Attacking Client Side JIT Compilers
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Introduction

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Overview

- Introduction
- Firefox JIT(s)
- LLVM JIT
- JIT Code Emission Bugs
- JIT Exploitation Primitives
- JIT Hardening
- JIT Engine Comparison
- Our Tools and Techniques
Introduction to JITs

- Interpreters and JIT Engines
  - Parse high level languages
  - Generate bytecode
  - Optimize and compile bytecode to native code

- They are everywhere
  - Browsers
  - Language runtimes (Java, Ruby, C#)
Introduction to JITs

10 PRINT "HELLO WORLD"
20 GOTO 10

"Compiler"

pushq %rbp
movq %rsp,%rbp
leaq 0x0041(%rip),%rdi
movl $0x0000,%eax
callq 0x10f36

User

Developer
Introduction to JITs

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User

Saturday, August 6, 2011
Introduction to JITs

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10 PRINT "HELLO WORLD"
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```

```
pushq %rbp
movq %rsp,%rbp
leaq 0x0041(%rip),%rdi
movl $0x0000,%eax
callq 0x10f36
```
Introduction to JITs

- Compilers and JITs have been around for a while and come in a few different designs and architectures
Introduction to JITs

10 PRINT "HELLO WORLD"
20 GOTO 10

Lexer → Parser → IR Generator → IR Optimizer

"Compiler"

Target Generator

JIT

pushq %rbp
movq %rsp,%rbp
leaq 0x0041(%rip),%rdi
movl $0x0000,%eax
callq 0x10f36
Introduction to JITs

```javascript
a = new Array();
```

```assembly
JSOP_NEWARRAY

mov $0x8963778, %edx
lea 0x50(%ebx), %ecx
mov %ecx, 0x14(%esp)
mov %esp, %ecx
mov %ebx, 0x1c(%esp)
movl $0x8962ec5, 0x18(%esp)
call 0x8265670
```
Introduction to JITs

- Bytecode / Bitcoin / Intermediate Representation (IR)
  - Both trusted and untrusted
  - Expressive and bloated (slower)
  - Simple and slim (faster)
  - Potentially usable to an attacker
    - Overwrite bytecode
Introduction to JITs

- **Untrusted bytecode**
  - Can be delivered from untrusted sources
    - Flash, CLR, LLVM
  - Completely external to the compiler

- **Trusted bytecode**
  - Produced internally by a trusted front end
    - SpiderMonkey
  - Still potentially usable to an attacker with control of the process
Introduction to JITs

- Tracing
  - Only JIT CPU-intensive code
  - Enables Optimizations
  - Types are generally known from tracing
• Introduced in Firefox 3.5
• Tracing JIT
• Uses NanoJIT as a backend assembler
TraceMonkey

- TraceMonkey JITs hot code blocks
  - The recorder traces execution of SpiderMonkey IR
    - 8 Iterations before TraceMonkey kicks in
  - Produces trace trees
  - Emits optimized LIR for NanoJIT to compile
- Doesn’t handle type changes well
• **CodeAlloc class**
  - Handles allocating JIT pages that will hold code
  - Allocates memory RWX

• **CodeList class**
  -_inline meta-data for tracking the location of code chunks within JIT pages
  - *Next* *Lower* *Terminator* pointers at static offsets
    - Creates a doubly linked list of JIT pages
    - Overwriting these will give you an arbitrary 4 byte write
    - Similar to the original heap unlink attacks

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Introduction to JITs

- **Method**
  - JITs entire functions / methods
  - Usually generates unoptimized code
    - Not based on previous execution runs
  - Slow type lookups are usually required
JaegerMonkey

- Introduced in Firefox 4.0
- Method JIT
- Uses the Nitro assembler backend from WebKit
- SpiderMonkey bytecode → Native Code
- Uses an Inline Cache for handling type changes in property accesses
JaegerMonkey

- Fast paths are native code emitted by the JIT
  - Pure native code emitted by the JIT for predefined operations

- Slow paths are through the execution of bytecode
  - Inline cache hits sometimes have to go back through slow bytecode execution

- Stub calls are into C++ code from JIT pages
  - Typically exist to augment a fast path
JaegerMonkey

- **ExecutableAllocator class**
  - Handles allocating JIT pages to hold code
  - Allocates memory RWX

- **ExecutablePool class**
  - Handles managing the larger page size allocations into pools to hold native code
  - Pools are chosen based on the size of code that needs to be stored
Inline Caching

- Inline Caching
- JavaScript is dynamically typed
- How do you JIT a generic function that handles multiple types?

```javascript
function a = blah(var b) {
    for(i=0; i<10; i++) {
        b += i;
    }
}

blah("hello");
blah([0, 1, 2, 3]);
```

- Inline caches handle rewriting methods or property accesses at runtime to handle different and unexpected types.
Inline Caching

- **Intermediate**: foo()
- **Native**: foo() {
  handle_bool
  ...
  ...
}

**Inline Cache**

- **Intermediate**: foo()
- **Native**: foo() {
  handle_bool
  handle_int
}

**Inline Cache**

- **Intermediate**: foo(23)
- **Native**: foo() {
  handle_bool
  handle_int
  handle_str
}

- **Intermediate**: foo("str")
- **Native**: foo() {
  handle_bool
  handle_int
  handle_str
}
An instruction set, a suite of libraries and a collection of tools designed around compilation.

A suite of libraries from the start

Initially used GCC as a front end

Now supports C, C++ and Objective-C natively

Many other compiler projects now support LLVM

- Python, Ruby, Haskell, PHP, etc

Popular for implementing compiler back ends
LLVM

hello.c ➔ Clang ➔ IR ➔ Optimizer ➔ IR ➔ Optimizer ➔ IR ➔ Object File ➔ Linker ➔ JIT ➔ Native

mov eax, 0x1234
jmp -0x5

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hello.c

Source

Clang

IR

Optimizer

IR

Optimizer

IR

Object File

Linker

JIT

Native

mov eax, 0x1234
jmp -0x5
LLVM

• Typical integration progression:
  • I have a project that compiles something
  • Need to make it faster or
  • Need a backend to actually produce native code.
• Integrate with LLVM!
LLVM Integration

- “The LLVM JIT and You”
- Popular integration strategies
  - Emit IR directly, create a Module
    - MacRuby, GHC
  - Have your own VM instruction set, translate instruction by instruction to LLVM equivalents, then emit
    - Rubinius, ClamAV
LLVM JIT

- Assume a Module is created
- Connect a Module to an ExecutionEngine
- Request a handle to a function, ask the ExecutionEngine to run it
- ExecutionEngine emits code for the function, and stubs for all outgoing calls to non-emitted code
LLVM JIT

Platform Dependent

Platform Independent

ExecutionEngine

JIT

JITState

JITCodeEmitter

JITMemoryManager

Resources

TargetJITInfo
X86JITInfo

Memory

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JITs and Security

- Compiling traditional executables is typically done by developers
- Code compilation is a trust boundary
  - You’ve accepted your vendor’s code and binary
  - But now you’re compiling my untrusted code
Incorrect Code Emission

- JITs don’t always produce perfect code
- Compiler bugs are often caught during development and testing
- What can happen when the JIT emits incorrect code?
Incorrect Code Emission

- Java x64 JIT bug patched on June 18th, 2011
- Intended code emission:
  
  ```
  addq (%rsp),0xffffffff2b ; add 0xffffffff2b to the value at %rsp
  popfq                   ; pop 64 bits from stack, load
  ; the lower 32 bits into RFLAGS
  ```

- Unintended code emission:
  
  ```
  addq %rsp,0xffffffff2b ; shift the stack pointer!
  popfq                  ; pop 64 bits from stack+0xffffffff2b
  ; load the lower 32 bits into RFLAGS
  ```
Incorrect Code Emission

- Many examples
  - Mozilla Bugzilla ID 635295 (Firefox 4.0 Beta)
    - Execution of an invalid branch due to an inline cache that existed for a free’d object
  - MS11-044 Microsoft .NET CLR JIT
    - The JIT produced code that confused an object as NULL or non-NULL
    - This was a great logic bug example!
Incorrect Code Emission

- What usually triggers them?
  - Use after free
  - Integer over/underflows (miscalculation of code paths)
  - Incorrect logic during code emission

- Are incorrect JIT code emissions a new bug class?
  - Depends on the root cause
  - Not for us to decide, but should be debated
JIT Primitives + Traditional Bugs

- JIT engines can be:
  - the source of vulnerabilities
  - a means to exploit them
Exploitation Primitives

- JITs introduce unique exploitation primitives that would otherwise not be present in an application
  - JIT Spray
  - RWX Page Permissions
  - Reusable code sequences at predictable addresses
JIT Spray

- Dion Blazakis 2010
- Flash ActionScript
- Create enough constants to contain native shell code, link together by semantic NOPs
- Transfer execution to mid-instruction, set up a stage 2, and begin executing
- I’m told by people smarter than me you can do it in 2 bytes with a short jmp
JIT Spray

• JIT Spray in Firefox through JaegerMonkey

• Not perfect, JaegerMonkey emits unoptimized code

• Lots of bytes in the way we can’t control

```
var constants = [ 0x12424242, 0x23434343, 0x34444444, 0x45454545, 0x56464646, 0x67474747, 0x78484848, /test/ ]
```

```
0x40a05e: call 0x82d1820 NewInitArray ; create an array
0x40a063: mov %eax,%edi              ; $edi holds returned array object
0x40a065: mov 0x24(%edi),%edi        ; load obj->slots in to $edi
0x40a068: movl $0xffff0001,0x4(%edi)  ; JSVAL_TYPE_INT32 to object->slots[1]
0x40a06f: movl $0x12424242,(%edi)     ; 1st constant into object->slots[0]
0x40a075: mov %eax,%edi
0x40a077: mov 0x24(%edi),%edi
0x40a07a: movl $0xffff0001,0xc(%edi)
0x40a081: movl $0x23434343,0x8(%edi) ; 2nd constant
0x40a088: mov %eax,%edi
0x40a08a: mov 0x24(%edi),%edi
0x40a08d: movl $0xffff0001,0x14(%edi)
0x40a094: movl $0x34444444,0x10(%edi) ; 3rd constant
0x40a09b: mov %eax,%edi
0x40a09d: mov 0x24(%edi),%edi
0x40a0a0: movl $0xffff0001,0x1c(%edi)
0x40a0a7: movl $0x45454545,0x18(%edi) ; 4th constant
```
JIT Spray

- JIT Spray in Firefox through TraceMonkey
  - Floating point games
  - \(-6.828527034422786e-229 = 0x9090909090909090\)
  - \(0x90 = x86\) NOP instruction

```javascript
var a = -6.828527034422786e-229;
var b = -6.828527034422786e-229;
var c = -6.828527034422786e-229;
var d = -6.828527034422786e-229;
```

```assembly
0x429eda: movl $0x90909090,0x5c0(%esi)
0x429ee4: movl $0x90909090,0x5c4(%esi)
0x429eee: movl $0x90909090,0x5c8(%esi)
0x429ef8: movl $0x90909090,0x5cc(%esi)
0x429f02: movl $0x90909090,0x5d0(%esi)
0x429f0c: movl $0x90909090,0x5d4(%esi)
0x429f16: movl $0x90909090,0x5d8(%esi)
0x429f20: movl $0x90909090,0x5dc(%esi)
```
Memory Protections

- Nearly all JITs we surveyed produce RWX pages
  - Weakens DEP
  - Breaks assumptions behind copy-on-write mirror pages
    - Knowledge of both RW/RX pages not required
  - Blind Execution
    - Overwrite RWX JIT page contents
    - Trigger the original JIT’d script
- This isn’t going away for Inline Cache designs without some performance impact
Memory Protections

- RWX pages can be reused
  - Array index read/write
    - Point into JIT page
    - Write raw shell code, trigger JavaScript
    - Read branch addresses back to C++ in a DLL

- Overflows
  - Heap overflow in adjacent RW page

Firefox 5.0

- 02808000-0280c000  rw-p  Read/Write Heap memory
- 0280c000-0281c000  rwxp  Read/Write/Execute JIT page

- ROP
- No need to find that VirtualAlloc stub
ROP Gadgets are small sequences of code found in an existing DLL or .text

- Combine them to get arbitrary code execution

- Predictable instructions on JIT pages at static offsets

- JIT’s produce lots of native code
  - You aren’t constrained to just one library mapping
  - Does not require controllable constants like JIT Spray
gaJITs

- Finding usable gaJITs depends on the JIT design
  - ret or branch-based control flow?
  - inline caching
  - (in)frequent calls to C++ stubs
- How does script function A get turned into native code B where native code B contains gaJIT X
  - Requires the right source code to generate them
  - Requires a specific gaJIT-finding tool
JIT Feng Shui

- Our version of Heap Feng Shui... except for JITs
  - Heap Feng Shui
    - Alex Sotirov 2007
    - Influence the heap layout via JavaScript
  - JIT Feng Shui
    - Untrusted input influences JIT output
    - Specific inputs create predictable code patterns
  - We could have called it jiuJITsu..
JIT Feng Shui

- Controlling register contents with a TraceMonkey gaJIT
  
gaJIT at offset 0x9e18 (10 matches)
  pop esi ; pop edi ; pop ebx ; pop ebp ; ret

- LLVM

- Portable shellcode!
JIT Feng Shui + gaJITs

- Circumvents constant masking
  - Defeated by NOP padding
  - Much harder with allocation restrictions
- Difficult and noisy
  - Requires a JIT spray to map enough pages
- Not researched on other JITs / architectures yet
JIT Protections

- The OS provides some basic protections to the process
  - (ASLR) Address Space Layout Randomization
  - (DEP) Data Execution Prevention
  - Code Signing
- JITs can negate these by design
- JIT engines have no control over their input
  - ... but completely control their output
Emission Randomization

- Memory for emission is allocated via mmap or VirtualAlloc
  - VirtualAlloc is not randomized by default
    - You can request the address you want mapped
    - V8 and IE9 do this
  - mmap on Linux randomizes anonymous mappings
- Extend ASLR to compiler-allocated memory
Randomization

Allocation Randomization

64
32
0
• Intra-page offsets (bottom 10 bits) are still predictable
• Since you’re emitting code, you can shift each function emitted by inserting NOPs
Randomization

Allocation Randomization

NOP Padding

64
32

0
Randomization

- Function emission is still predictable
- If you’re batching the functions you’re emitting, you can shuffle the order at which they’re produced
Randomization

Allocation Randomization  Function Shuffling  NOP Padding

64 32

0
Guard Pages

- Firefox 5.0 adjacent heap and JIT pages
  
  02808000-0280c000 rw-p Read/Write heap memory
  0280c000-0281c000 rwxp Read/Write/Execute JIT page

- If an overflow occurs in the first RW heap mapping, an attacker can write native code into the RWX page

- Guard pages prevent heap overflows from writing to RWX JIT pages
  
  02808000-0280c000 rw-p Read/Write heap memory
  0280c000-0281c000 r--p Read Only memory
  0281c000-0282c000 rwxp Read/Write/Execute JIT page
Constant Folding

- 4-byte constants allow room to insert instructions on x86
- Chained 4-byte chunks allows for a stage 1 payload
- Solution: Fold large constants into 2-byte maximum constants and reassemble at runtime.
- Problem: If the instructions are predictable an attacker can bypass this by injecting the right constants
- V8 did this for a while, now they use constant blinding
Constant Blinding

- XOR all untrusted immediate values by a secret cookie
- Generate a random value at startup
  - untrusted immediate $\oplus$ secret cookie
- Emit code that XORs the value at runtime

```
xor eax, 0x00112233
```
```
mov eax, 0x84521310
xor eax, 0x84433123
```
Allocation Restrictions

- JIT Spray requires mapping a lot of memory
- Capping the number of pages helps mitigate this attack
- For language runtimes, some info about code can be known ahead of time
  - code size
  - libraries used
- Unfortunately, this protection mechanism makes more sense for browsers than language runtimes
## JIT Comparison

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<th>Jaeger Monkey</th>
<th>Trace Monkey</th>
<th>LLVM</th>
<th>JVM</th>
<th>Flash / Tamarin</th>
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<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>
JIT Comparison

- IE9 doesn’t require guard pages
- Tamarin/TraceMonkey (NanoJIT) implemented random NOP padding but forgot to enable it
- Guard pages in Chrome are brand new as of 8/4/2011
- As a result of our research, Firefox should be implementing some of these very soon
jitter

- jitter is our toolchain for:
  - Tracing JIT code emission
  - Tracking JIT memory permissions
  - JIT Fuzzer coverage
  - Searching for gaJITs

- Implemented as a set of Nerve scripts
  - Uses ragweed debugging framework
  - We also wrote a native Java JIT hook
jitter

- Support for LLVM and Firefox JITs
  - Nerve breakpoint files for specific JIT hook points
  - Interact with the process at each breakpoint with Ruby
  - Extract arguments, data, instructions
- Generic script for tracking JIT page allocations
  - Just needs a list of call sites
  - Can be used to start support of new JIT engines
- gaJIT finder is built-in
  - Receives an array of JIT pages
  - Output locations for repeated gaJITs
  - Easily repurposed for other ROP tools
fuzzer(s)

- Fuzzing JIT engines is difficult
  - Testcases must have valid syntax
  - Multiple components before you hit the JIT
- Rubinius Fuzzer (LLVM JIT)
- JavaScript grammar fuzzer (Firefox JITs)
- Fuzzer driver framework
fuzzing bitcode

- We attempted to fuzz LLVM bitcode directly
- Dumb-fuzzing at first
  - Way too many coredumps to go through
- LLVM’s BitcodeReader was not designed with security in mind
- Found a parsing bug; submitted patch
Ruby fuzzing

- Ruby fuzzing for targeting Rubinius
  - Generated Ruby code from a subset of Ruby grammar
  - Avoided Rubinius VM to target other Ruby implementations
    - MacRuby, JRuby, YARV, MRI, etc
- Fuzzer driver also in Ruby (Hoke)
rubyfuzz

- Modeled Ruby grammar as Ruby objects
  - Terminals ➔ Arrays
  - Non-terminals ➔ Generators
- Permuted method invocations, block definitions, block invocations and other Ruby constructs
- Seeded with common Ruby idioms
JavaScript Fuzzer

- JavaScript Grammar fuzzer for Firefox JITs
- Targets the JIT and interpreter only; not the DOM
- Describe JavaScript in flat text files
  - types, methods, properties, keywords, and operators
- Parse text files and serialize into Ruby OpenStruct
- Iterate over the grammar
  - Follow JSOP bytecode instructions to
    - Fast Paths
    - Inline Caches
    - C++ Stubs
- Hundreds of millions of iterations through ./js
A bug our fuzzer found

• Our fuzzer found a critical bug in SpiderMonkey

```javascript
a = new Array();
a.length = 4294967240;
b = function bf(prev, current, index, array) {
  document.write(current);
  current[0] = "hello";
}
a.reduceRight(b, 1, 2, 3);
```

• Info Leak: read arbitrary data from current

• Code Execution: call a method on current
A note on fuzzing for info leaks
- Fuzzing should be fast
- Instrumentation to monitor individual memory access is slow

Differential fuzzing for info leaks
- Can be generalized to multiple implementations of any language spec

Two JavaScript implementations
- d8 (v8) / js (Mozilla)
- Feed them identical testcases
- Record the output
  - What is the expected output type/value?
Questions