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
Critical Infrastructure: Critically Insecure

- 2010: Stuxnet infiltrates and destroys Iranian nuclear centrifuges
  - **Software exploited**: Siemens Windows apps and PLCs
  - Sets Iranian nuclear program back 3-5 years

- 2020: Hundreds of US infrastructure networks penetrated by SolarWinds hack
  - **Software exploited**: Microsoft Exchange
  - Supply-line hack infects network monitors at Pentagon, Treasury, Microsoft, Intel, Cisco, ...

- 2021: Colonial Oil Pipeline Hack
  - **Software exploited**: Unpatched Windows VPN
  - Leaked password to unused account, no multifactor authentication, no data backups
  - weeks of oil shortages in eastern US, tens of thousands of miles of pipeline checks

- 2010: Stuxnet infiltrates and destroys Iranian nuclear centrifuges
  - **Software exploited**: Siemens Windows apps and PLCs
  - Sets Iranian nuclear program back 3-5 years
(In)famous Linux Vulnerabilities

- **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 500 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-overrun
  - direct code-injection
  - return-to-libc
  - return-oriented programming (RoP)
  - implementation disclosure-assisted code-reuse attacks
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>
```

```
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>
```

<table>
<thead>
<tr>
<th>Argument</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>argc</td>
<td>4 bytes</td>
</tr>
<tr>
<td>argv</td>
<td>4 bytes</td>
</tr>
<tr>
<td>buf</td>
<td>64 bytes</td>
</tr>
<tr>
<td>saved EBP</td>
<td>4 bytes</td>
</tr>
<tr>
<td>saved EIP</td>
<td>4 bytes</td>
</tr>
<tr>
<td>argc</td>
<td>4 bytes</td>
</tr>
<tr>
<td>argv</td>
<td>4 bytes</td>
</tr>
</tbody>
</table>

bottom of stack (higher addresses)
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 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 *.* aaaaaaaaaaaaaaaaaaaaaaaaa
<addr of buf>

argc (4 bytes)
argv (4 bytes)
bottom of stack (higher addresses)
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>

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>
erase *.* aaaaaaaa
aaaaaaaaaaaaaaaa
 aaa
 <addr of buf>

argc (4 bytes)
argv (4 bytes)
bottom of stack (higher addresses)
**Code-injection Example**

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

---

**Assembly Code:**

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

---

**Stack Diagram:**

- **Top of Stack (Lower Addresses):**
  - lea eax,[ebp-48h]
  - push eax
  - call <system>
  - `erase *.* aaaaaaaa aaaaaaaaaaaaaaaaaa`

- **Bottom of Stack (Higher Addresses):**
  - `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;
}
```

**Assemblers**

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

**Top of stack (lower addresses)**

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

**Bottom of stack (higher addresses)**

- argv (4 bytes)
- <addr of "erase *.* ..."
Code-injection Example

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>
Pernicious Vulnerabilities
[SourceFire Vulnerability Research 2013]

TOP HIGH SEVERITY VULNERABILITIES

- Buffer Errors: 24%
- SQL Injection: 21%
- Access Control: 10%
- Code Injection: 10%
- Not enough info: 8%
- Input Validation: 7%
- Resource Management: 4%
- Path Traversal: 3%
- 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;
}
```

data "erase"
data ".*.*"
data "aaaa..."
data <addr1>
data <addr2>
data <addr2>
data <addr3>

top of stack (lower addresses)

buf (64 bytes)
saved EBP (4 bytes)
saved EIP (4 bytes)
argv (4 bytes)
argc (4 bytes)
caller’s stack frame
bottom of stack (higher addresses)
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>
```

top of stack (lower addresses)
```
erase *. *
aaaaaaa...
```

```
<addr1>
<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 *.*
 aaaaaaaaa...

aaaa

<addr1>

aaaa

<addr2>

<addr2>

<addr3>
ROP Example

\text{init\_display: ...}
\text{< \ldots 1024 \text{ bytes ...} >}
\text{system: ...}
\text{addr2: add eax, 512}
\text{ret}
\text{ ...}
\text{addr1: mov eax, [init\_display]}
\text{call eax}
\text{pop ebx}
\text{ret}
\text{ ...}
\text{addr3: call eax}
\text{ret}

\text{eax = init\_display}

\text{top of stack (lower addresses)}
\text{erase *.*}
\text{aaaaaaa...}

\begin{array}{c}
\text{aaaa}
\end{array}
\begin{array}{c}
\text{<addr1>}
\end{array}
\begin{array}{c}
\text{aaaa}
\end{array}
\begin{array}{c}
\text{<addr2>}
\end{array}
\begin{array}{c}
\text{<addr2>}
\end{array}
\begin{array}{c}
\text{<addr3>}
\end{array}
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 *.*
aaaaaaaa...

<addr1+5>

<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

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

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

<addr1+5>
<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: ...

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

eax = init_display+512

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 *.*
aaaaaaaa...

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

**init_display:** ...

< ... 1024 bytes ... >

**system:** ...

**addr2:**

```assembly
mov eax, [init_display]
call eax
pop ebx
ret
```

**addr1:**

```assembly
add eax, 512
ret
```

**addr3:**

```assembly
call eax
ret
```

---

**eax = init_display+1024 = system !!!**

**top of stack (lower addresses):**

- `erase *.*`
- `aaaaaaa...`

```
| addr1+5 > |
| <addr2 > |
| <addr2 > |
| <addr3 > |
```

---

- `aaaa`
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+1024 = system !!!

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
...
add1: 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 2nd 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 2nd exploit
  - Five months later, Pinkie Pie finds a yet another (partial) exploit, gets paid another $40K
Code-reuse Conflict Timeline

- '96: stack smashing
- '97: return into libc
- '98: ASLR bypass
- '99: Borrowed Code
- '00: ROP
- '01: ROP w/o returns
- '02: JIT spraying
- '03: ROP on ARM & SPARC
- '04: Blind ROP
- '05: side-channel attacks on div. code
- '06: Gadget-stitching
- '07: JIT ROP++
- '08: JIT spray on ARM
- '09: x86 ROP
- '10: Opaque CFI
- '11: Isomeron
- '12: ROPecker
- '13: SafeDispatch
- '14: Oxymoron
- '15: XnR Memory

Stackguard: stack layout randomization
ASLR: stack layout randomization
PropPolce: instruction set randomization
XFI: heap randomization
CFI: G-Free
ASLP: librand, bin-CFI
shadow stacks: binary stirring
randomization layout in-situ
CoFIR: Modular CFI & CFI for JITs
CPI: Forward-Edge CFI
Secure commodity software AFTER it is compiled and distributed, by automatically modifying it at the binary level.
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) Heuristic-free & Machine Learning-based Binary Disassembly
   - automatically recovers high-level program structure from binary software product
   - Superset Disassembly (NDSS’18): recover a superset of the control-flow graph
   - Finding the Undecidable Path (PAKDD’14): Optimize CFG via machine learning

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
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</td>
</tr>
<tr>
<td>8B ...</td>
<td></td>
<td>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: Superset Disassembly

<table>
<thead>
<tr>
<th>Hex</th>
<th>Included Disassembly</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>L2: mov</td>
</tr>
<tr>
<td>88</td>
<td>loopne</td>
</tr>
<tr>
<td>B0</td>
<td>jmp L1</td>
</tr>
<tr>
<td>50</td>
<td>mov</td>
</tr>
<tr>
<td>FF</td>
<td>jmp L2</td>
</tr>
<tr>
<td>FF</td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td></td>
</tr>
</tbody>
</table>

Byte Sequence: FF E0 5B 5D C3 0F 88 B0 50 FF FF 8B
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)
Preserving Code Pointers

- 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.

<table>
<thead>
<tr>
<th>Original</th>
<th>Rewritten</th>
</tr>
</thead>
<tbody>
<tr>
<td>jump eax</td>
<td>jump table[eax]</td>
</tr>
</tbody>
</table>
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
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: De-shingling

- 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>
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</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>
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 $B$:

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


## 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>
<td>0</td>
<td>117</td>
<td>99.988%</td>
</tr>
<tr>
<td>Mfc42</td>
<td>0</td>
<td>47</td>
<td>99.987%</td>
</tr>
<tr>
<td>mplayerc</td>
<td>0</td>
<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.
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

<table>
<thead>
<tr>
<th>Software</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosbox</td>
<td>99.99%</td>
</tr>
<tr>
<td>Notepad++</td>
<td>99.99%</td>
</tr>
<tr>
<td>gzip</td>
<td>99.98%</td>
</tr>
<tr>
<td>vpr</td>
<td>99.98%</td>
</tr>
<tr>
<td>mdf</td>
<td>99.98%</td>
</tr>
<tr>
<td>parser</td>
<td>99.98%</td>
</tr>
<tr>
<td>gap</td>
<td>99.98%</td>
</tr>
<tr>
<td>bzip2</td>
<td>99.98%</td>
</tr>
<tr>
<td>twolf</td>
<td>99.98%</td>
</tr>
<tr>
<td>mesa</td>
<td>99.98%</td>
</tr>
<tr>
<td>art</td>
<td>99.98%</td>
</tr>
<tr>
<td>quake</td>
<td>99.98%</td>
</tr>
</tbody>
</table>
Windows STIR Runtime Overhead

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

gzip  vpr  mcf  parser  gap  bzip2  twolf  mesa  art  equake
Custom Safety Policy Enforcement with Machine-provable Assurance

1. Untrusted binary code
2. Binary Rewriter
3. Verifier
4. Deploy or reject
5. Secure binary
6. Safety policy
An API Policy

**function** conn = ws2_32::connect(
   SOCKET, struct sockaddr_in *, int) -> int;

**function** cfile = kernel32::CreateFileW(
   LPCWSTR, DWORD, DWORD, LPSECURITY_ATTRIBUTES,
   DWORD, DWORD, HANDLE) -> HANDLE WINAPI;

**event** e1 = conn(_, {sin_port=25}, _) -> 0;
**event** e2 = cfile("*.exe", _, _, _, _, _, _) -> _;

**policy** = e1* + e2*;

**Policy:** Applications may not both open email connections and create files whose names end in "*.exe".
Reference Monitor In-lining

- In-line security checks as rewriting progresses
  - checks uncircumventable due to control-flow and memory safety
  - ensures *complete mediation*

![Diagram of Rewritten Binary, Rewritten Code, Inline Reference Monitor, System Libraries]

66
REINS - "Rewriting and In-lining System"

- Prototype targets full Windows XP/7/8 OS
  - significantly harder than Linux
- 2.4% average runtime overhead
- 15% average process size increase
- Tested on SPEC2000, malware, and large GUI binaries
  - Eureka email client and DOSBox, much larger than any previous implementation had accomplished
  - won Best Student Paper at ACSAC
Control-Flow Safety

- Used PittSField approach [McCamant & 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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<td>cmp [eax], 0xF4</td>
</tr>
<tr>
<td></td>
<td>cmovz eax, [eax+1]</td>
</tr>
<tr>
<td></td>
<td>and eax, 0x0FFFFFFFF0</td>
</tr>
<tr>
<td></td>
<td>call eax</td>
</tr>
</tbody>
</table>
### Jump Table w/ Masking

**Original Instruction:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text:0040CC9B</td>
<td>FF DO</td>
<td>call eax</td>
</tr>
</tbody>
</table>

**Rewritten Instruction:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.tnew:0052A1C0</td>
<td>80 38 F4</td>
<td>cmp byte ptr [eax], F4h</td>
</tr>
<tr>
<td>.tnew:0052A1C3</td>
<td>0F 44 40 01</td>
<td>cmovz eax, [eax+1]</td>
</tr>
<tr>
<td>.tnew:0052A1C7</td>
<td>FF D0</td>
<td>and eax, 0x0FFFFFFF0</td>
</tr>
<tr>
<td>.tnew:0052A1CE</td>
<td></td>
<td>call eax</td>
</tr>
</tbody>
</table>

**Original Possible Target:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text:00411A40</td>
<td>5B</td>
<td>pop ebp</td>
</tr>
</tbody>
</table>

**Rewritten Possible Target:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.told:00411A40</td>
<td>F4 B9 4A 53 00</td>
<td>F4 dw 0x534AB0</td>
</tr>
</tbody>
</table>

**Rewritten Jump Table:**

<table>
<thead>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.tnew:00534AB0</td>
<td>5B</td>
<td>pop ebp</td>
</tr>
</tbody>
</table>

**Rewritten Target:**

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<tbody>
<tr>
<td>.tnew:00534AB0</td>
<td></td>
<td>pop ebp</td>
</tr>
</tbody>
</table>
Next Two Lectures

- **Wednesday:** Some of our most recent work for Navy and DARPA
  - automated binary software *attack surface reduction* using technologies underlying STIR

- **Monday:** The sciences behind it all...
  - Theory of In-lined Reference Monitors (IRMs)
  - Computability theory and Enforceability theory


