Reference monitors

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*Original slides from Vitaly Shmatikov

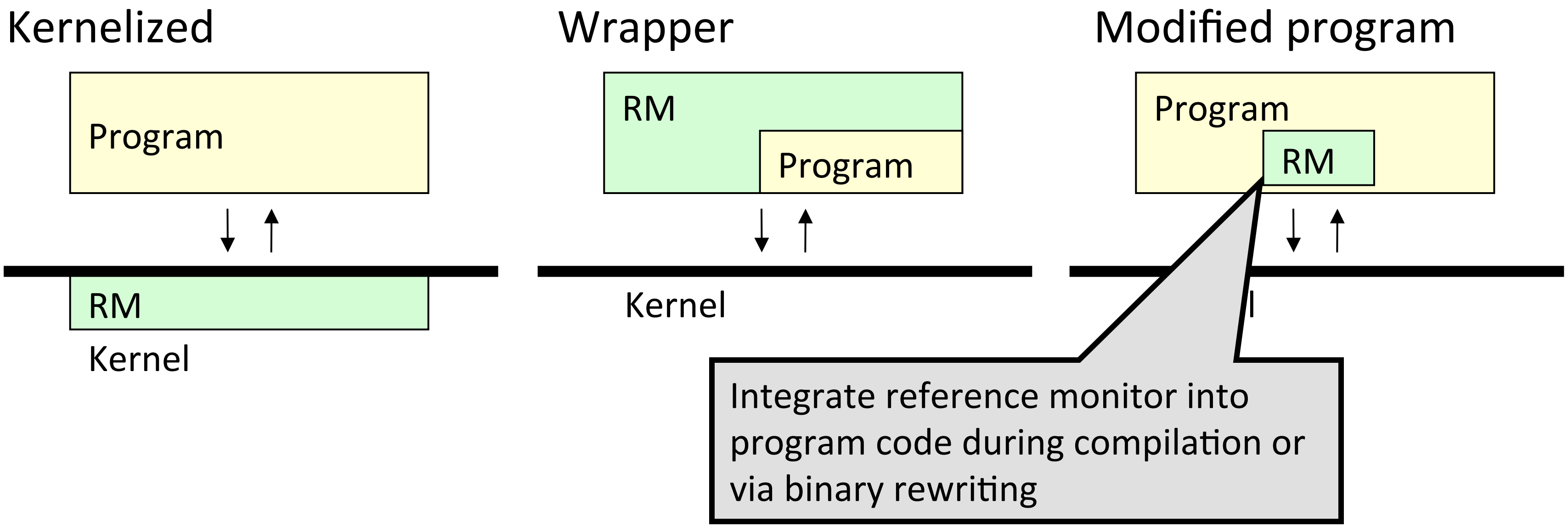
Reference Monitor

- Observes execution of the program/process
  - At what level? Possibilities: hardware, OS, network
- Halts or confines 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

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, don't execute data as if it were code
- 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
- 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”

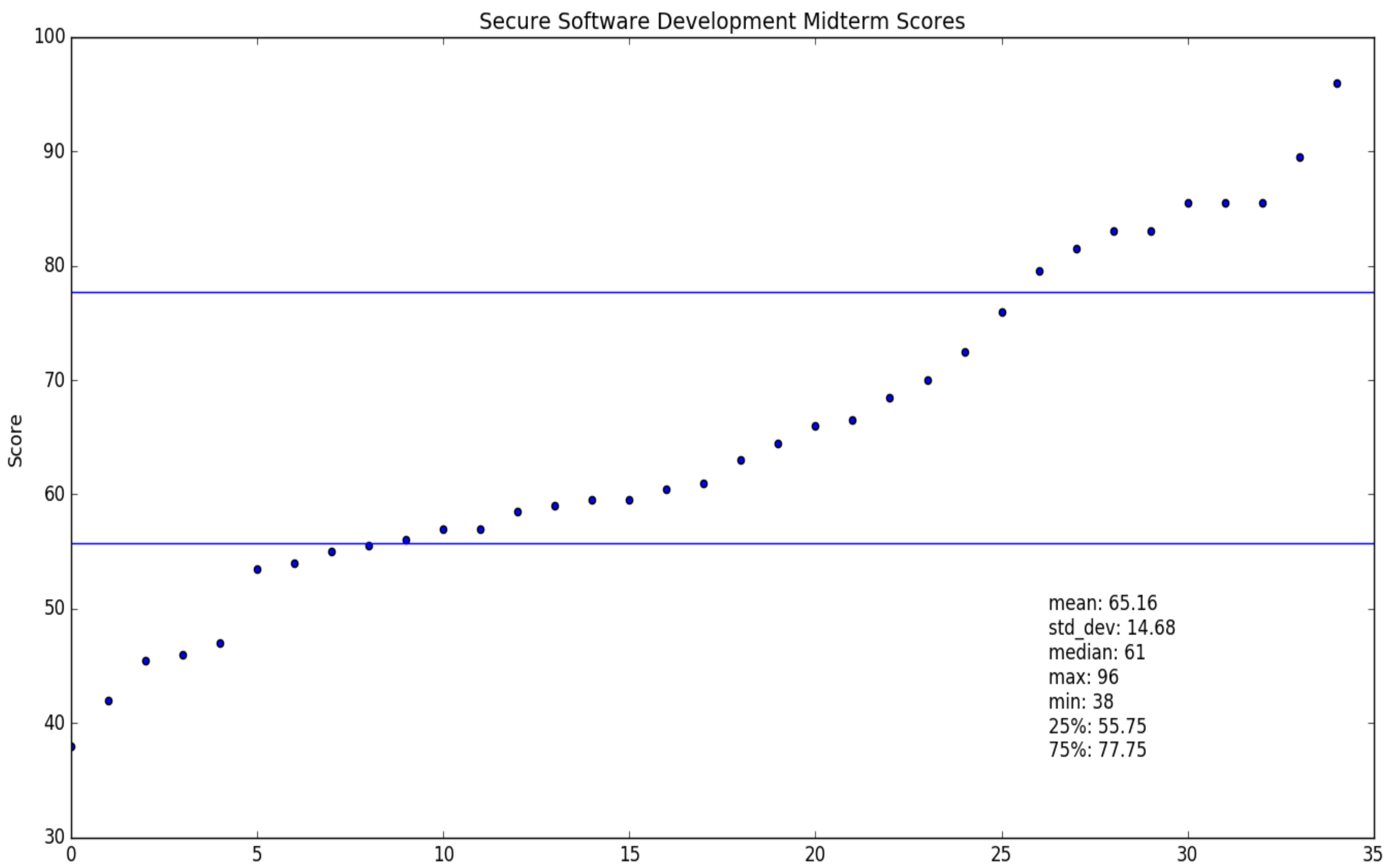
saves context, flushes TLB, etc.

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

Midterm grades



Modern Hardware Meets Security

- Modern hardware: large number of registers, big memory pages
- Isolation $\Rightarrow$ 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 write 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 are masked so that all memory writes are to addresses within the segment
    - Coarse-grained memory safety (vs. array bounds checking)
  - Code is 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

Simple SFI Example

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

  … x := x | 1200

  write x

convert x into an address that lies within the fault domain

What if the code jumps right here?

- Better SFI: tmp := x & 00FF

  tmp := tmp | 1200

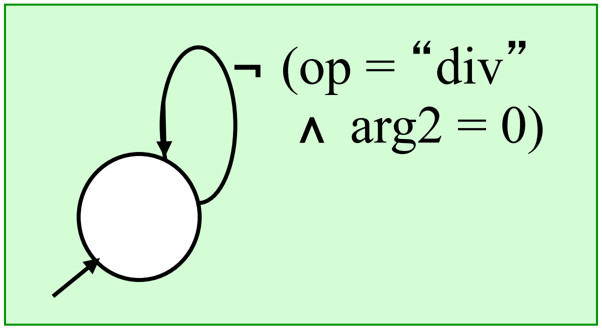
  write tmp

Inline Reference Monitor

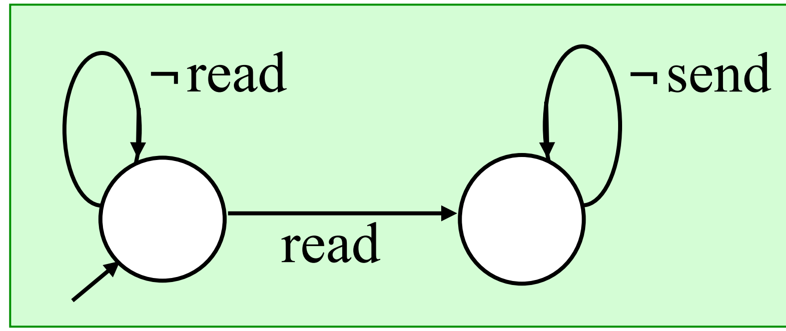
- Generalize SFI to more general safety policies than just memory safety
  - Policy specified in some formal language
  - Policy deals with application-level concepts: access to system resources, network events, etc.
    - "No process should send to the network after reading a file", "No process should 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

M. Abadi, M. Budiu, U. Erlingsson, J. Ligatti

Control-Flow Integrity:
Principles, Implementations, and Applications

(CCS 2005)

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

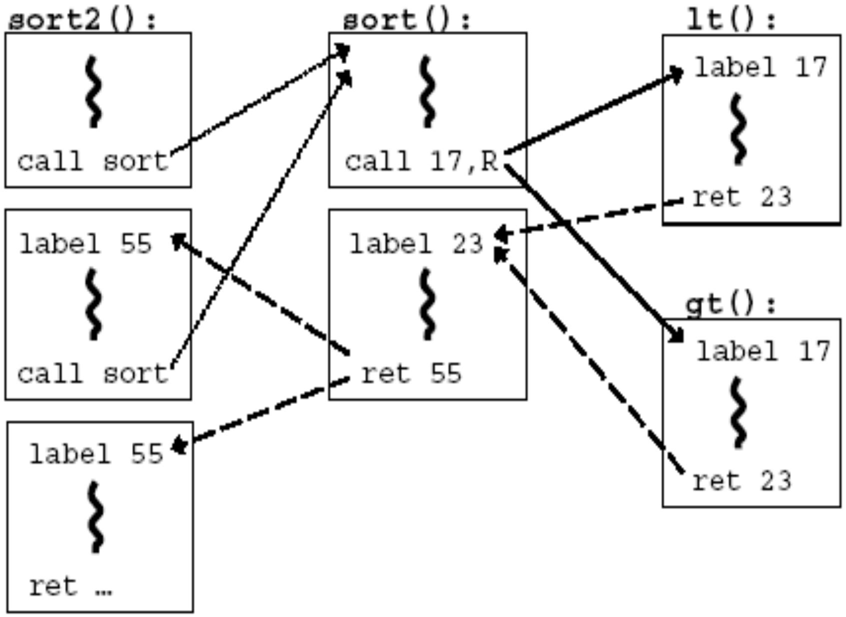
- Use binary rewriting to instrument code with runtime checks (similar to SFI)
- Inserted checks ensure that the execution always stays within the statically determined CFG
  - Whenever an instruction transfers control, destination must be valid according to the CFG
- Goal: prevent injection of arbitrary code and invalid control transfers (e.g., return-oriented-programming)
  - 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
FF E1               jmp  ecx          ; computed jump
```

Destination

```
Opcode bytes        Instructions
8B 44 24 04         mov  eax, [esp+4]    ; dst
```

Instrumented code

```
B8 77 56 34 12      mov  eax, 12345677h   ; load ID-1
40                  inc  eax              ; add 1 for ID
39 41 04            cmp  [ecx+4], eax     ; compare w/dst
75 13               jne  error_label      ; if != fail
FF E1               jmp  ecx              ; jump to label
```

```
3E 0F 18 05         prefetchnta           ; label
78 56 34 12            [12345678h]        ;    ID
8B 44 24 04         mov  eax, [esp+4]     ; dst
...
```

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

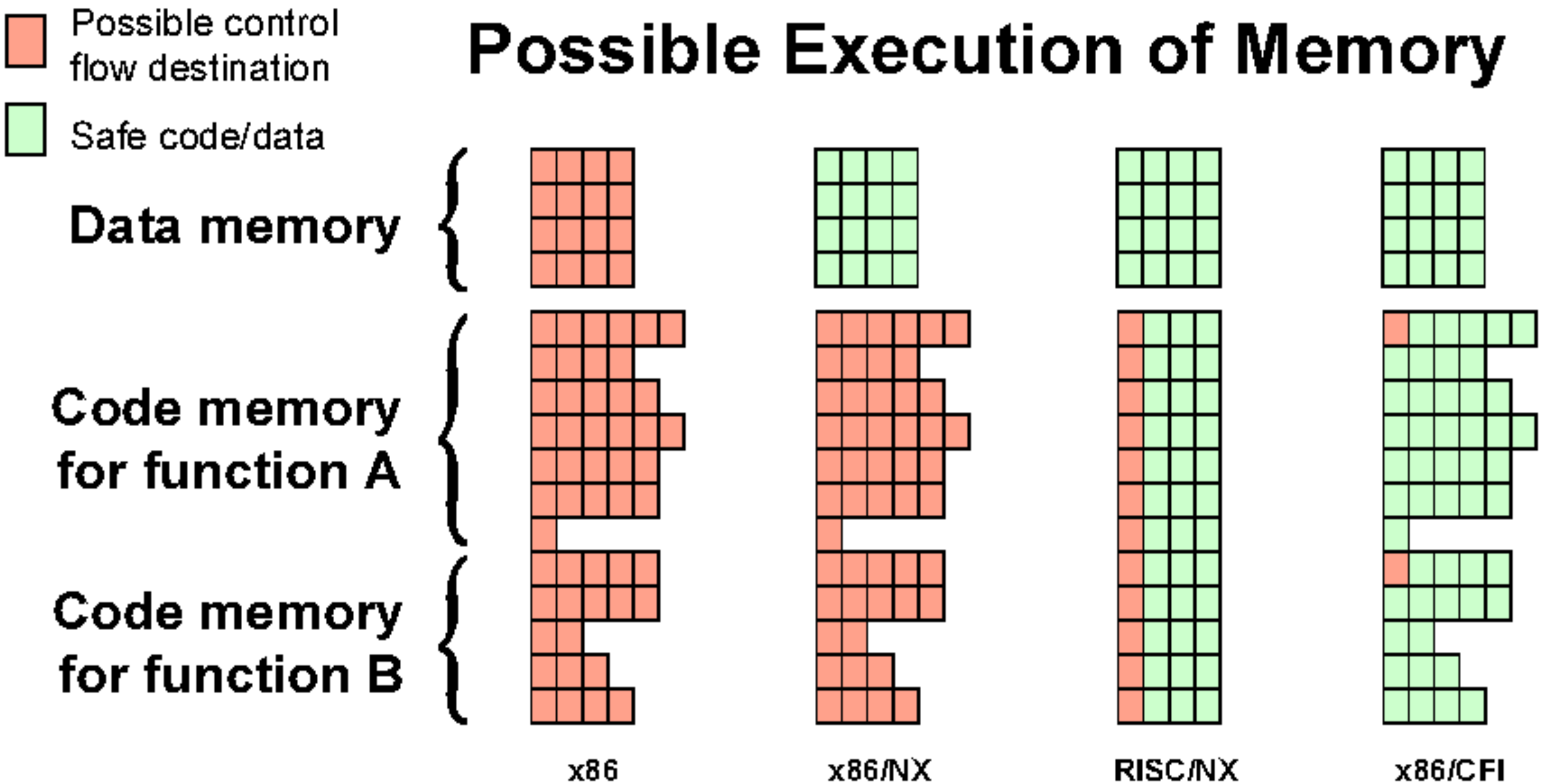
- Suppose a call from A goes to C, and a call from B goes to either C, or D (when can this happen?)
  - CFI will use the same tag for C and D, but this allows an "invalid" call from A to D
  - Possible solution: duplicate code or inline
  - Possible solution: multiple tags
- Function F is called first 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
- CFI to prevent circumvention
- 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