Make JIT-Spray Great Again

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JIT Overview

JIT

Just-In-Time Compilation (JIT)

- Generate native machine code from higher-level language

  JavaScript
  PHP
  Java
  ActionScript
  ...

  → x86_32, x86_64, ARM, AArch64

- Performance gain compared to interpreted execution

Just-In-Time Compilation (JIT)

- Several compilers and optimization layers

JS:

- Baseline, IonMonkey
- ChakraCore (2 Tier JIT)
- Baseline, DFG, FTL
- TurboFan

Java: HotSpot JIT

PHP: HHVM JIT

ActionScript: NanoJIT

Linux Kernel: eBPF

.Net: RyuJIT

JIT

Just-In-Time Compilation (JIT)

- Several compilers and optimization layers

JS: Baseline, Baseline ... HotSpot JIT ... HHVM JIT

More than 13 compilation engines.
What could possibly go wrong?

ActionScript: NanoJIT

Linux Kernel: eBPF

.Net: RyuJIT

JIT-Spray (x86)

JIT-Spray

1. Hide native instructions in constants of high-level language

```
c =  0xa8909090
c += 0xa8909090
```

x86 Disassembly @ offset 1

```
01: 90     nop
02: 90     nop
03: 90     nop
04: a805   test al, 5
06: 90     nop
07: 90     nop
08: 90     nop
```

Emitted JIT Code

```
00: b8909090a8  mov eax, 0xa8909090
05: 05909090a8  add eax, 0xa8909090
```

JIT-Spray

1. Hide native instructions in constants of high-level language

2. Force allocations to predictable address regions

```
function JIT(){
   c =  0xa8909090
   c += 0xa8909090
}

While (not address_hit){
   createFuncAndJIT()
}
```

predictable?!

```
0x20202021: 90     nop
0x20202022: 90     nop
0x20202023: 90     nop
0x20202024: a805   test al, 5
0x20202025: 90     nop
0x20202026: 90     nop
0x20202027: 90     nop
```

JIT-Spray

1. Hide native instructions in constants of high-level language

2. Force allocations to predictable address regions

```
function JIT(){
```

predictable?!

Used to bypass ASLR and DEP
No info leak and code reuse necessary
→ Memory corruptions are easier to exploit

```
}
```

Prominent JIT-Spray on x86

JIT-Spray

Flash JIT-Spray (Dionysus Blazakis, 2010)

- Targets ActionScript (Tamarin VM)
- Long XOR sequence gets compiled to XOR instructions

```
var y = (
    0x3c54d0d9 ^
    0x3c909058 ^
    0x3c59f46a ^
    0x3c90c801 ^
```

→

```
03470069    B8 D9D0543C    MOV EAX,3C54D0D9
0347006E    35 5890903C    XOR EAX,3C909058
03470073    35 6AF4593C    XOR EAX,3C59F46A
03470078    35 01C8903C    XOR EAX,3C90C801
```

- First of its kind known to public

JIT-Spray

Writing JIT Shellcode (Alexey Sintsov, 2010)

- Nice methods to ease and automate payload generation:
  - split long instructions into instructions <= 3 bytes

```
; 5 bytes
mov ebx, 0xb1b2b3b4
```

```
mov ebx, 0xb1b2xxxx ; 3 bytes
mov bh, 0xb3        ; 2 bytes
mov bl, 0xb4        ; 2 bytes
```

  - semantic nops which don't change flags

```
00: b89090906a   mov eax, 0x6a909090
05: 05909090a8   add eax, 0xa8909090
```

```
03: 90     nop
04: 6a05   push 5
```

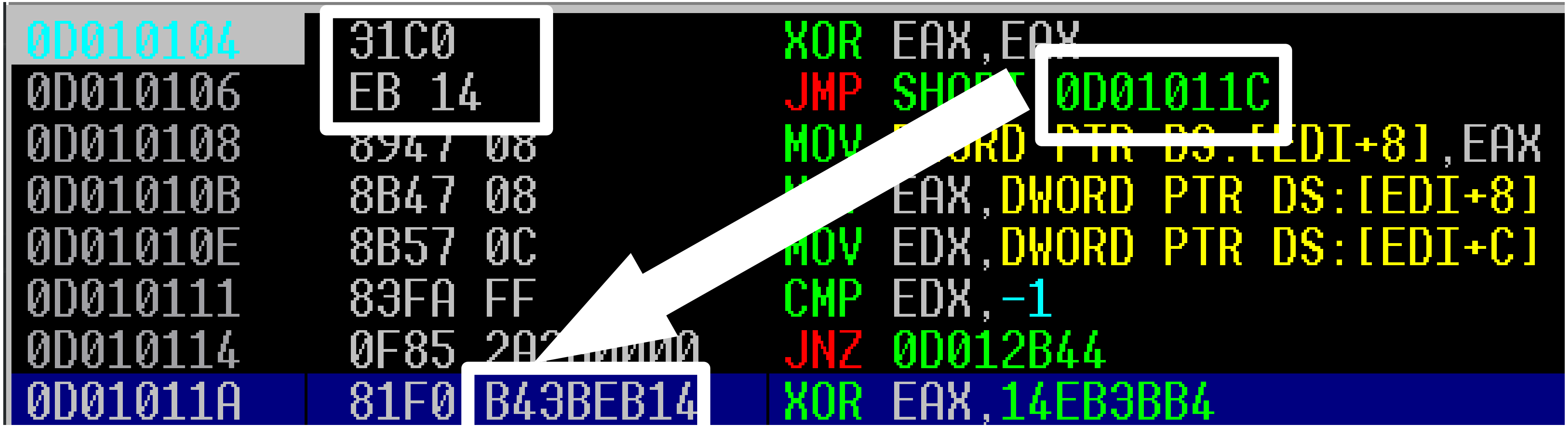
JIT-Spray

JIT-Spray Attacks & Advanced Shellcode
(Alexey Sintsov, 2010)

- JIT-Spray in Apple Safari on Windows possible:
  - use two of four immediate bytes as payload
  - connect payload bytes with short jumps (stage0)
  - copy stage1 payload to RWX JIT page and jump to it

JIT-Spray

JIT-Spray Attacks & Advanced Shellcode
(Alexey Sintsov, 2010)



JIT-Spray

Attacking Clientside JIT Compilers
(Chris Rohlf & Yan Ivnitskiy, 2011)

- In depth analysis of LLVM and Firefox JIT engines
- JIT-Spray techniques (i.e., with floating point values)
- JIT gadget techniques (gaJITs)
- Comparison of JIT hardening measurements

JIT-Spray

Attacking Clientside JIT Compilers (Chris Rohlf & Yan Ivnitskiy, 2011)

- In d… nes
- JIT-S… values)
- JIT g…
- Com…

	V8	IE9	Jaeger Monkey	Trace Monkey	LLVM	JVM	Flash / Tamarin
Secure Page Permissions	✗	✓	✗	✗	✗	✗	✗
Guard Pages	✓	✗	✗	✗	✗	✗	✗
JIT Page Randomization	✓	✓	✗	✗	✗	✗	✗
Constant Folding	✗	✗	✗	✗	✗	✗	✗
Constant Blinding	✓	✓	✗	✗	✗	✗	✗
Allocation Restrictions	✓	✓	✗	✗	✗	✗	✗
Random NOP Insertion	✓	✓	✗	✗	✗	✗	✗
Random Code Base Offset	✓	✓	✗	✗	✗	✗	✗

JIT-Spray

Flash JIT – Spraying info leak gadgets (Fermin Serna, 2013)

- Bypass ASLR and random NOP insertion:
  - spray few instructions to predictable address – prevents random NOPS
  - trigger UAF bug and call JIT gadget
  - JIT gadget writes return address into heap spray, continue execution in JS
- Mitigated with constant blinding in Flash 11.8

JIT-Spray

Exploit Your Java Native Vulnerabilities on Win7/JRE7 in One Minute (Yuki Chen, 2013)

- JIT-Spray on Java Runtime Environment
- 3 of 4 bytes of one constant usable as payload
- Spray multiple functions to hit predictable address (32-bit)
- Jump to it with EIP control

JIT-Spray

Exploit Your Java Native Vulnerabilities on Win7/JRE7 in One Minute (Yuki Chen, 2013)

```
public int spray(int a) {
    int b = a;
    b ^= 0x90909090;
    b ^= 0x90909090;
    b ^= 0x90909090;
    return b;
}
```

```
0x01c21507: cmp    0x4(%ecx),%eax
0x01c2150a: jne    0x01bbd100       ;
0x01c21510: mov    %eax,0xffffc000(%esp)
0x01c21517: push   %ebp
0x01c21518: sub    $0x18,%esp
0x01c2151b: xor    $0x90909090,%edx
0x01c21521: xor    $0x90909090,%edx
0x01c21527: xor    $0x90909090,%edx
 ...
 0x01c21539: ret
```

(32-bit)

ASM.JS JIT-Spray on OdinMonkey (x86)

ASM.JS

- Strict subset of JS
- OdinMonkey: Ahead-Of-Time (AOT) compiler in Firefox
- Appeared in 2013 in Firefox 22
- No need to frequently execute JS as in traditional JITs
- Generates binary blob with native machine code
- ASM.JS JIT-Spray possible until Firefox 52 (2017) (CVE-2017-5375, CVE-2017-5400)

ASM.JS

Simple ASM.JS module

```
function asm_js_module(){
    "use asm"
    function asm_js_function(){
        var val = 0xc1c2c3c4;
        return val|0;
    }
    return asm_js_function
}
```

ASM.JS

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```
function asm_js_module(){
    'use asm'
    function asm_js_function(){
        var val = 0xc1c2c3c4;
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}
```

- Prolog directive

ASM.JS

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    }
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}
```

- Prolog directive
- ASM.JS module body

ASM.JS

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    "use asm"
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        return val|0;
    }
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}
```

- Prolog directive
- ASM.JS module body
- Your “calculations”

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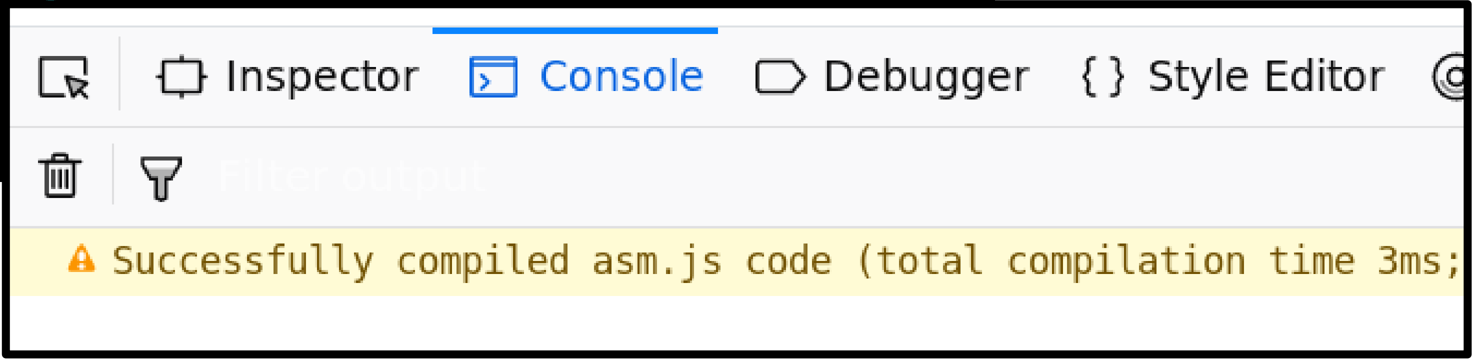
Simple ASM.JS module

```
function asm_js_module(){
    "use asm"
    function asm_js_function(){
        var val = 0xc1c2c3c4;
        return val|0;
    }
}
```



- Prolog directive
- ASM.JS module body
- Your "calculations"

ASM.JS

Inject Code to Predictable Addresses

- Request ASM.JS module several times

```
modules = []
for (i=0; i<=0x2000; i++){
        modules[i] = asm_js_module()
}
```

ASM.JS

Inject Code to Predictable Addresses

```
"use asm"
function asm_is_function(){
    var val = 0xc1c2c3c4;
    return val|0;
}
```

Value appears in machine code

```
10100023 b8c4c3c2c1        mov     eax,0C1C2C3C4h
10100028 6690              xchg    ax,ax
1010002a 83c404            add     esp,4
1010002d c3                ret
```

ASM.JS

Inject Code to Predictable Addresses

- Unblinded constant **0xc1c2c3c4** appears many times

```
09bf9024  c1c2c3c4 c4839066 0d8bc304 00000000
0a720024  c1c2c3c4 c4839066 0d8bc304 0a721000
0a730024  c1c2c3c4 c4839066 0d8bc304 0a731000
0a740024  c1c2c3c4 c4839066 0d8bc304 0a741000
0a750024  c1c2c3c4 c4839066 0d8bc304 0a751000
0a760024  c1c2c3c4 c4839066 0d8bc304 0a761000
...
```

ASM.JS

Inject Code to Predictable Addresses

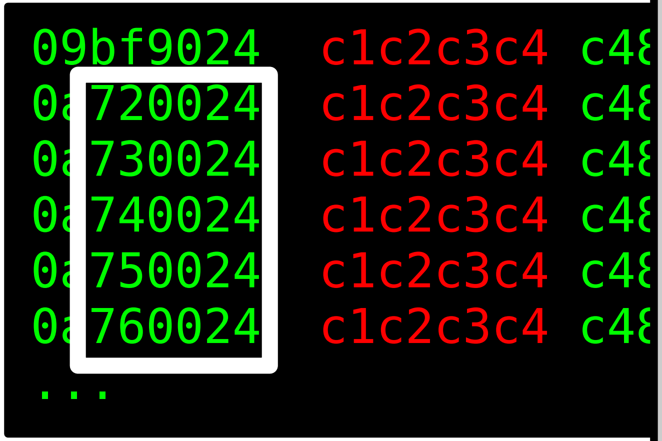
- Unblinded constant **0xc1c2c3c4** appears many times

```
09bf9024  c1c2c3c4
0a720024  c1c2c3c4
0a730024  c1c2c3c4
0a740024  c1c2c3c4
0a750024  c1c2c3c4
0a760024  c1c2c3c4
...
```

– many module requests yield many copies

Inject Code to Predictable Addresses

- Unblinded constant **0xc1c2c3c4** appears many times



– many module requests yield many copies

– aligned to predictable addresses

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Inject Code to Predictable Addresses

- Unblinded constant **0xc1c2c3c4** appears many times

```
09bf9024  c1c2c3c4 c48
0a720024  c1c2c3c4 c48
0a730024  c1c2c3c4 c48
0a740024  c1c2c3c4 c48
0a750024  c1c2c3c4 c48
0a760024  c1c2c3c4 c48
...
```

– many module requests yield many copies

– aligned to predictable addresses

→ **ASM.JS JIT-Spray unlocked**

ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

```
"use asm"
function asm_js_function(){
    // attacker controlled
    // ASM.JS code
}
return asm_js_function
```

How to inject arbitrary code?

ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

- Arithmetic instructions

```
"use asm"
function asm_js_function(){
    var val = 0;
    val = (val + 0xa8909090)|0;
    val = (val + 0xa8909090)|0;
    val = (val + 0xa8909090)|0;
    // ...
    return val|0;
}
```

```
01: 90     nop
02: 90     nop
03: 90     nop
04: a805   test al, 5
06: 90     nop
07: 90     nop
08: 90     nop
```

ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

- Setting array elements

```
'use asm';
var asm_js_heap = new stdlib.Uint32Array(buf);
function asm_js_function(){
    asm_js_heap[0x10] = 0x0ceb9090
    asm_js_heap[0x11] = 0x0ceb9090
    asm_js_heap[0x12] = 0x0ceb9090
    asm_js_heap[0x13] = 0x0ceb9090
```

ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

- Setting array elements

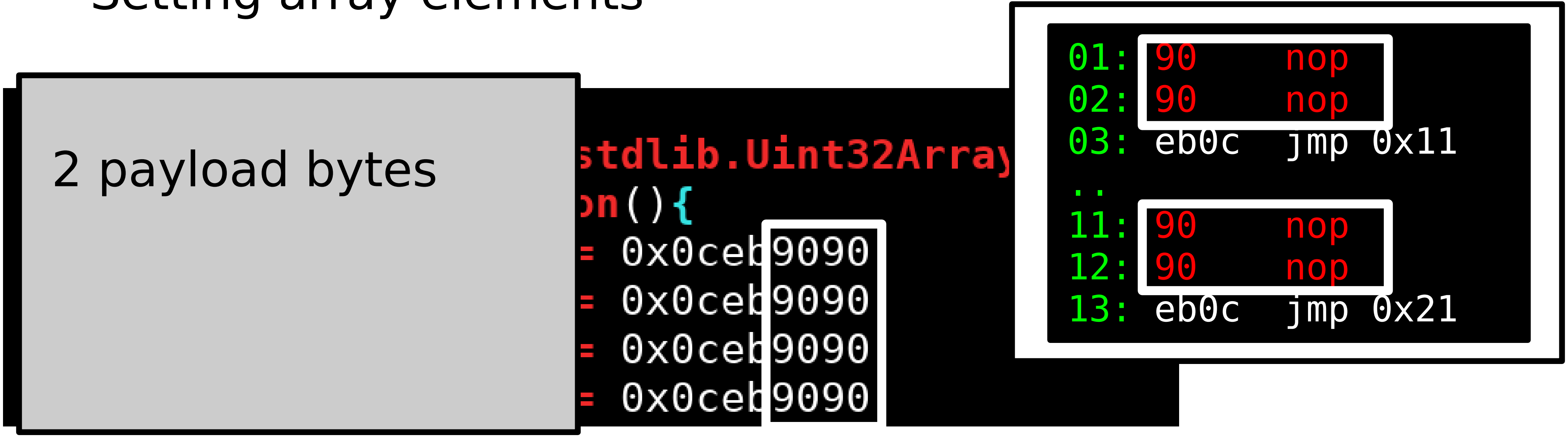
```
'use asm';
var asm_js_heap = new stdlib.Uint32Array
function asm_js_function(){
    asm_js_heap[0x10] = 0x0ceb9090
    asm_js_heap[0x11] = 0x0ceb9090
    asm_js_heap[0x12] = 0x0ceb9090
    asm_js_heap[0x13] = 0x0ceb9090
```

```
01: 90     nop
02: 90     nop
03: eb0c   jmp 0x11
..
11: 90     nop
12: 90     nop
13: eb0c   jmp 0x21
```

ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

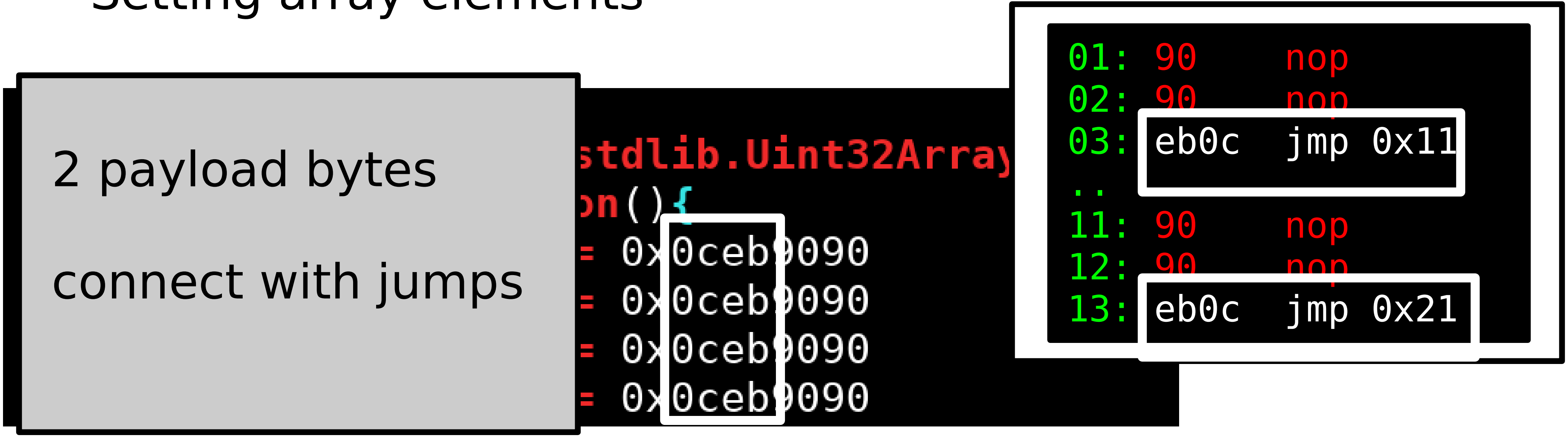
- Setting array elements



ASM.JS Payloads

ASM.JS Statements Suitable to Embed Code

- Setting array elements



ASM.JS Payloads

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ASM.JS Statements Suitable to Embed Code

- Foreign function call with double values

```
"use asm"
var ffi_func = ffi.func
function asm_js_function(){
    var val = 0.0
    val = +ffi_func(
        2261634.5098039214,        // 0x4141414141414141
        156842099844.51764,        // 0x4242424242424242
        1.0843961455707782e+16,    // 0x4343434343434343
        7.477080264543605e+20)     // 0x4444444444444444
```

ASM.JS Payloads

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ASM.JS Statements Suitable to Embed Code

- Foreign function call with double values

```
0x00: movsd xmm1, mmword [****0530]
0x08: movsd xmm3, mmword [****0538]
0x10: movsd xmm2, mmword [****0540]
0x18: movsd xmm0, mmword [****0548]
...

****0530:
41414141 41414141 42424242 42424242
****0540:
43434343 43434343 44444444 44444444
...
```

– constants are referenced

– same executable region

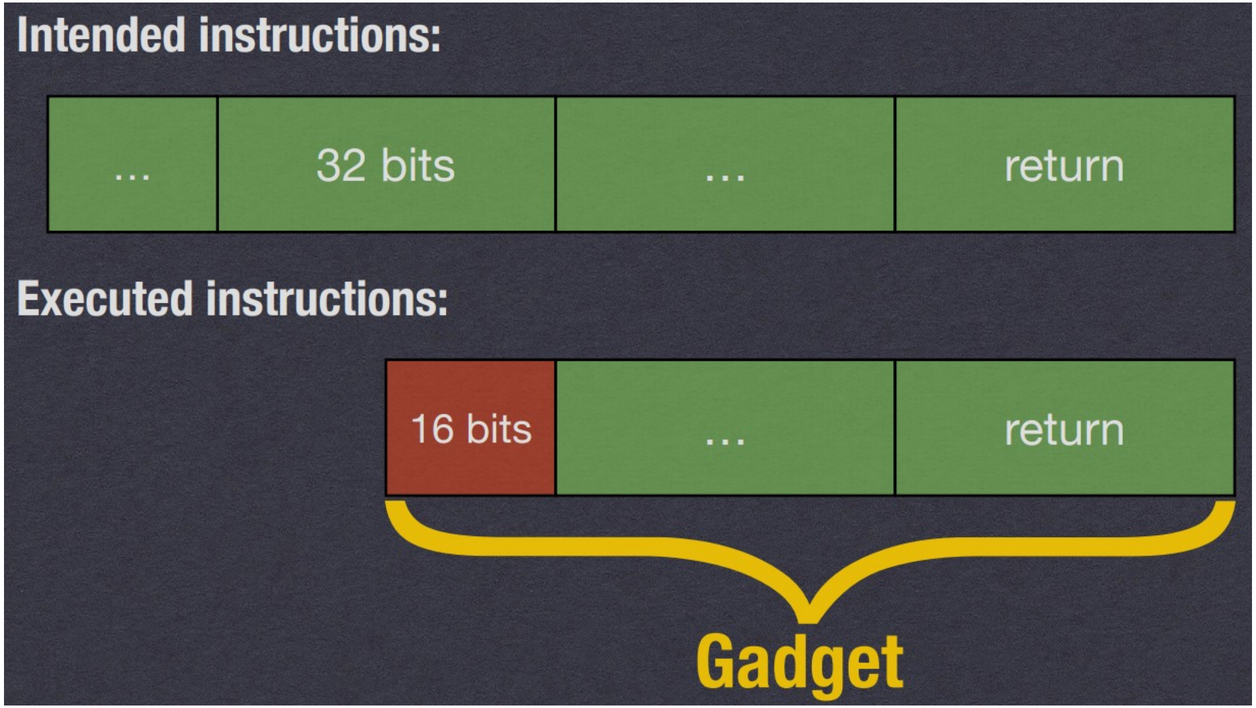
– continuous in address space

→ **gapless, arbitrary shellcode possible**

JIT-Spray (ARM)

JIT-Spray (ARM)

Too leJIT to Quit (Lian et al., 2015)



- Target: JSC DFG JIT
- Thumb-2:
  - mixed 16-bit and 32-bit instructions
  - 16-bit alignment

http://wp.internetsociety.org/ndss/wp-content/uploads/sites/25/2017/09/09ExtendingJIT.slide_.pdf

JIT-Spray (ARM)

A Call to ARMs (Lian et al., 2017)

- Control JIT to emit **32-bit** ARM **AND** instructions

- Force interpretation of **AND** instruction as **two** consecutive **16-bit Thumb-2** instructions

- **1st** instruction: attacker operation
  2nd instruction: PC-relative jump

→ self-sustained payload without resynchronization
(target: Firefox' IonMonkey)

JIT-Spray (ARM)

A Call to ARMs (Lian et al., 2017)

- Control JIT to emit **32-bit** ARM **AND** instructions

- F … tive
  1

- **1**
  2

JIT-Spray on architecture with fixed instruction length and instruction alignment

→ self-sustained payload without resynchronization
(target: Firefox' IonMonkey)

JIT-based Code Reuse

JIT-Code Reuse

- Similar to JIT-Spray but requires **info leak**

- Abuse JIT to achieve various goals:

  – two payload bytes are enough to create gadgets
  → bypass static ROP protections

  – hide code within direct branch offsets
  → bypass Execute-Only Memory

  – find 4-byte constants missed by constant blinding
  → bypass constant blinding and create gadgets

More Flaws beyond JIT-Spray

Beyond JIT-Spray

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JIT-related flaws

- More exploit-mitigation bypasses
  - DEP and CFG Bypass (Tencent, 2015)
  - Chakra-JIT CFG Bypass (Theori, 2016)
  - ACG Bypass (Ivan Fratric, 2018)

Beyond JIT-Spray

JIT-related flaws

- Vulnerabilities in JIT-compilers
  - Web Assembly bugs found by Google P0
  - Safari JIT (Pwn2Own 2017, Pwn2Own 2018)
  - Chrome 63 (Windows OSR Team)
  - Chakra JIT (CVE-2018-8137, CVE-2018-0953)

Summary

Summary

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- JIT-Spray simplified client-side exploitation in the past
- ASM.JS in OdinMonkey (x86) was the perfect JIT-Spray target
- JIT-Spray was possible on x86 and ARM
- JIT-Spray seems infeasible in a large (64-bit) address space, under ASLR and Control-Flow Integrity
- JIT compilers have a big attack surface and remain prone to vulnerabilities

Thank you!

Questions?