based fault isolation



- **Even when running in the same virtual address space, limit some code components to access only a part of the address space**
  - This subspace is called a “fault domain”

Software Fault Isolation

- **Virtual address segments**
  - Fault domain (guest) has two segments, one for code, the other for data.
  - Each segment share a unique upper bits (segment identifier)
  - Untrusted module can ONLY jump to or write to the same upper bit pattern (segment identifier)
- **Components of the technique**
  - Segment Matching
    - Optimization: instead of checking, simply override the segment bits
      - Originally, the term "sandboxing" referred to this overriding
  - Data sharing
  - Cross-domain Communication

Segment Matching

- **Insert checking code before every unsafe instruction**
  - To prevent subversion of checks, use dedicated registers, and ensure that all jumps and stores use these registers
    - Need only worry about indirect accesses
    - Don't forget that returns are indirect jumps too
- **Checking code determines whether the unsafe instruction has the correct segment identifier**
- **Trap to a system error routine if checking fails – pinpoint the offending instruction**

Segment Matching

`dedicated-reg` ⇐ `target address`

Move target address into dedicated register.

`scratch-reg` ⇐ `(dedicated-reg>>shift-reg)`

Right-shift address to get segment identifier.

`scratch-reg` *is not a dedicated register.*

`shift-reg` *is a dedicated register.*

`compare scratch-reg and segment-reg`

`segment-reg` *is a dedicated register.*

`trap if not equal`

Trap if store address is outside of segment.

`store instruction uses dedicated-reg`

5 instructions, Need 5 dedicated registers (segment value needs to be different for code and data) and it can pinpoint the source of faults. Can reduce the number of registers by hard-coding some values (e.g., number of shift bits).

Optimization 1: Address Sandboxing

- **Reduce runtime overhead further compared to segment matching by not pinpointing the offending instruction**
- **Before each unsafe instruction, inserting codes can set the upper bits of the target address to the correct segment identifier**

Address Sandboxing

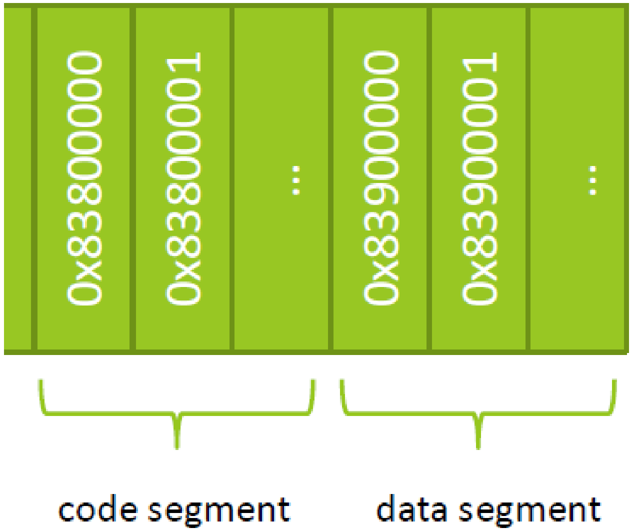
`dedicated-reg` ⇐ `target-reg&and-mask-reg`

Use dedicated register `and-mask-reg` *to clear segment identifier bits.*

`dedicated-reg` ⇐ `dedicated-reg|segment-reg`

Use dedicated register `segment-reg` *to set segment identifier bits.*

`store instruction uses dedicated-reg`



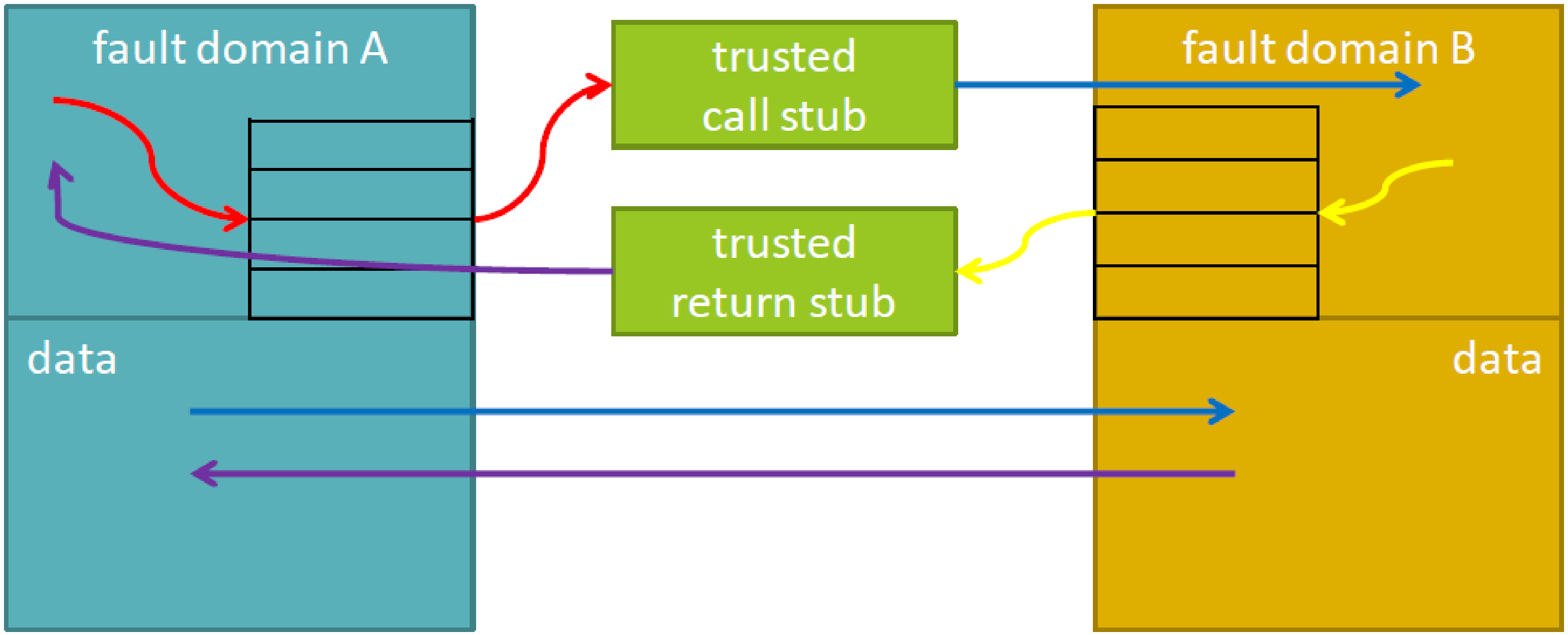
3 instructions, Require 5 dedicated registers (since mask and segment registers will be different for code and data)

Correctness: Relies on the *invariant* that dedicated registers always contain valid values before any control transfer instruction.

Data sharing

- Read-only sharing can be achieved in several ways:
  - **Option 1: Don’t restrict read acceses**
  - **Option 2: Allow reads to access some segments other than that of untrusted code**
  - **Option 3: Remap shared memory into the address space of both the untrusted and trusted domains**
- Read-write sharing can use similar techniques.

cross fault domain communication



- trusted stubs to handle RPC
  - for each pair of fault domains
  - stub: copy arguments, re/store registers, switch the exe. stack, validate dedicated regs but! no traps or address space switching (thus, cheaper than HW RPC)
- jump tables to transfer control
  - consists of jump instructions of which target address is legal, outside the domain

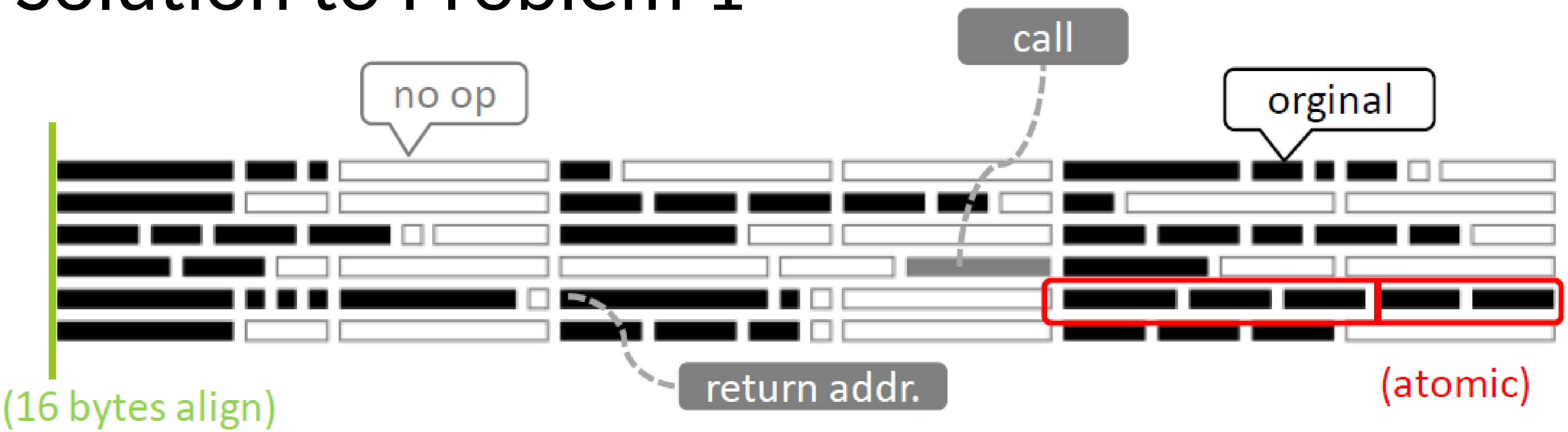
SFI details (continued)

- **Need compiler assistance**
  - To set aside dedicated registers
  - *But we cannot trust the compiler*
    - Programs may be distributed as binaries, and we can’t trust the compiler used to compile that untrusted binary
- **Need a verifier**
  - Verification is quite simple
    - Dedicated registers should be loaded only after address-sandboxing operations
    - All direct memory accesses and direct jumps should stay within untrusted domain. Implementation operates on binary code
      - Note that SFI checks all indirect accesses and control-transfers at runtime
  - Was implemented on RISC architectures
- **Precursor to proof-carrying code [Necula et al]**
  - Code producer provides the proof, consumer needs to check it.
    - Proof-checking is much easier than proof generation
    - Especially in an automated verification setting:
      - producer needs to navigate a humongous search space to construct a proof tree
      - consumer needs to just verify that the particular tree provided is valid

SFI for CISC Architectures (x86)

- **Difficulties of bringing SFI to CISC**
  - Problem 1: Variable-length instructions
    - What happens if code jumps to the middle of an instruction
  - Problem 2: Insufficient registers
    - SFI requires 5 dedicated registers for segment matching
    - SFI requires 5 dedicated registers for address sandboxing
    - x86 has very few general-purpose registers available
      - – eax, ebx, ecx, edx, esi, edi
    - PittsSFIeld: uses ebx as a dedicated register AND treats esp and ebp as sandboxed registers (adds needed checks)

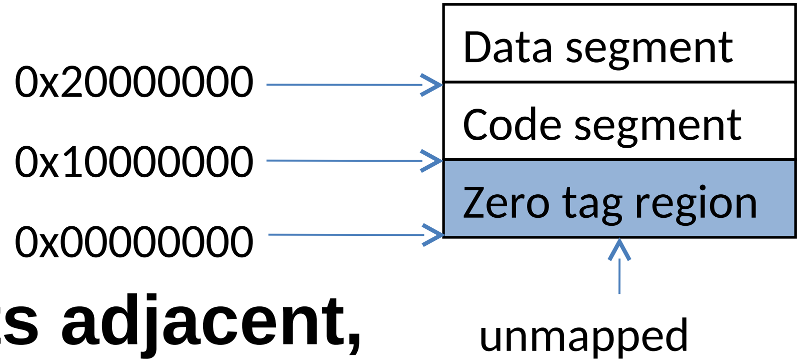
Solution to Problem 1



- padding with no-ops to enforce alignment constraints (power of two)
  - because CISC architectures allow various instruction streams, which makes SFI harder
- `call` placed at the end of chunks
  - because the next addresses are targets of returns
  - they also have low 4 bits zero due to 16 bytes align
- put unsafe operation and its corresponding check together in a chunk
  - atomic, i.e. unsafe op. must be followed by check; no dedicated registers required

Solution to Problem 2

- **Hardcode segments**
  - Avoids need for segment registers etc.



- **Make code and data segments adjacent, and differ by only one bit in their addresses**
  - Sandboxing now achieved using a single instruction
    - and 0x20ffffff, %ebx
    - Store using ebx
  - For indirect jumps, use:
    - and 0x10fffff0, %ebx
    - Jump using ebx
- **Alternative approach**
  - Use x86 segment (CS, DS, ES) registers!
    - Very efficient but not available on x86_64

Control Flow Integrity (CFI)

Control-flow Integrity (CFI) [Abadi et al]

- **Unrestricted control-flow transfers (CFTs) can subvert the IRM**
  - Simply jump past checks, or
  - Jump into IRM code that updates critical IRM data
- **Approach**
  - Compute permissible targets for control-flow transfer
    - Uses static analysis to determine valid targets
      - Coarse-grained analysis:
        - Can be as simple as listing all valid functions and return targets
      - Fine-grained analysis:
        - for each function pointer, compute a safe superset of all possible values
        - for each function, compute a safe superset of all possible call sites
  - At runtime, check actual targets against the permissible ones
    - Note: No need to check direct calls, just indirect calls and (all) returns

CFI: Forward Edge Vs Backward Edge

- **Forward edge**
  - Enforce policies on targets of indirect calls
- **Backward edge**
  - Enforce policies on returns
  - Coarse-grained is not enough if your goal is to protect benign code from control-flow hijack
    - ROP restricted to gadgets beginning at valid return targets ("call-site gadgets") is still too powerful
    - Shadow stack or safe stack can enforce the ultimate fine-grained backward edge policy (match all returns with the corresponding calls)
      - But there may be some corner cases in terms of compatibility
    - Recent intel processors include hardware support for shadow stacks
  - For protecting the IRM, coarse-grained protection is enough

Coarse-Grained CFI

- **Takes into account the type of control transfer, but not much additional info available at the control transfer source ("context insensitive")**
- **Here is a typical policy**
  - All calls should go to beginning of functions
  - All returns should go to instructions following calls
  - No control flow transfers can target instructions belonging to IRM
- **Main benefits**
  - Simple
    - no need for any nontrivial static analysis
    - efficient implementation using compact read-only tables
  - Does not pose compatibility problems
  - Sufficient for protecting IRMs

Fine-Grained CFI

- **Context sensitive: Uses one or more of the following types of info from the control transfer site**
  - Location of the source instruction
  - Types of arguments to indirect function calls
  - Possible data flows into the variable holding the code pointer or the arguments
- **Benefits**
  - Increased security by reducing the # of possible targets
- **Drawbacks**
  - Increased complexity (static analysis *and* enforcement)
  - Poses compatibility challenges with separate compilation and dynamic loading
- **Status**
  - Type-based fine-grained CFI available in LLVM/GCC (but not default)
  - Particularly important for C++ because of widespread use of function pointers (virtual functions)

CFI for Securing the IRM

- **Coarse-grained version is sufficient to protect IRM**
  - Like SFI, CFI is self-protecting
    - CFI checks the targets of jump, so it can prevent unsafe CFTs that attempt to jump just beyond CFI checks
    - In PittSFIeld, this was achieved by ensuring that the check and access operations were within the same bundle
      - Jumps can only go to the beginning of a bundle, so you can't jump between check and use
  - Because of this, SFI and CFI provide a foundation for securing untrusted code using inline checks.
  - CFI can also be applied to protect against control-flow hijack attacks
    - Jump to injected code (easy)
    - Return to libc (most obvious cases are easy)
    - Return-oriented programming (requires considerable effort to devise ROP attacks that defeat CFI)
    - **But not a foolproof defense**
- **In addition:**
  - IRM code shouldn't assume that untrusted code will follow ABI conventions on register use
  - IRM code should use a separate stack
    - To prevent return-to-libc style attacks within IRM code

CFI Implementation Strategies

- **Approach 1 (proposed in the original CFI paper)**
  - Associate a constant index with each CFT target
  - Verify this index before each CFT
    - Ideal for fine-grained approach, where static analysis has computed all potential targets of each indirect CFT instruction
  - Issues
    - If locations L1 and L2 can be targets of an indirect CFT, then both locations should be given the same index
    - If another CFT can go to either L2 or L3, then all three must have same index
    - A particular problem when you consider returns
      - Accuracy can be improved by using a stack, but then you run into the same compatibility issues as stack smashing defenses that store a second copy of return address

CFI Instrumentation

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

                                   can be instrumented as (a):

81 39 78 56 34 12   cmp   [ecx], 12345678h   ; comp ID & dst        78 56 34 12    ; data 12345678h      ; ID
75 13               jne   error_label        ; if != fail           8B 44 24 04    mov   eax, [esp+4]    ; dst
8D 49 04            lea   ecx, [ecx+4]       ; skip ID at dst       ...
FF E1               jmp   ecx                ; jump to dst

                              or, alternatively, instrumented as (b):

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
```

Figure 2: Example CFI instrumentations of a source x86 instruction and one of its destinations.

- Method (a): unsafe, since ID is embedded in callsite (could be used by attacker)
- Method (b): safe, but pollute the data cache

Approach 1: Assumptions

- **UNQ: Unique IDs.**
  - choose longer ID to prevent ensure the uniqueness
  - Otherwise: jump in the middle of a instruction or arbitrary place (in data or code)
- **NWC: Non-Writable Code.**
  - Code could not be modified. Otherwise, verifier is meaningless, thus all the work is meaningless……
- **NXD: Non-Executable Data**
  - Otherwise, attacker can execute data that begins with a correct ID.

All the assumptions should hold. Otherwise, this CFI implementation can be defeated.

Approach 1: Implementation

- **Although the enforcement technique can support some fine-grained policies, the implementation only attempts coarse-grained enforcement**
  - Indirect calls can only target functions whose addresses are taken in the program
  - Returns can only target instructions following calls

CFI Implementation: Simplified Approach Using Tables

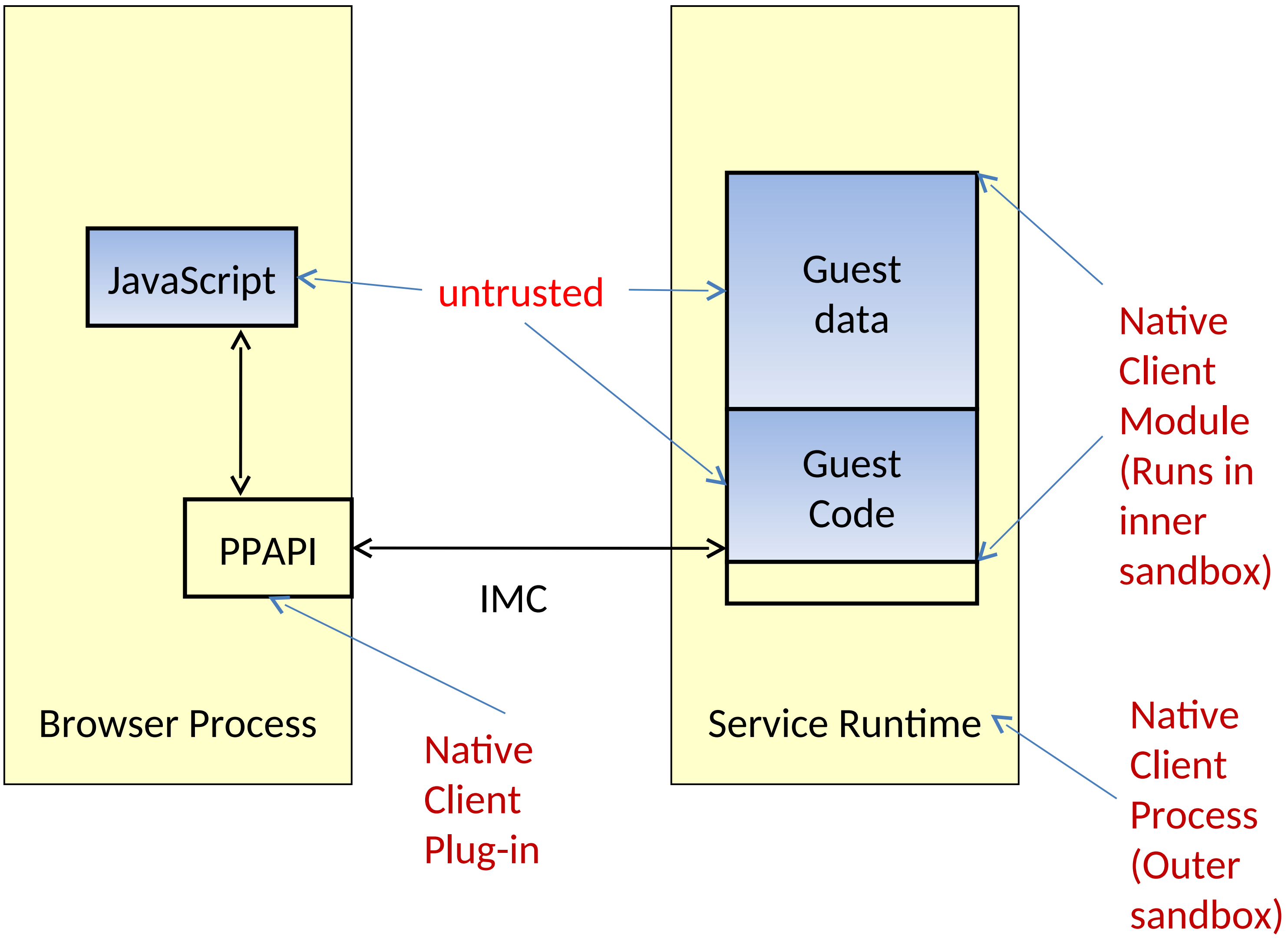
- Use an array *V* indexed by address, and holding the following values
  - Function_begin, Valid_return, Invalid
- A call to target *X* is permitted if *V*[*X*] == Function_begin
- A return to target *X* is permitted if *V*[*X*] == Valid_return
- Otherwise, CFT is not permitted
  - Note that CFI implementations need only check indirect CFTs
- Store *V* in read-only memory to protect it

Case Study I:
Google Native Client (NaCl)

Motivation

- **Browsers already allow Javascript code from arbitrary sites, but its performance is inadequate for some applications**
  - Games
  - Fluid dynamics (physics simulation)
- **Permitting native code from arbitrary sites is too dangerous!**
- **NaCl is an environment + toolchain that uses SFI/CFI to enables safe native code execution**

System Architecture



Native Client Approach

- **Dual sandbox for safe native code execution**
  - SFI for inner sandbox that runs downloaded native code
    - Basically, PittSFIeld with two important differences
      - – 32-byte bundles rather than 16 byte bundles
      - – x86_32 segmentation feature for limiting data access (instead of inserting checking instructions)
    - Native code must be generated by NaCl compiler toolchain
      - – safety properties verified at client site at load-time
  - Code in the inner sandbox can call permitted functions in the (trusted) service runtime, e.g., display/rendering functions
    - Service runtime is not subject to SFI
- **For added security**
  - Both these run within a separate process disjoint from the browser
  - This process is sandboxed using seccomp (“outer sandbox”)

Safety Properties Checked At Load-time

- All instructions are reachable by fall-through disassembly from starting address
- All direct transfers to valid instruction boundaries
- All indirect control transfer use nacljmp (pseudo) instruction
- No instructions overlap 32-byte boundary
- No self modifying code
- code is not writable (and cannot be made writable at runtime)
- Statically linked with a fix start address of text segment
- to simplify and speedup sandboxing checks
- The binary is padded up to the nearest page with hlt

Case Study II:
WebAssembly (Wasm)

Motivation and Status

- **Same use case as NaCl**
  - Support safe downloaded native code in browsers
  - Work seamlessly with the same origin policy
- **"Virtualizes" untrusted code within a single process, enabling safe execution alongside trusted code**
  - In all major browsers
  - Cloud deployments, e.g., within Cloudflare CDN
- **Allows (more or less) arbitrary C/C++ code to be downloaded and run safely**
  - Relies on LLVM compiler that translates to Wasm
  - If you are curious, you should check this out!
    - Install and try out the emscripten package

Wasm Approach

- **Unlike NaCl's use of intel instructions, WebAssembly uses an abstract instruction set (wasm)**
- **Wasm designed with safety in mind**
  - CFI
    - Structured control flow (i.e., no need to check direct transfers)
    - Indirect calls use type-based forward edge checks
      - Use only four basic types for arguments
    - Returns use safe stack protected from memory errors
  - SFI is based on a simple version of memory safety
    - Variables whose addresses are not taken are referenced by indices and stored in safe index spaces
    - Variables whose addresses are taken are stored in a *linear memory section.* Accesses are bounds-checked to prevent overflow to other regions
- **Wasm translated into native code before run**
  - Wasm compiler (but not C/C++ compiler) is responsible for secure translation

A Sampling of Untrusted Code Security Research By Past CSE 508/509 Students and Seclab

- Model-carrying code (SOSP 2003)
- Isolated program execution (ACSAC 2003)
- Safe execution via one-way isolation (NDSS 2005)
- Proactive integrity protection (IEEE S&P 2008)
- Secure software installation (DIMVA 2008)
- System-wide integrity protection (ACSAC 2014)
- Integrity protection for Windows (ACSAC 2015)