CMPSC 447
Software Fault Isolation

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Motivation

- Memory errors may allow unauthorized access to memory – objects other than the one that a pointer is assigned
  - Stack objects
  - Heap objects
- Recall stack overflow

Motivation

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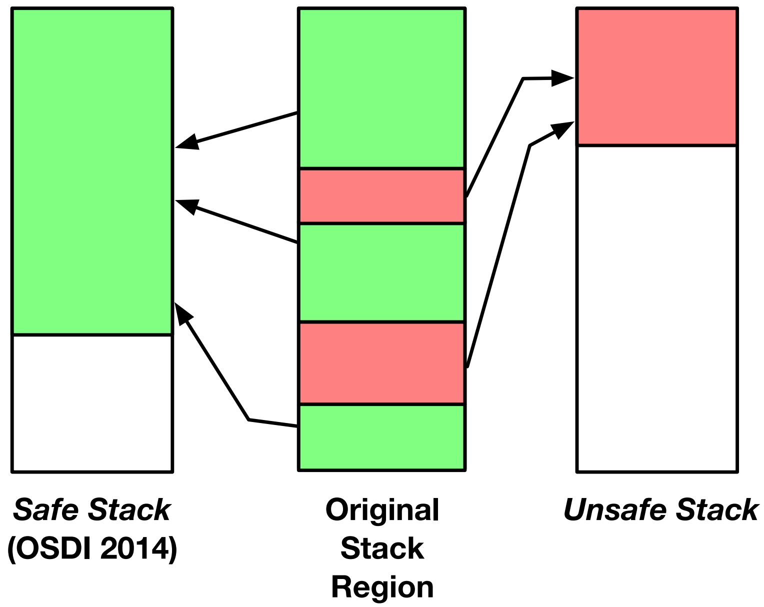
- Memory errors may allow unauthorized access to memory – objects other than the one that a pointer is assigned
  - Stack objects
  - Heap objects
- Problem: a process is a single address space where all memory is accessible all of the time
  - All data memory is readable
  - And most data memory is writable
  - Data memory is not executable, but enables code reuse

Motivation

- Can we build an infrastructure to limit the memory accessible to individual instructions within the same process?

Motivation

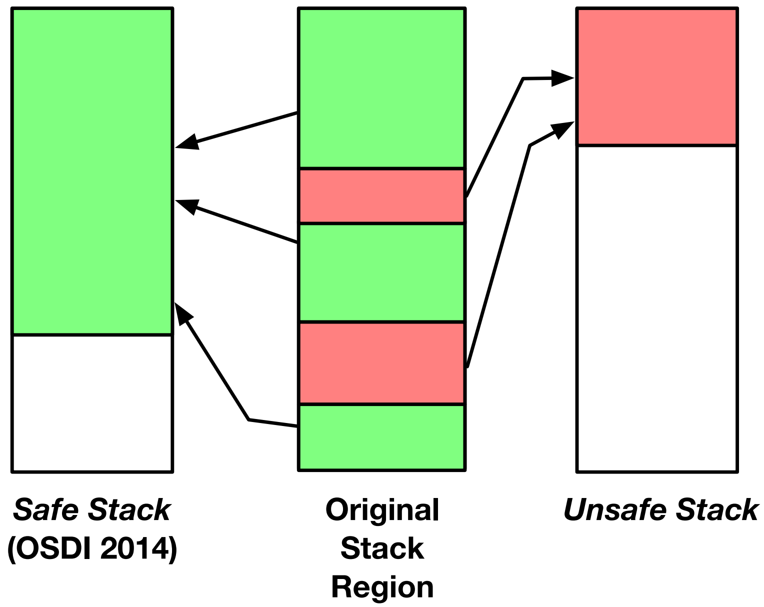
- Example: multiple stacks



- Original stack has objects with distinct security requirements
  - Distribute objects among multiple stacks

Motivation

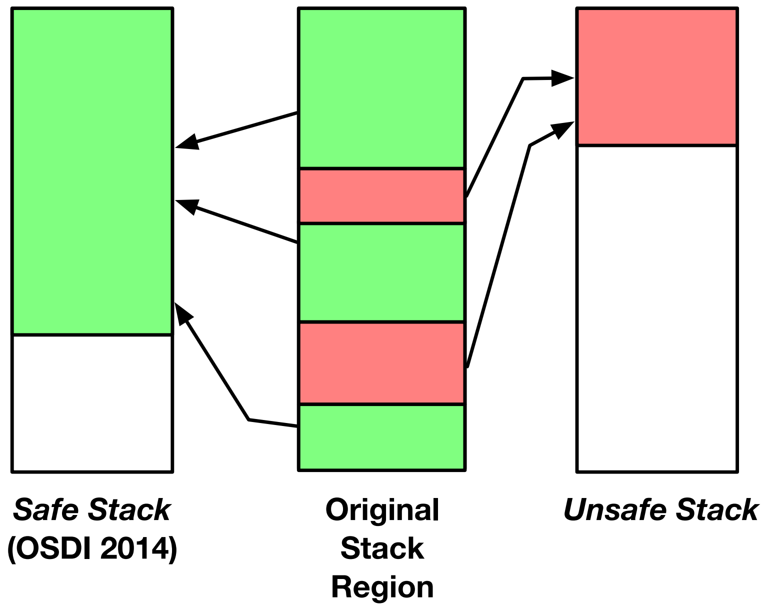
- Example: multiple stacks



- Safe Stack: Objects whose accesses are free of spatial errors – Kaiming: all memory errors
  - Instructions that use such pointers refer to the safe stack

Motivation

- Example: multiple stacks



- Safe Stack: Objects whose accesses are free of spatial errors – Kaiming: all memory errors
  - Memory errors on unsafe stack accesses cannot modify safe stack objects – Why not?

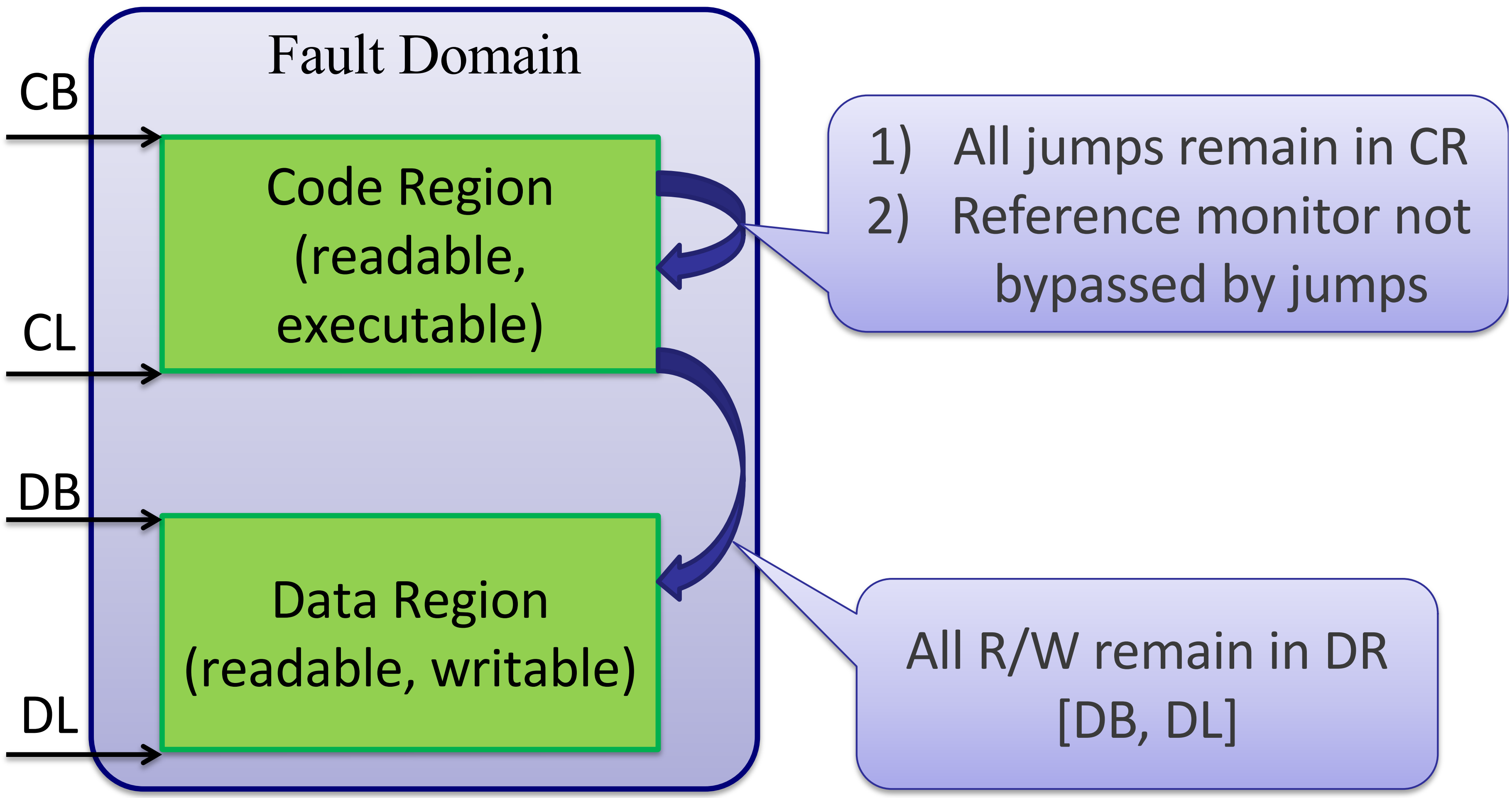
Software Fault Isolation (SFI)

- Use an inlined reference monitor to isolate components into “logical” address spaces in a process
    - Conceptually: check each read, write, & jump to make sure it is within the component’s logical address space
- Originally proposed in 1993 for MIPS [Wahbe et al. SOSP 93]
    - PittSFIeld extended it to x86 [McCammant & Morrisett 06]

Fault Domains

- Each domain is a "logical" address space within a process's address space
  - Separate Code and Data Regions (Harvard architecture)
  - Code region is readable and executable
  - Data region is readable and writable

SFI Policy


Fault Domain
CB
CL
DB
DL
Code Region (readable, executable)
Data Region (readable, writable)
1) All jumps remain in CR
2) Reference monitor not bypassed by jumps
All R/W remain in DR [DB, DL]

One SFI: Interpretation

```
void interp(int pc, reg[], mem[], code[]) {

    while (true) {
        if (pc < CB) exit(1);
        if (pc > CL) exit(1);
        int inst = code[pc], rd = RD(inst), rs1 = RS1(inst),
                  rs2 = RS2(inst), immed = IMMED(inst);
        switch (opcode(inst)) {
        case ADD: reg[rd] = reg[rs1] + reg[rs2]; break;
        case LD:  int addr = reg[rs1] + immed;
                  if (addr < DB) exit(1);
                  if (addr > DL) exit(1);
                  reg[rd] = mem[addr];
                  break;
        case JMP: pc = reg[rd]; continue;

          ...
        }
        pc++;
    }
}
```

Interpretation

- Interpret programs written in a particular language
  - Execution engine interprets each command, and checks that each operation is safe before doing it
- Examples
  - SafeTcl, old Java implementations, Perl (sometimes)
  - and a lot of scripting languages
  - …

Pros & Cons of Interpreter

Pros:

- Easy to implement (small TCB)
- Works even with binaries (high-level language-independent)
- Easy to enforce other aspects of OS policy

Cons:

- Terrible execution overhead (x25? x70?)
- But it's a start.

Partial Evaluation (PE)

- A technique for speeding up interpreters
  - Specialize a program with respect to the part of the input that is statically known
- Example

```
int f (int x, int i) {
  if (x>0) return i;
  else return (i+1);
}
… a = f(10, b) …
… a = f(-10, c) …
```

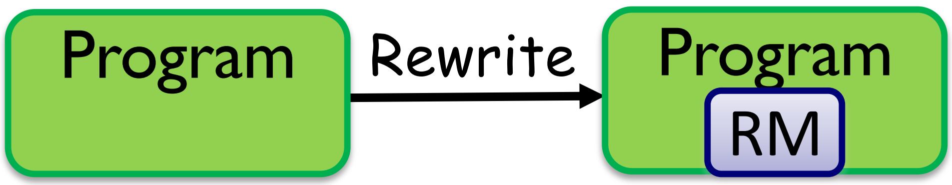
same as a = b

same as a = c + 1

Partial Evaluation for Faster SFI

- We know what the code is.
- *Specialize* the interpreter to the code.
  - Unroll the loop – one copy for each instruction
  - Specialize the switch to the instruction
  - Compile the resulting code

IRM via Program Rewriting



- The rewritten program should satisfy the desired security policy
- Examples:
  - Source-code level
    - CCured [Necula et al. 02]
  - Java bytecode-level rewriting: PoET [Erlingsson and Schneider 99]; Naccio [Evans and Twyman 99]

Enforcing SFI Policy

- Insert monitor code into the target program before unsafe instructions (reads, writes, jumps, …)

```
[r3+12] := r4 //unsafe mem write
```

↓

```
r10 := r3 + 12
if r10 < DB then goto error
if r10 > DL then goto error
[r10] := r4
```

SFI: Binary Rewriting

- A hand-written, specialized binary rewriter
  - Insert monitor code into the target program before dangerous instructions

```
0:  add r1,r2,r3
1:  ld r4,r3(12)
...
```

→

```
add r1,r2,r3
add r5,r3,12
cmp r5,DB
jb _exit
cmp r5,DL
ja _exit
ld r4,r5(0)
...
```

Optimizations

- Naïve SFI is OK for security
    - But the runtime overhead is too high
- Performance can be improved through a set of optimizations

Special Address Patterns

- Both code and data regions form contiguous segments
  - Upper bits are all the same and form a region ID
  - Address validity checking: only one check is necessary
- Example: DB = 0x12340000; DL = 0x1234FFFF
  - The region ID is 0x1234
  - "[r3+12]:= r4" becomes

```
r10 := r3 + 12
r11 := r10 >> 16 // right shift 16 bits to get the region ID
if r11 <> 0x1234 then goto error
[r10] := r4
```

Ensure, So No Check

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- Force the upper bits in the address to be the region ID
  - Called masking
  - No branch penalty
- Example: DB = 0x12340000 ; DL = 0x1234FFFF
  - "[r3+12]:= r4" becomes

```
r10 := r3 + 12
r10 := r10 & 0x0000FFFF
r10 := r10 | 0x12340000
[r10] := r4
```

Force the address to be in data region

Wait! Program Semantics?

- "Good" programs won't get affected
  - For bad programs, we do not care about whether its semantics are destroyed
- PittSField reported 12% performance gain for this optimization
- Cons: does not pinpoint the policy-violating instruction

One-Instruction Masking

- Idea
  - Make the region ID to have only a single bit on
  - Make the zero-tag region unmapped in the virtual address space
- Benefit: cut down one instruction for masking
- Example: DB = 0x20000000 ; DL = 0x2000FFFF
  - Region ID is 0x2000
  - "[r3+12]:= r4" becomes

```
r10 := r3 + 12
r10 := r10 & 0x2000FFFF
[r10] := r4
```

  - Result is an address in DR or in the (unmapped) zero-tag region
- PittSField reported 10% performance gain for this optimization

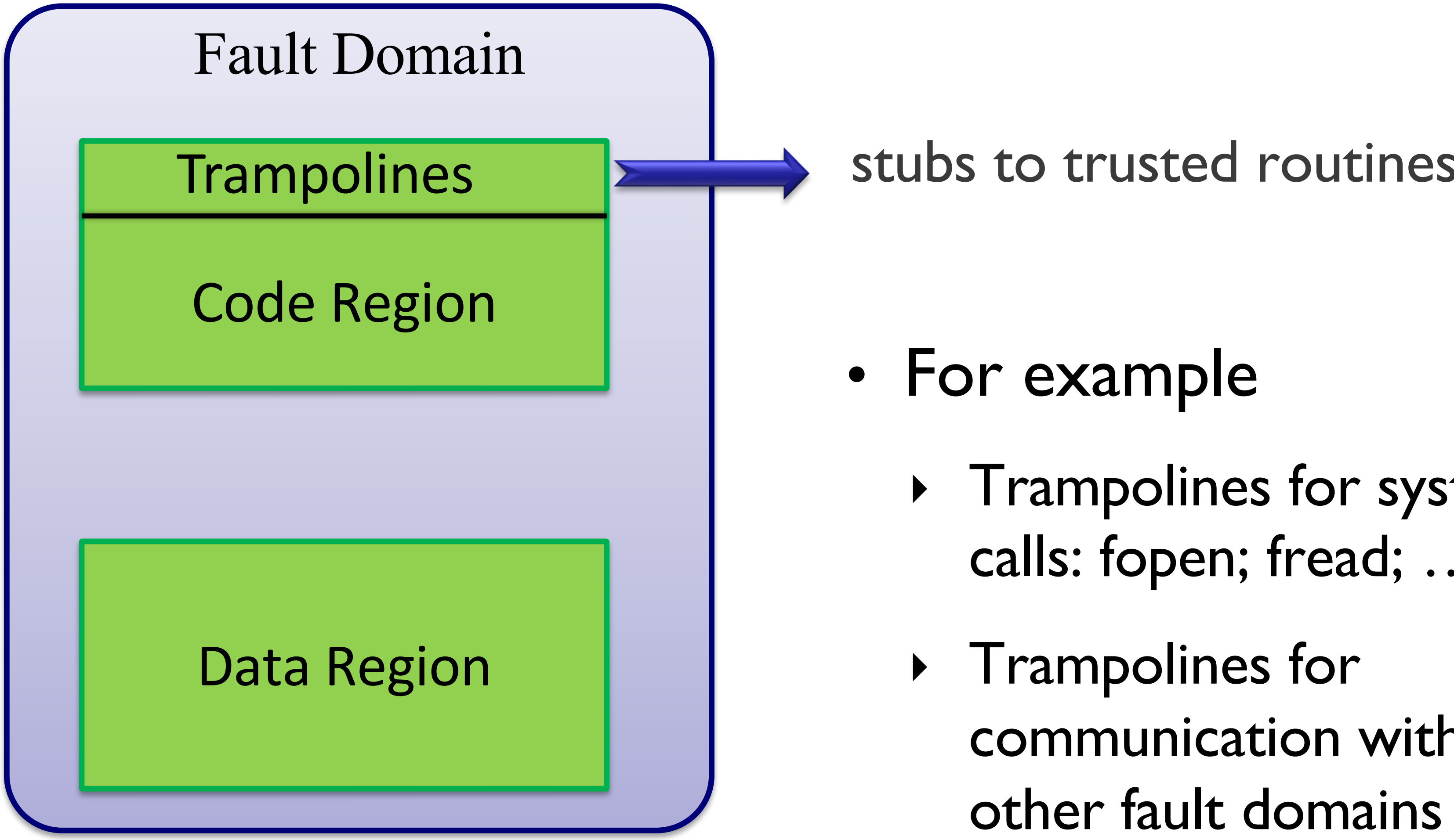
Fault Isolation vs. Protection

- Protection is fail stop
  - Control ("Sandbox") reads, writes, and jumps
  - Guarantee integrity and confidentiality
  - 20% overhead on 1993 RISC machines
  - XFI JPEG decoder: 70-80%
- Fault isolation: covers only writes and jumps
  - Guarantee integrity, but not confidentiality
  - 5% overhead on 1993 RISC machines
  - XFI JPEG decoder: Writes only: 15-18%
- As a result, most SFI systems do not sandbox reads

Jumping Outside of Domain

- Sometimes need to invoke code outside of the domain
  - For system calls; for communication with other domains
  - Danger: Cannot allow untrusted code to invoke code outside of the fault domain arbitrarily
- Idea:
  - Insert a jump table into the (immutable) code region
  - Each entry is a control transfer instruction whose target address is a legal entry point outside of the domain

A Fixed Jumptable (Trampoline)



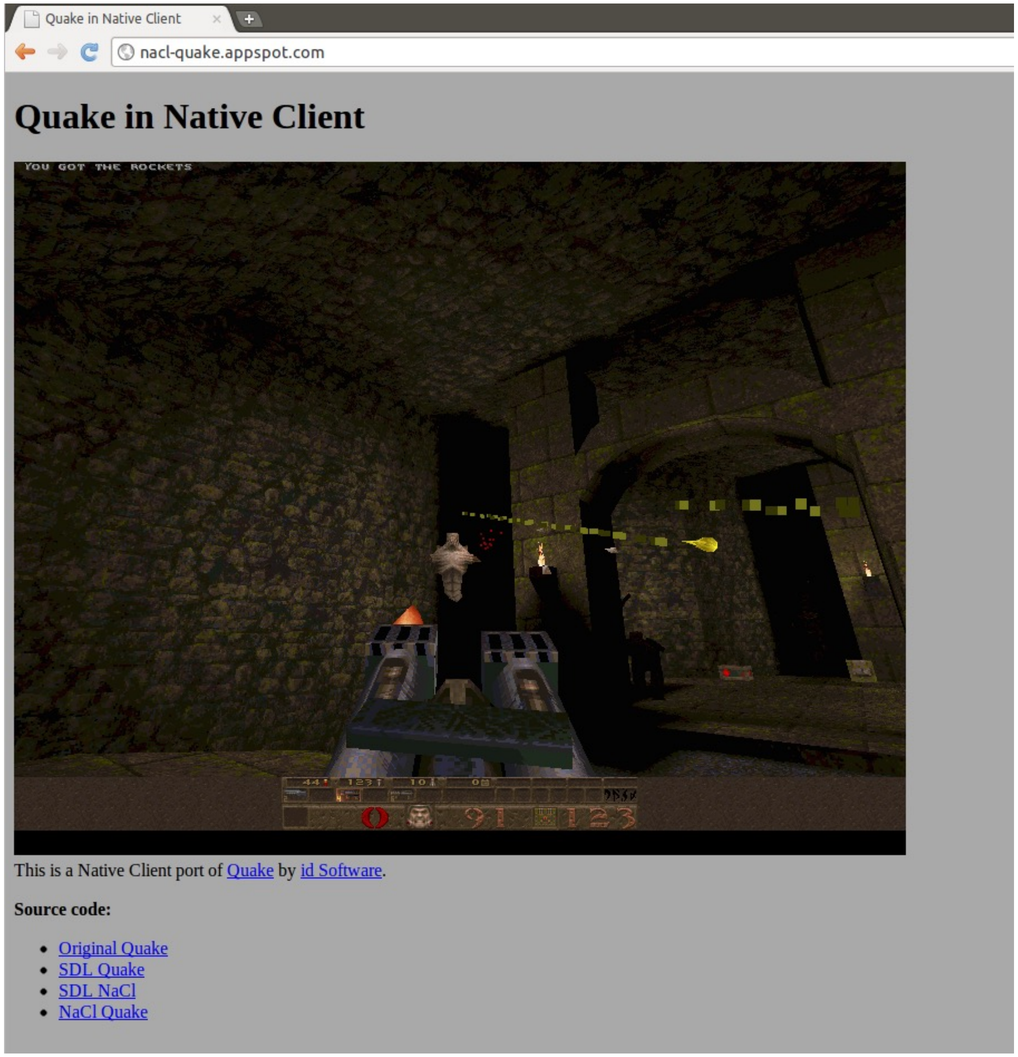
- For example
  - Trampolines for system calls: fopen; fread; …
  - Trampolines for communication with other fault domains

Trusted Stubs

- Stubs are outside of the fault domain
  - Why?
- Stubs can implement security checks
  - E.g., can restrict fopen to open files only in a particular directory
  - Or can disallow fopen completely
    - Just not install a jump table entry for it
  - It can implement system call interposition

Google Native Client (NaCl)

- SFI service in Chrome
  - [Yee et al. Oakland 09]
- Goal: Download native code and run it safely in the Chrome browser
  - Much safer than ActiveX controls
  - Much better performance than JavaScript, Java, etc.



NaCl: Code Verification

- Code is verified before running
  - Allow restricted subset of x86 instructions
    - No unsafe instructions: memory-dependent jmp and call, privileged instructions, modifications of segment state …
  - Ensure SFI checks are correctly implemented for memory safety

NaCl Sandboxing

- x86-32 sandboxing based on hardware segments
  - Sandboxing reads and writes for free
  - 5% overhead for SPEC2000
- However, hardware segments not available in x86-64 or ARM
  - Still need masking instructions [Sehr et al. 10]
  - x86-64/ARM: 20% for sandboxing memory writes and computed jumps

NaCl SDK

- Modified GCC tool-chain
  - Inserts appropriates masks, alignment requirements
- Trampolines allow restricted system-call interface and also interaction with the browser
  - Pepper API: access to the browser, DOM, 3D acceleration, etc.

Questions for SFI

- Binary rewriting on off-the-shelf binaries
  - All current SFI implementations require the cooperation of the code producer
- What happens with discontiguous hunks of memory?
- Does this really scale to secure systems?
  - So that we can partition a large system into domains of least privileges