Efficient Software-Based Fault Isolation

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Software Extensibility

Operating Systems
- Kernel modules
- Device drivers
- Unix vNodes

Application Software
- PostreSQL
- OLE
- Quark Xpress, Office

But:
Flaws in extension modules could cause flaws in the entire system
- Crashes
- Data corruption

Hardware Isolation

is slow

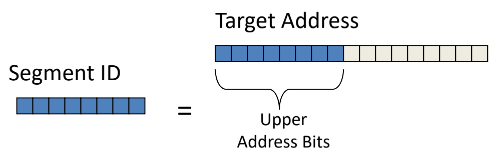
- Traps, address space switches, TLB flushes…
- Performance doesn't necessarily improve with integer performance

Software Isolation

- Load each untrusted module into its own **fault domain**
- Provide **write protection** so that untrusted code can't corrupt data
- **Limit execution** so that untrusted code can't hijack operating system resources or crash containing program

Implementation

- Fault domains are **segments**



- Untrusted code gets **code** and **data** segments
- Write protection
  - Segment matching
  - Address sandboxing

Graphic stolen from Tony Bock

Segment Matching

```
store using target-address
```

Becomes:

```
dedicated-reg <= target-address
scratch-reg <= (dedicated-reg >> shift-reg)
compare scratch-reg segment-reg
trap if not equal
store using dedicated-reg
```

Address Sandboxing

```
store using target-address
```

Becomes:

```
dedicated-reg <= target-address & mask-reg
dedicated-reg <= dedicated-reg | segment-reg
store using dedicated-reg
```

Process Resources

- Need to protect file handles, other process resources.
  - Make operating system aware of fault domains
  - Require fault domains to access process resources through RPC

Implementation

Segment Matching
- Four dedicated registers
- Five extra instructions
- Trap indicates exact instruction that caused failure

Address Sandboxing
- Five dedicated registers
- Two extra instructions
- No indication of failure

Optimization

Compiler customization or **object patching**

Data Sharing

- All data is readable from fault domains
- Pages mapped into multiple fault domains allow cross-fault-domain communication

Cross-Domain RPC

- Generate stubs for interfaces in trusted code.
- Stubs responsible for:
  - Copying arguments
  - Preserving machine state
  - Trapping failures and time-outs
- But no traps or address space switching

Performance

- Encapsulation overhead
- Cross-fault-domain RPC cost
- Effect on user programs

Performance

Sequoia 2000 Query	Untrusted Function Manager Overhead	Software-Enforced Fault Isolation Overhead	Number of Cross-Domain Calls	DEC-MIPS-PIPE overhead (Predicted)
Query 6	1.4%	1.7%	60989	18.6%
Query 7	5.0%	1.8%	121986	38.6%
Query 8	9.0%	2.7%	121978	31.2%
Query 10	9.6%	5.7%	1427024	31.9%

Native Client: A Sandbox for Portable, Untrusted x86 Native Code

- S&P 09'
- Google Inc
  - Bennet Yee, David Sehr, Gregory Dardyk, J. Bradley Chen, Robert Muth, Tavis Ormandy, Shiki Okasaka, Neha Narula, and Nicholas Fullagar
- Best paper award

Everyone uses the web browser

- Browser is the most important tool to get the information in modern society.
  - **Restricted environment** for safety purpose.
    - Interpreter-based sandbox
    - Slow
  - **Native plug-ins** for extra performance or functionality requirements.
    - Fast, versatile
    - Trust-based protection but not safe

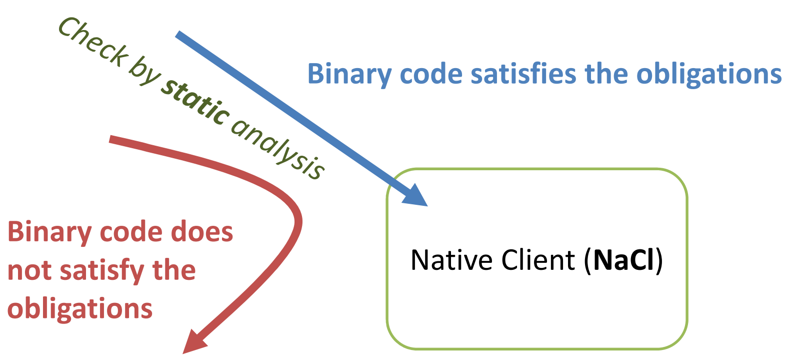
Native code == unsafe?

- *"No fundamental reason why native code should be unsafe"*
  - Traditional difficulties:
    - The problem of deciding the outcome of arbitrary native code with executing it is undecidable.
    - Many unexpected side effects during code execution.
      - Exception, interrupt, racing condition, I/O.
- But a **safe** and **efficient** isolated environment can be created for **restricted** native code.

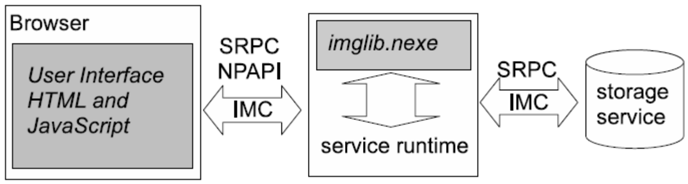
Threat model

- Achieve comparable safety to accepted systems such as JavaScript.
  - Input: arbitrary code and data
    - support multi-threading, inter-module communication
  - Restrictions (**Obligations**):
    - No code page writing: No self-modification code, No JIT
    - No direct system call: No I/O
    - No hardware exception/interrupt: failsafe
    - No ambiguous indirect control flow transfer
    - Isolated direct memory access

Obey me or die



Microkernel-based architecture



Untrusted native code runs in its own private address space created by X86 segment registers (%cs, %ds, %gs, %fs, %ss).

NaCl module and the browser runs in the same process.

All dangerous interfaces are forbidden or monitored by the sandbox (including the instructions modifying the segment registers).

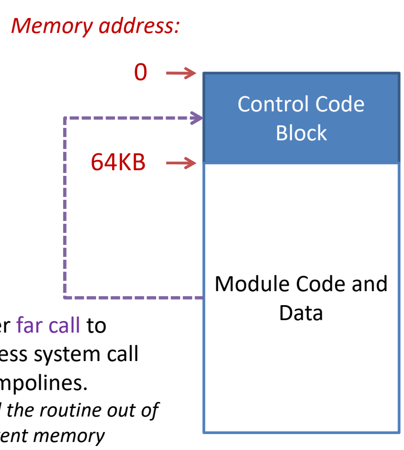
Obligations for control flow transfer

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.

Security properties under obligations

- A static code analysis will ensure:
  - *Data integrity*
    - All memory addresses are within the sandbox
    - Otherwise, a segmentation fault given (%cs, %ds,… are set)
  - *Reliable disassembly*
    - All possible jump targets are known (mandatory 32byte alignment for all jump instructions)
  - *No unsafe instructions*
    - Disassembler is reliable
  - *Control flow integrity*
    - Same reason for reliable disassembly

Load a NaCl module



User far call to access system call trampolines.
(call the routine out of current memory segmentation)
All far calls are under control

1. Verify the module code according to the obligations.
2. Load control code block into memory *(including system call trampolines, thread context data)*.
3. Load the module code and data into memory.
4. Set the segment registers to establish a private memory space *(64KB afterwards, 64KB is the zero offset)*.
5. Transfer the control to the module code.

Applications, tools, and availability

- Applications
  - Allow developer to choose any language in the browser (not just JavaScript).
  - Allow simple, computationally intensive extensions for web applications
  - Binary-level sandbox without a trusted compiler
- Tools: GCC tool chain
  - on Ubuntu Linux, MacOS, Windows XP
- Availability: open source, part of Chrome
  - http://code.google.com/p/nativeclient/

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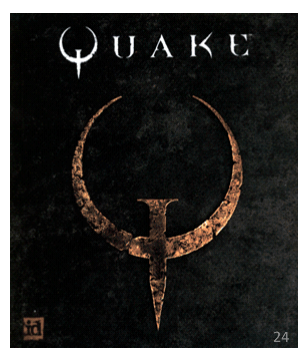
Easier than you imagine

- Ported programs mentioned:
  - SPEC CPU 2000 benchmarks
  - Some graphics computation demo
  - H.264 video decoder
  - Physics simulation system
  - FPS game (Quake)



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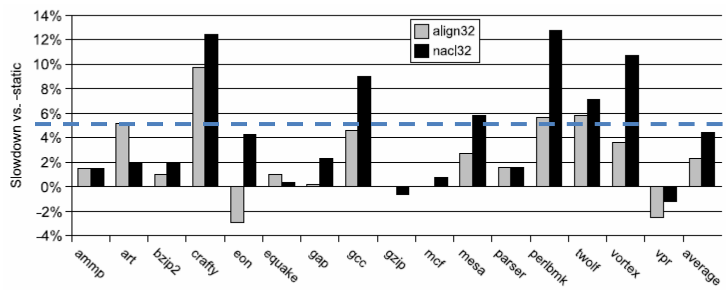
Insignificant performance overhead



Max space overhead is **57.5%** code size increment for gcc in SPEC CPU 2000.

Mandatory alignment for jump targets impacts the instruction cache and increases the code size *(more **significant** if compared to **dynamic linked** executables)*.

