SOURCE-FREE BINARY SOFTWARE
SECURITY RETROFITTING

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Mission-critical Software Environments

- **Myth:** In mission-critical environments, all software is custom, rigorously tested, and formally verified.

- **Reality:** Most mission-critical environments use commodity software and components extensively.
  - Commercial Off-The-Shelf (COTS)
    - widely available to attackers
  - mostly closed-source
    - independent security audit not feasible
  - supports mainstream OSes (Windows) and architectures (Intel)
  - some effort at secure development, but no formal guarantees
2010: Stuxnet infiltrates and destroys Iranian nuclear centrifuges

- **Software exploited:** Siemens Windows apps and PLCs
- Sets Iranian nuclear program back 3-5 years

2012: Shamoon virus destroys 30K power control workstations owned by Saudi Aramco

- **Software exploited:** unpatched Windows NT
- "All told, the Shamoon virus was probably the most destructive attack that the private sector has seen to date." —Leon Panetta

2014: NOAA satellite system compromised

- **Software (potentially) exploited:** Windows Mobile
- "GOES and ESPC did not consistently ensure that Microsoft Windows AutoRun feature was disabled." —Office of Inspector General [OIG-14-025-A]
Top Linux Vulnerabilities of 2014

- **Heartbleed**
  - OpenSSL vulnerability disclosed April 2014
  - allowed anyone to anonymously grab arbitrary data (e.g., master keys) from internet-facing services
  - affected ~66% of all web servers, email servers, chat servers, VPNs, clients, etc.
  - all versions vulnerable since 2011!

- **Shellshock**
  - Bash shell vulnerability disclosed September 2014
  - allowed complete compromise - remote code execution
  - all versions vulnerable since 1989(!)
Are In-house Projects “More Secure”?

- **Idea:** Build all your own custom software in-house from scratch (or contract trusted third-party to build from scratch).
  - expensive, time-consuming
  - error-prone (not built by specialists)
    - 63% of in-house IT projects fail to meet their own specs [Standish Group, 2011 CHAOS Report]
  - poor compatibility, hard to maintain
  - very questionable security assurance
    - vulnerable to insider threats, less tested, shaky design, etc.
    - assurance usually based on myth of “security by obscurity”

- Many COTS advantages
  - constantly updated for new threats
  - tested on a mass scale
  - crafted & maintained by specialists
  - cheaper, mass-produced
Why is Software so Insecure?

- Huge and constantly evolving
  - Windows XP has 40 million lines of code
  - Microsoft Office had 30 million lines in 2006
  - Debian 5.0 has a staggering 324 million lines!
    - contrast: Space shuttle has only 2.5 million moving parts!

- Often written in unsafe languages
  - C, C++, VC++, Visual Basic, scripting languages, ...

- Increasingly sophisticated attacks
  - buffer-overflow
  - direct code-injection
  - return-to-libc
  - return-oriented programming (RoP)
  - implementation disclosure-assisted code-reuse attacks
void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}

8D 45 B8          lea eax,[ebp-48h]
50                 push eax
FF 15 BC 82 2F 01  call <system>
65 72 61 73 65 20  .data “erase”
2A 2E 2A 20        .data “*.*”
61 (x24)           .data “aaaa...”
61 61 61 61        .data “aaaa”
30 FB 1F 00        <addr of buf>

---

top of stack (lower addresses)

buf (64 bytes)

saved EBP (4 bytes)

saved EIP (4 bytes)

argv (4 bytes)

argc (4 bytes)

bottom of stack (higher addresses)
Code-injection Example

void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}

lea eax,[ebp-48h]
push eax
call <system>
.data "erase"
.data "*.*"
.data "aaaaa..."
.data "aaaa"
<addr of buf>

lea eax,[ebp-48h]
push eax
call <system>
erase *.* aaaaaaaaa
aaaaaaaaaaaaaaaaaaaa
<addr of buf>
### Code-injection Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf,argv[1]);
    ...
    return;
}
```

```
8D 45 B8      # lea eax,[ebp-48h]
50            # push eax
FF 15 BC 82 2F 01  # call <system>
65 72 61 73 65 20  # .data "erase"
2A 2E 2A 20    # .data "*.*
61 (x24)       # .data "aaaaa..."
61 61 61 61    # .data "aaaa"
30 FB 1F 00    # <addr of buf>
```

**top of stack (lower addresses)**

- lea eax,[ebp-48h]
- push eax
- call <system>

**bottom of stack (higher addresses)**

- erase *
- aaaaaaaaa
- aaaaaaaaaaaaaaaaaaaaa
- aaaa
- <addr of buf>
- argv (4 bytes)
- argc (4 bytes)
Code-injection Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf,argv[1]);
    ...
    return;
}
```

```
lea eax,[ebp-48h]
push eax
call <system>
.data "erase"
.data "*.*
.data "aaaaa..."
data "aaaa"
<addr of buf>
```

- top of stack (lower addresses)
- bottom of stack (higher addresses)
- argc (4 bytes)
- argv (4 bytes)
- aaaa
- aaaaaaaaaaaaa
- aaaaaaaaaaaaaaaaaaaaa
- <addr of buf>

8D 45 B8 50 FF 15 BC 82 2F 01 65 72 61 73 65 20 2A 2E 2A 61 61 61 61 30 FB 1F 00
Code-injection Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf,argv[1]);
    ...
    return;
}
```

8D 45 B8
50
FF 15 BC 82 2F 01
65 72 61 73 65 20
2A 2E 2A 20
61 (x24)
61 61 61 61
30 FB 1F 00

lea eax,[ebp-48h]
push eax
call <system>
data “erase”
data “*. *”
data “aaaaa...”
data “aaaa”
<addr of buf>

lea eax,[ebp-48h]
push eax
call <system>
erase *.* aaaaaaaa
aaaaaaaaaaaaaaaa

lea eax,[ebp-48h]
push eax
call <system>
<addr of buf>

argv (4 bytes)
<addr of “erase *.* ...”>
bottom of stack (higher addresses)
```c
void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ... return;
}
```
Pernicious Vulnerabilities

[SourceFire Vulnerability Research 2013]

TOP HIGH SEVERITY VULNERABILITIES

- Buffer Errors: 24%
- SQL Injection: 21%
- Access Control: 10%
- Code Injection: 10%
- Everything Else: 13%
- Path Traversal: 3%
- Resource Management: 4%
- Input Validation: 7%
- Not enough info: 8%
- Everything Else: 13%
Defense: DEP + ASLR

- Data Execution Prevention (DEP)
  - set stack memory non-executable (hardware-enforced)
- Address Space Layout Randomization (ASLR)
  - randomize locations of libraries on-load
- Counter-attack
  - don’t insert any code onto the stack
  - jump directly to existing code fragments
  - called a “code-reuse” attack
ROP Example

```c
void main(int argc, char *argv[])
{
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
```

```
61 72 61 73 65 20 .data “erase”
2A 2E 2A 20 .data “*.*”
61 (x58) .data “aaaa…”
BC 82 2F 04 .data <addr1>
61 61 61 61 .data “aaaa”
82 8C 2E 04 .data <addr2>
82 8C 2E 04 .data <addr2>
7F 22 30 04 .data <addr3>
```

Diagram:
- **Top of stack (lower addresses):**
  - caller’s stack frame
  - argc (4 bytes)
  - argv (4 bytes)
  - argc (4 bytes)
  - saved EBP (4 bytes)
  - saved EIP (4 bytes)
- **Bottom of stack (higher addresses):**
  - buf (64 bytes)
void main(int argc, char *argv[]) {
    char buf[64];
    strcpy(buf, argv[1]);
    ...
    return;
}
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2:  add eax, 512
        ret
...

addr1:  mov eax, [init_display]
        call eax
        pop ebx
        ret
...

addr3:  call eax
        ret

top of stack (lower addresses)

erase *.*
aaaaaaa...

aaaa

<addr1>

aaaa

<addr2>

<addr2>

<addr3>
ROP Example

init_display: ...

< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
ret

addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr3: call eax
ret

eax = init_display

top of stack (lower addresses)

erase *.*

aaaaaaa...

aaaa

<addr1>

aaaa

<addr2>

<addr2>

<addr3>
### ROP Example

```plaintext
init_display: ...

< ... 1024 bytes ... >

system: ...

addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr2: add eax, 512
ret

addr3: call eax
ret
```

```

eax = init_display

top of stack (lower addresses)

erase *.*

aaaaaaa...

aaaa

<addr1+5>

aaaa

<addr2>

<addr2>

<addr3>
```
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr2: add eax, 512
ret

addr3: call eax
ret
top of stack (lower addresses)
erase *.*
aaaaaaaa...

aaa
 addr1+5>
aaaa
<addr2>
<addr2>
<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...

addr1: mov eax, [init_display]
call eax
pop ebx
ret
...

addr3: call eax
ret

eax = init_display

top of stack (lower addresses)

erase *.*
aaaaaaa...

aaaa
<addr1+5>
aaaa
<addr2>
<addr2>
<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

ddr2:    add eax, 512
         ret
         ...
ddr1:    mov eax, [init_display]
call eax
call eax
pop ebx
ret
         ...
ddr3:    call eax
         ret

top of stack (lower addresses)
erase *.*
aaaaaaaa...

eax = init_display
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
call eax
pop ebx
ret
...
addr3: call eax
ret

eax = init_display+512
top of stack (lower addresses)
erase *.*

* * * * 

aaaaaaa...
ROP Example

init_display: ...

< ... 1024 bytes ... >

system: ...

addr2: add eax, 512
        ret

addr1: mov eax, [init_display]
call eax
        pop ebx
        ret

addr3: call eax
        ret

eax = init_display+512

top of stack (lower addresses)

erase *.*

aaaaaaa...

aaaa

<addr1+5>

aaaa

<addr2>

<addr2>

<addr3>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2: add eax, 512
ret
...
addr1: mov eax, [init_display]
call eax
pop ebx
ret
...
addr3: call eax
ret

eax = init_display+1024 = system !!!
top of stack (lower addresses)
erase *.*
aaaaaaaaa...

aaaa
<addr1+5>
aaaa
<addr2>
<addr2>
<addr3>
# ROP Example

```
addr1: mov eax, [init_display]
call eax
pop ebx
ret

addr2: add eax, 512
ret

addr3: call eax
ret
```

```
init_display: ...
< ... 1024 bytes ... >
system: ...
```

```
eax = init_display+1024 = system !!!
```

<table>
<thead>
<tr>
<th>top of stack (lower addresses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>erase <em>.</em></td>
</tr>
<tr>
<td>aaaaaaaaa...</td>
</tr>
</tbody>
</table>

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>aaaa</td>
</tr>
<tr>
<td>&lt;addr1+5&gt;</td>
</tr>
<tr>
<td>aaaa</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr2&gt;</td>
</tr>
<tr>
<td>&lt;addr3&gt;</td>
</tr>
</tbody>
</table>
ROP Example

init_display: ...
< ... 1024 bytes ... >
system: ...

addr2:  
add eax, 512
ret

addr1:  
mov eax, [init_display]
call eax
pop ebx
ret

addr3:  
call eax
ret

eax = init_display+1024 = system !!!

top of stack (lower addresses)

erase *.*
aaaaaaa...

aaaa

<addr1+5>
aaaa

<addr2>

<addr2>

<addr3>
Battling Code-reuse Attacks

- **Microsoft’s 2012 BlueHat Competition**
  - Focused on RoP Mitigation
  - $260,000 total for top three solutions
    - Successful attack against 2\textsuperscript{nd} place solution was published two weeks later

- **Google Pwnium Competition**
  - Hacker Pinkie Pie paid $60K for Chrome RoP exploit
  - Google fixes the exploit
  - Five months later, Pinkie Pie finds a new RoP exploit in the fixed Chrome, gets paid another $60K
  - Google fixes the 2\textsuperscript{nd} exploit
  - Five months later, Pinkie Pie finds a yet another (partial) exploit, gets paid another $40K
Secure commodity software AFTER it is compiled and distributed, by automatically modifying it at the binary level.

**My Research: Security Retrofitting**

- **UNTRUSTED**
  - untrusted binary code
  - Binary Rewriter
  - secure binary

- **TRUSTED**
  - Verifier
  - reject
  - deploy
Advantages

- No need to get code-producer cooperation
- No need to customize the OS/VM
- No custom hardware needed (expensive & slow)
- Not limited to any particular source language or tool chain
- Can enforce consumer-specific policies
- Maintainable across version updates (just re-apply rewriter to newly released version)
- Rewriter remains untrusted, so can outsource that task to an untrusted third party!
  - Local, trusted verifier checks results
Challenges

- Software is in purely binary form
  - no source, no debug info, no disassembly

- Diverse origins
  - various source languages, compilers, tools, ...

- Code-producers are uncooperative
  - unwilling to recompile with special compiler
  - unwilling to add/remove features
  - no compliance with any coding standard

- Highly complex binary structure
  - target real-world APIs (e.g., hundreds of thousands of Windows system dll’s and drivers)
  - multi-threaded, multi-process
  - event-driven (callbacks), dynamically linked (runtime loading)
  - heavily optimized (binary code & data arbitrarily interleaved)
Three Major Advances

1) Machine Learning-based Binary Disassembly
   - automatically recovers high-level program structure from binary software product
   - enough to perform automated security retrofitting

2) Native Code Instrumentation
   - method of automatically in-lining extra security checks into untrusted programs

3) Formal, Automated, Machine-validation
   - automatically PROVES (mathematically) that retrofitted software is immune to certain classes of attacks
Scope & Limitations

- Policies we enforce:
  - **Safety Policies** – “bad things” must not happen
    - access control policies
    - API trace policies (permissible API call sequences)

- Policies Outside our Scope:
  - **Liveness** – “good things” must eventually happen
    - Example: Availability
  - **Confidentiality** – secrets must not be disclosed (e.g., possibly disclosed by inaction)
First Step: Disassembly

- Disassemble this hex sequence
- Turns out x86 disassembly is an undecidable problem!

<table>
<thead>
<tr>
<th>Valid Disassembly</th>
<th>Valid Disassembly</th>
<th>Valid Disassembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF E0</td>
<td>jmp eax</td>
<td>FF E0</td>
</tr>
<tr>
<td>5B</td>
<td>pop ebx</td>
<td>5B</td>
</tr>
<tr>
<td>5D</td>
<td>pop ebp</td>
<td>5D</td>
</tr>
<tr>
<td>C3</td>
<td>retn</td>
<td>C3</td>
</tr>
<tr>
<td>0F 88 52</td>
<td>jcc</td>
<td>0F 88</td>
</tr>
<tr>
<td>0F 84 EC</td>
<td>mov</td>
<td>88 52 0F</td>
</tr>
<tr>
<td>8B ...</td>
<td></td>
<td>84 EC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8B ...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0F 88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0F 84 EC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8B ...</td>
</tr>
</tbody>
</table>
Disassembly Intractability

- Even the best reverse-engineering tools cannot reliably disassemble even standard COTS products
- Example: IDA Professional Disassembler (Hex-rays)

<table>
<thead>
<tr>
<th>Program Name</th>
<th>Disassembly Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsoft Foundation Class Lib (mfc42.dll)</td>
<td>1216</td>
</tr>
<tr>
<td>Media Player (mplayerc.exe)</td>
<td>474</td>
</tr>
<tr>
<td>Avant Web Browser (RevelationClient.exe)</td>
<td>36</td>
</tr>
<tr>
<td>VMWare (vmware.exe)</td>
<td>183</td>
</tr>
</tbody>
</table>
### innovation: De-shingling Disassembly

<table>
<thead>
<tr>
<th>Hex</th>
<th>Disassembled</th>
<th>Invalid</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Byte Sequence: FF E0 5B 5D C3 0F 88 B0 50 FF FF 8B

<table>
<thead>
<tr>
<th>Included Disassembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>jmp eax</td>
</tr>
<tr>
<td>pop</td>
</tr>
<tr>
<td>L1: pop</td>
</tr>
<tr>
<td>retn</td>
</tr>
<tr>
<td>jcc</td>
</tr>
<tr>
<td>L2: mov</td>
</tr>
<tr>
<td>loopne</td>
</tr>
<tr>
<td>jmp L1</td>
</tr>
<tr>
<td>mov</td>
</tr>
<tr>
<td>jmp L2</td>
</tr>
</tbody>
</table>
Problem: Pointers

- We just rearranged everything. Pointers will all point to the wrong places.
  - can’t reliably identify pointer data in a sea of unlabeled bytes

- Two kinds of relevant pointers:
  - pointers to static data bytes among the code bytes
  - pointers to code (e.g., method dispatch tables)
Preserving Static Data Pointers

- Put the de-shingled code in a NEW code segment.
  - Set it execute-only (non-writable)
- Leave the original .text section
  - Set it read/write-only (non-execute)
Almost half of all jump instructions in real x86 binaries compute their destinations at runtime.

- Exercise: Why? Examples?
- ...
- ...
- ...

Must ensure these jumps target new code locations instead of old.

- impossible to statically predict their destinations
Preserving Code Pointers

- Almost half of all jump instructions in real x86 binaries compute their destinations at runtime.
  - all method calls (read method dispatch table)
  - all function returns (read stack)
  - almost all API calls (read linker tables)
  - pointer encryption/decryption logic for security

- Must ensure these jumps target new code locations instead of old.
  - impossible to statically predict their destinations
Solution: Control-flow Patching

- Create a lookup table that maps old code addresses to new ones at runtime.
- Add instructions that consult the lookup table before any computed jump.

Original

| jump eax |

Rewritten

| jump table[eax] |
Optimizing

- With these three tricks we can successfully transform (most) real-world COTS binaries even without knowing how they work or what they do!
  - de-shingling disassembly
  - static data preservation
  - control-flow patching

- Limitations
  - runtime code modification conservatively disallowed
  - computing data pointers from code pointers breaks
  - These are compatibility limitations not security limitations.

- But it’s prohibitively inefficient (increases code size ~700%)
  - need to optimize the approach
Optimization Philosophy

1. If the optimization fails, we might get broken code but never unsafe code.

2. The optimizations only need to work for non-malicious, non-vulnerable code fragments.
   - If the code fragment is malicious or vulnerable, we don’t want to preserve it!
## Optimization #1: Pruning Shingles

- Lots of extra overlapping information
- Can we prune our disassembly tree?

<table>
<thead>
<tr>
<th>Hex</th>
<th>Path 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>jmp eax</td>
</tr>
<tr>
<td>E0</td>
<td>pop</td>
</tr>
<tr>
<td>5B</td>
<td>L1: pop</td>
</tr>
<tr>
<td>5D</td>
<td>retn</td>
</tr>
<tr>
<td>C3</td>
<td>jcc</td>
</tr>
<tr>
<td>0F</td>
<td></td>
</tr>
<tr>
<td>88</td>
<td></td>
</tr>
<tr>
<td>B0</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td></td>
</tr>
<tr>
<td>FF</td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td>L2: mov</td>
</tr>
</tbody>
</table>

![Hex Path Diagram](image-url)
Insight: Distinguishing real code bytes from data bytes is a “noisy word segmentation problem”.

- **Word segmentation**: Given a stream of symbols, partition them into words that are contextually sensible. [Teahan, 2000]
- **Noisy word segmentation**: Some symbols are noise (data).

**Machine Learning based disassembler**

- Based on $k$th-order Markov model
- Estimate the probability of the sequence $B$:

$$p(B|M_\alpha) = -\log \prod_{i=1}^{\|B\|} p(b_i|b_{i-1}^{i-k}, M_\alpha)$$


Disassembler Stats

# of instructions identified by our disassembler but not by IDA Pro
## PPM Disassembly Stats

<table>
<thead>
<tr>
<th>PPM Disassembler</th>
<th>False Negative</th>
<th>False Positive</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>7zFM</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>notepad</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>DosBox</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>WinRAR</td>
<td>0</td>
<td>39</td>
<td>99.982%</td>
</tr>
<tr>
<td>mulberry</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>scummvm</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>emule</td>
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<td>99.988%</td>
</tr>
<tr>
<td>Mfc42</td>
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<td>47</td>
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</tr>
<tr>
<td>mplayerc</td>
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<td>307</td>
<td>99.963%</td>
</tr>
<tr>
<td>revClient</td>
<td>0</td>
<td>71</td>
<td>99.893%</td>
</tr>
<tr>
<td>vmware</td>
<td>0</td>
<td>45</td>
<td>99.988%</td>
</tr>
</tbody>
</table>
Optimization #2: Lookup Table Compression

- Idea: Overwrite the old code bytes with the lookup table.
  - PPM disassembler identifies most code bytes
  - Also identifies subset that are possible computed jump destinations.
  - Overwrite those destinations with our lookup table.

<table>
<thead>
<tr>
<th>Original</th>
<th>Rewritten</th>
</tr>
</thead>
<tbody>
<tr>
<td>call eax</td>
<td>cmp [eax], 0xF4</td>
</tr>
<tr>
<td></td>
<td>cmovz eax, [eax+1]</td>
</tr>
<tr>
<td></td>
<td>call eax</td>
</tr>
</tbody>
</table>
Applications of our Rewriter

- Three Applications
  - Binary randomization for RoP Defense (STIR)
  - Opaque Control-Flow Integrity (O-CFI)
  - Machine-certified Software Fault Isolation (Reins)
RoP Defense Strategy

- RoP is one example of a broad class of attacks that require attackers to know or predict the location of binary features.

**Defense Goal**

Frustrate such attacks by randomizing the feature space.
**STIR – Self-Transforming Instruction Relocation**

**O-CFI – Opaque Control-Flow Integrity**

- Randomly reorder the program’s internal layout every time the program loads
  - Attacker cannot reliably locate code addresses for code-reuse attacks
  - Astronomically low chance of attack success
  - Exact attack probability is *mathematically computable* as an entropy calculation
STIR/O-CFI Implementation

- Supports Windows PE and Linux ELF files
- Tested on SPEC2000 benchmarks and the entire coreutils chain for Linux
- 1.5% program runtime efficiency overhead on average
  - Won 2nd place in the NYU-Poly AT&T Best Applied Security Paper of the Year competition
  - Conceals code reachability info to defeat even advanced attackers who can inspect portions of the randomized program memory image!
Gadget Reduction
Windows STIR Runtime Overhead

-10%  -5%  0%  5%  10%  15%  20%

gzip  vpr  mcf  parser  gap  bzip2  twolf  mesa  art  equake
Linux STIR Runtime Overhead

-15%
-10%
-5%
0%
5%
10%
15%
Control-Flow Safety

- Used PittSField approach [McCcamant & Morrisett, 2006]
  - Break binaries into chunks
    - chunk – fixed length (16 byte) basic blocks
  - Only one extra guard instruction necessary
  - Mask instruction only affects violating flows

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<tr>
<td></td>
<td>cmp [eax], 0xF4</td>
</tr>
<tr>
<td></td>
<td>cmovz eax, [eax+1]</td>
</tr>
<tr>
<td></td>
<td>and eax, 0x0FFFFFFF0</td>
</tr>
<tr>
<td>call eax</td>
<td>call eax</td>
</tr>
</tbody>
</table>
# Jump Table w/ Masking

## Original Instruction:

| .text:0040CC9B | FF DO | call eax |

## Original Possible Target:

| .text:00411A40 | 5B | pop ebp |

## Rewritten Instructions:

| .tnew:0052A1C0 | 80 38 F4 | cmp byte ptr [eax], F4h |
| .tnew:0052A1C3 | 0F 44 40 01 | cmovz eax, [eax+1] |
| .tnew:0052A1CE | FF D0 | and eax, 0x0FFFFFFF0 |

## Rewritten Jump Table:

| .told:00411A40 | F4 B9 4A 53 00 | F4 dw 0x534AB0 |

## Rewritten Target:

| .tnew:00534AB0 | 5B | pop ebp |
Selected References


