Attacking Client Side JIT Compilers

BlackHat 2011

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Introduction

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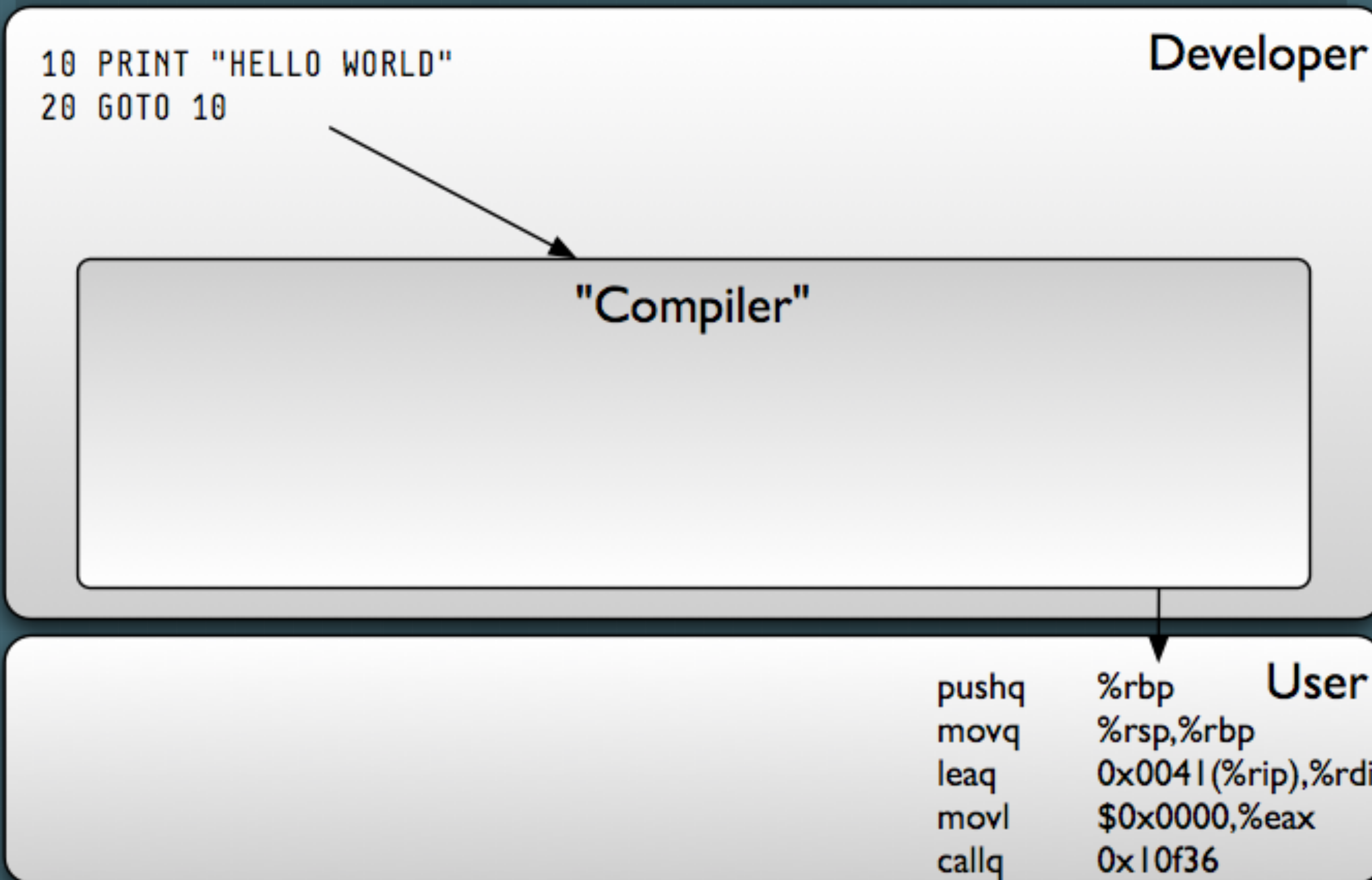
Overview

- 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

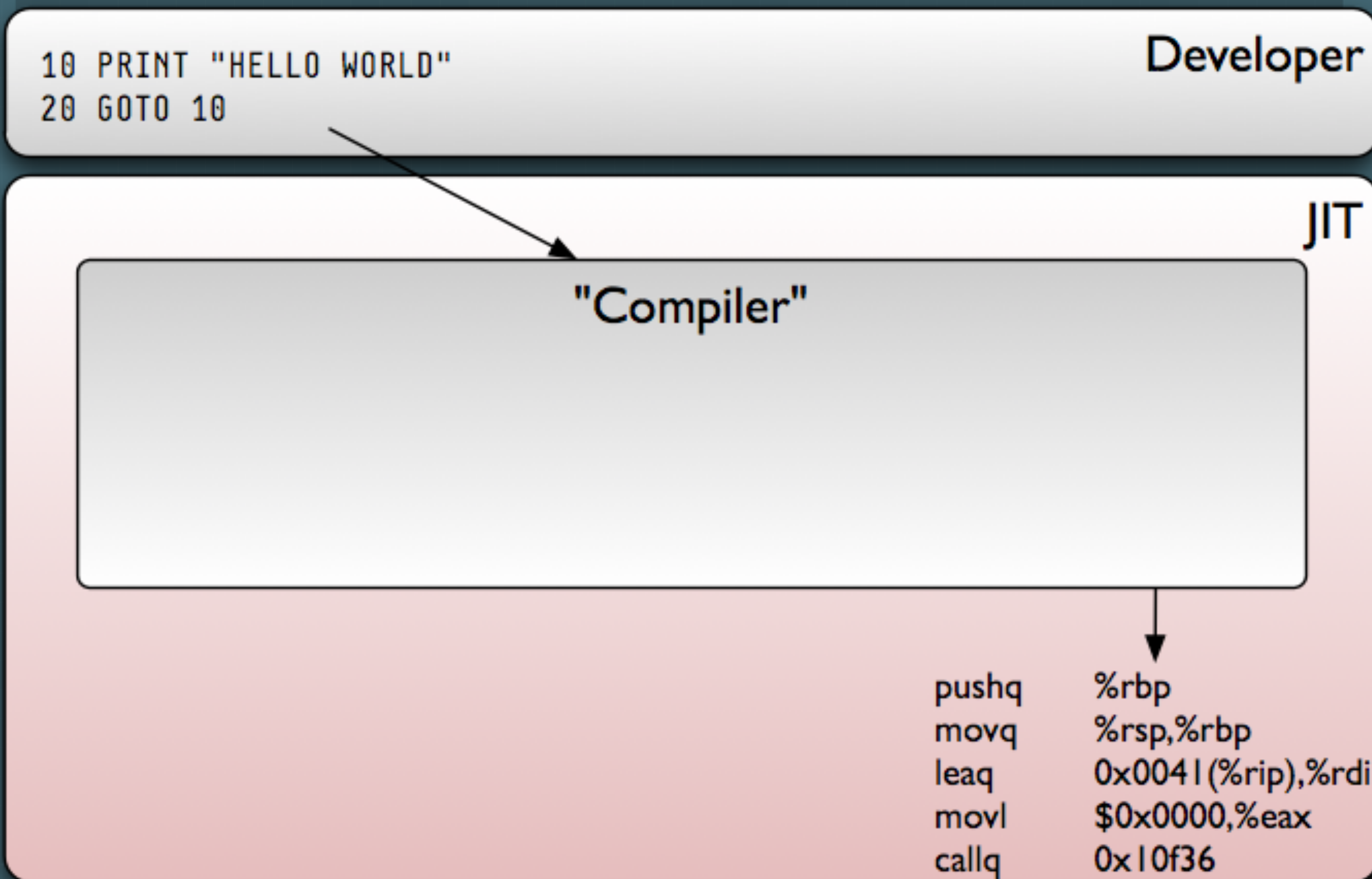
- Interpreters and JIT Engines
  - Parse high level languages
  - Generate bytecode
  - Optimize and compile bytecode to native code
- They are everywhere
  - Browsers
  - Language runtimes (Java, Ruby, C#)

Introduction to JITs

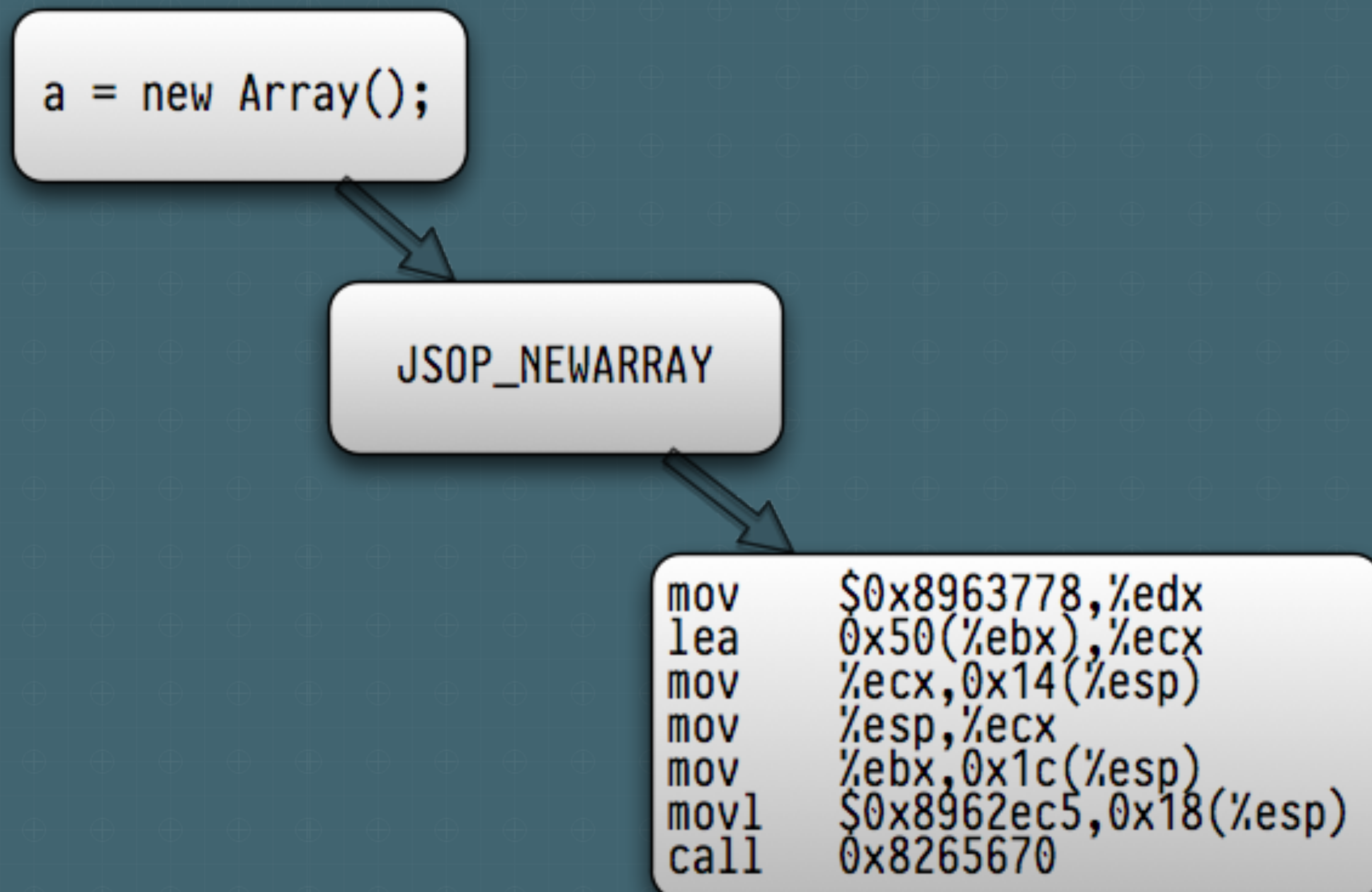


Introduction to JITs

Introduction to JITs



Introduction to JITs



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Introduction to JITs

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

Introduction to JITs

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

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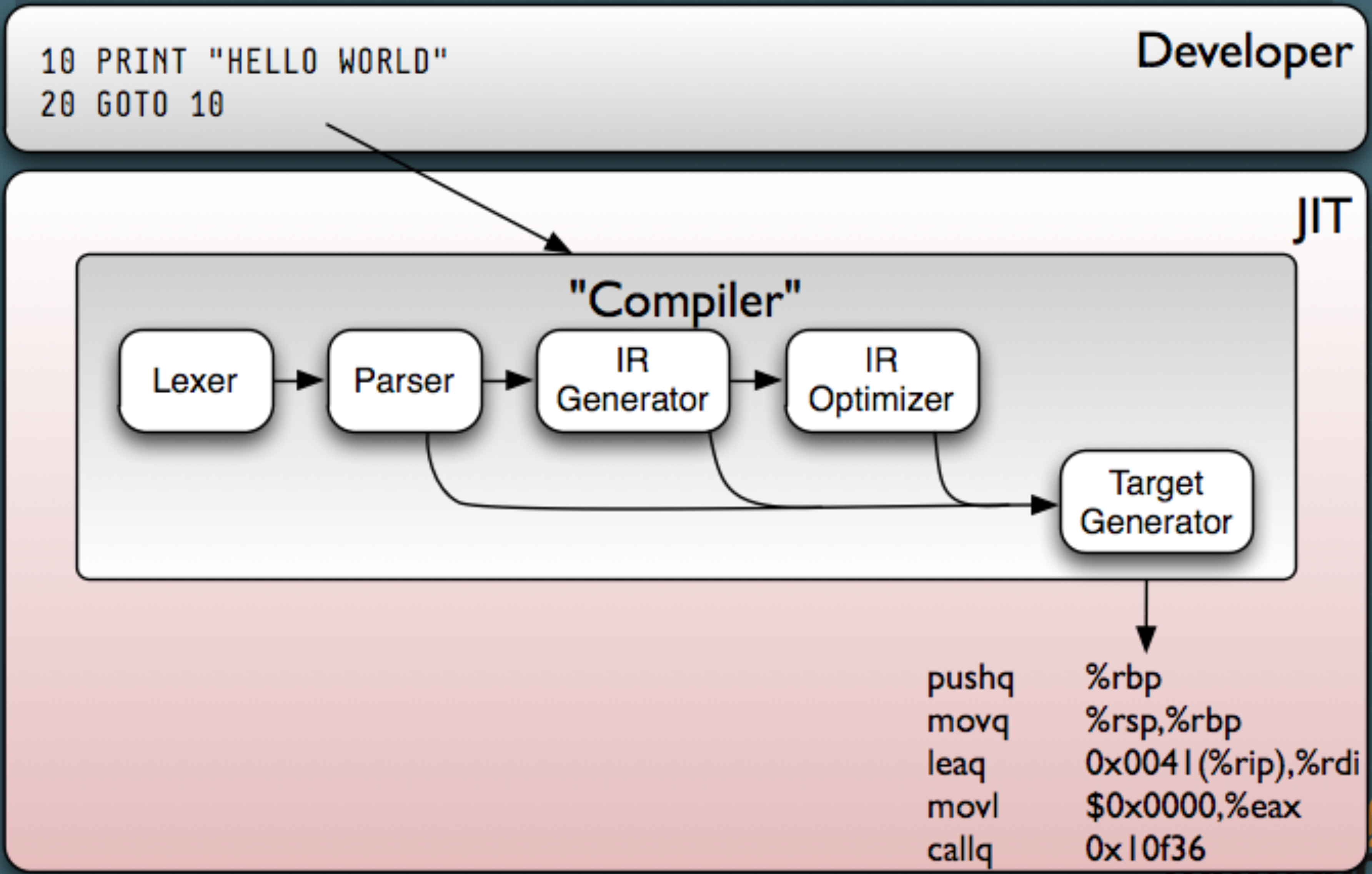
Introduction to JITs

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

Introduction to JITs



Introduction to JITs

- JITs come in a few different designs
  - Method
    - Firefox
    - LLVM
    - V8
  - Tracing
    - Firefox
    - Rubinius

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Introduction to JITs

- Tracing
  - Only JITs CPU-intensive code
  - Enables optimizations
  - Types are generally known from tracing

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TraceMonkey

- Introduced in Firefox 3.5
- Tracing JIT
- Uses NanoJIT as an assembler
- SpiderMonkey Bytecode LIR Bytecode
- NanoJIT LIR Native code

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TraceMonkey

- TraceMonkey JITs hot code blocks
  - The recorder traces execution of SpiderMonkey IR
  - Produces trace trees
  - Emits optimized code
- Doesn't handle type changes well

TraceMonkey

- CodeAlloc Class
  - Handles allocating JIT pages that will hold code
- CodeList Class
  - Inline meta-data for tracking the location of JIT pages

Introduction to JITs

- Method
  - JITs entire functions/blocks
  - Usually generates unoptimized code
  - 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 new types

JaegerMonkey

- Inline Caching
  - JavaScript is dynamically typed
  - It can JIT a generic function that handles multiple types

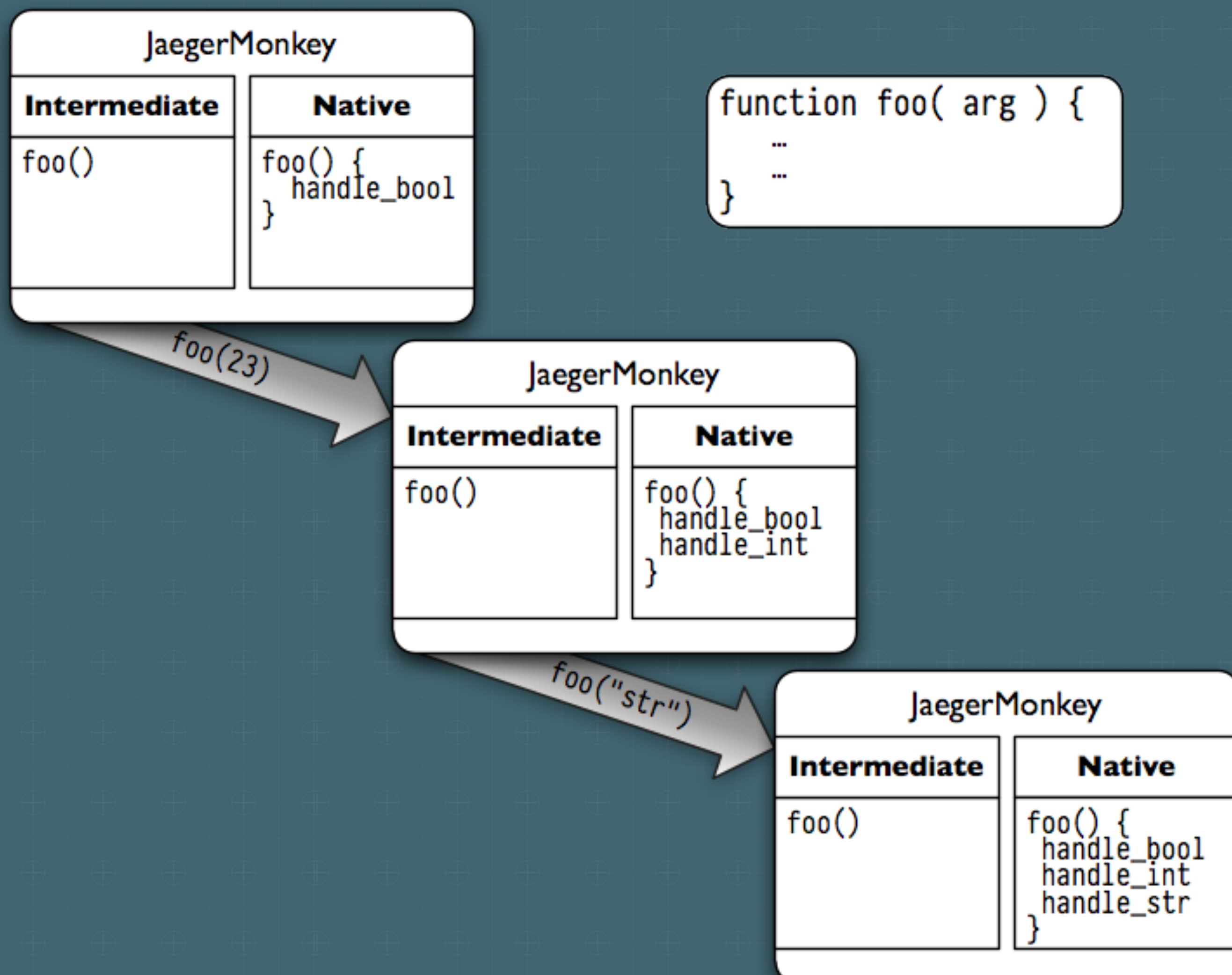
```
function a = blah(var b){
   for(i=0;i<10;i++) {
     b += i;
   }
}
```

  - The JIT emitted code needs to be rewritten for each new type it encounters

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

    - The Inline Cache makes this possible

JaegerMonkey



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

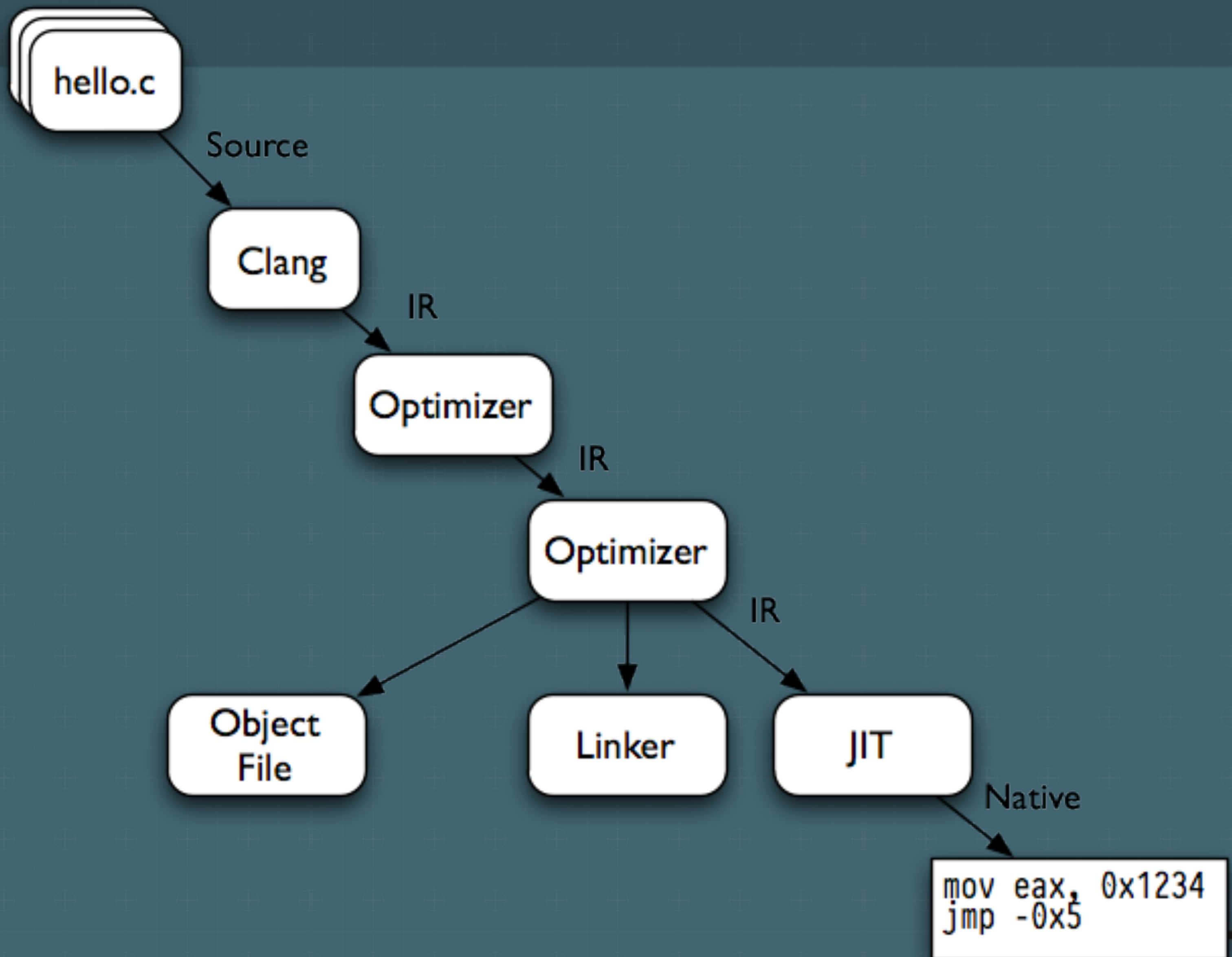
JaegerMonkey

- ExecutableAllocator Class
  - Handles allocating JIT pages to hold code
- ExecutablePool Class
  - Handles managing the larger allocations into *pools* to hold native code
  - Pools are chosen based on the size of the code that needs to be stored

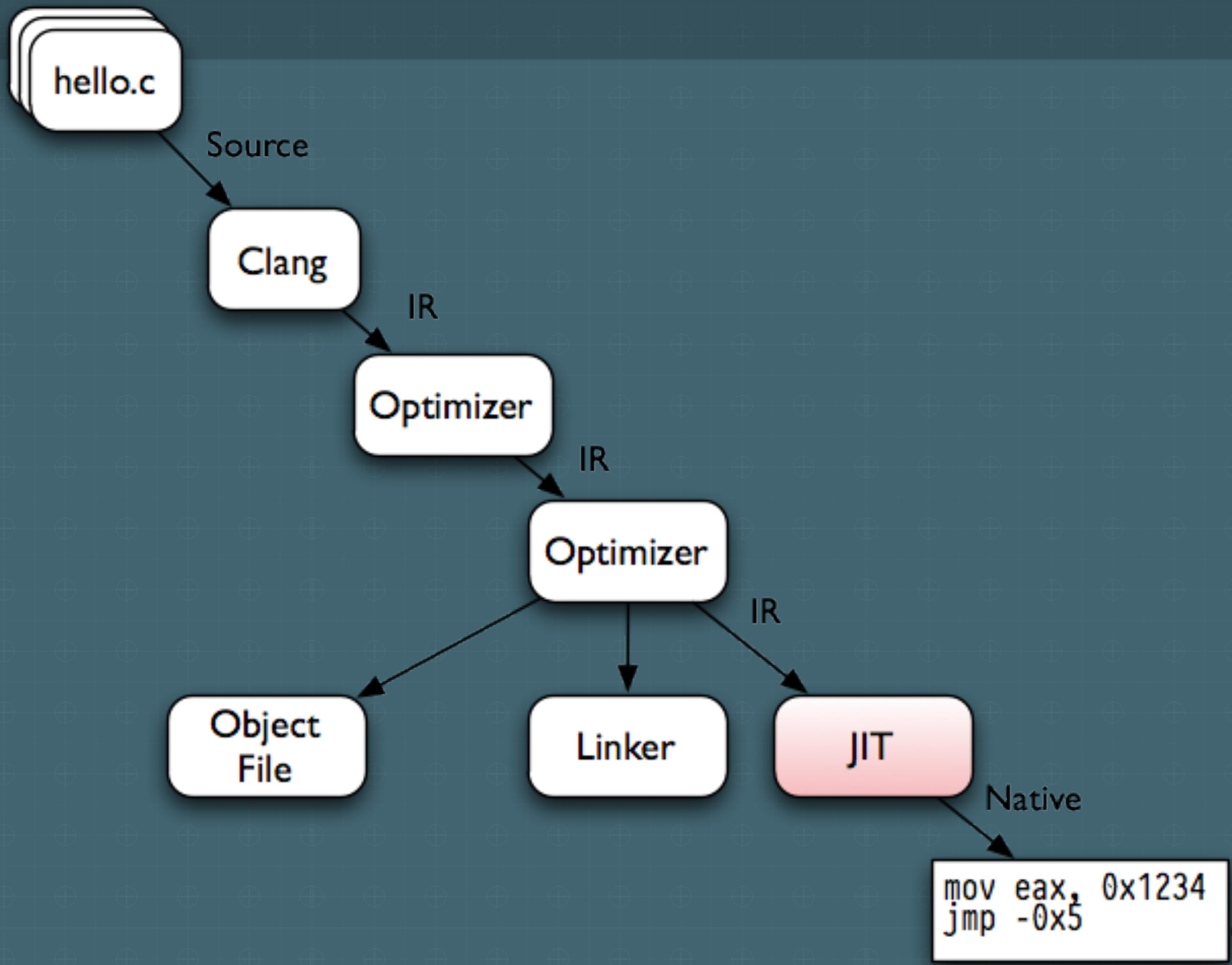
LLVM

- Originated in UIUC
- A suite of libraries from the start
- Initially used GCC as a front end
- Now supports C, C++ and Objective-C entirely
- Frontends available for
  - Python, Ruby, Haskell, PHP, etc

LLVM


hello.c
Source
Clang
IR
Optimizer
IR
Optimizer
IR
Object File
Linker
JIT
Native
mov eax, 0x1234
jmp -0x5

LLVM



hello.c
Source
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Native
mov eax, 0x1234
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LLVM

- Typical progression:
  - I have a project that compiles *something*
  - Need to make it faster
  - 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 for it
- ExecutionEngine emits code for the function, for all data it references and emits stubs for all functions it calls

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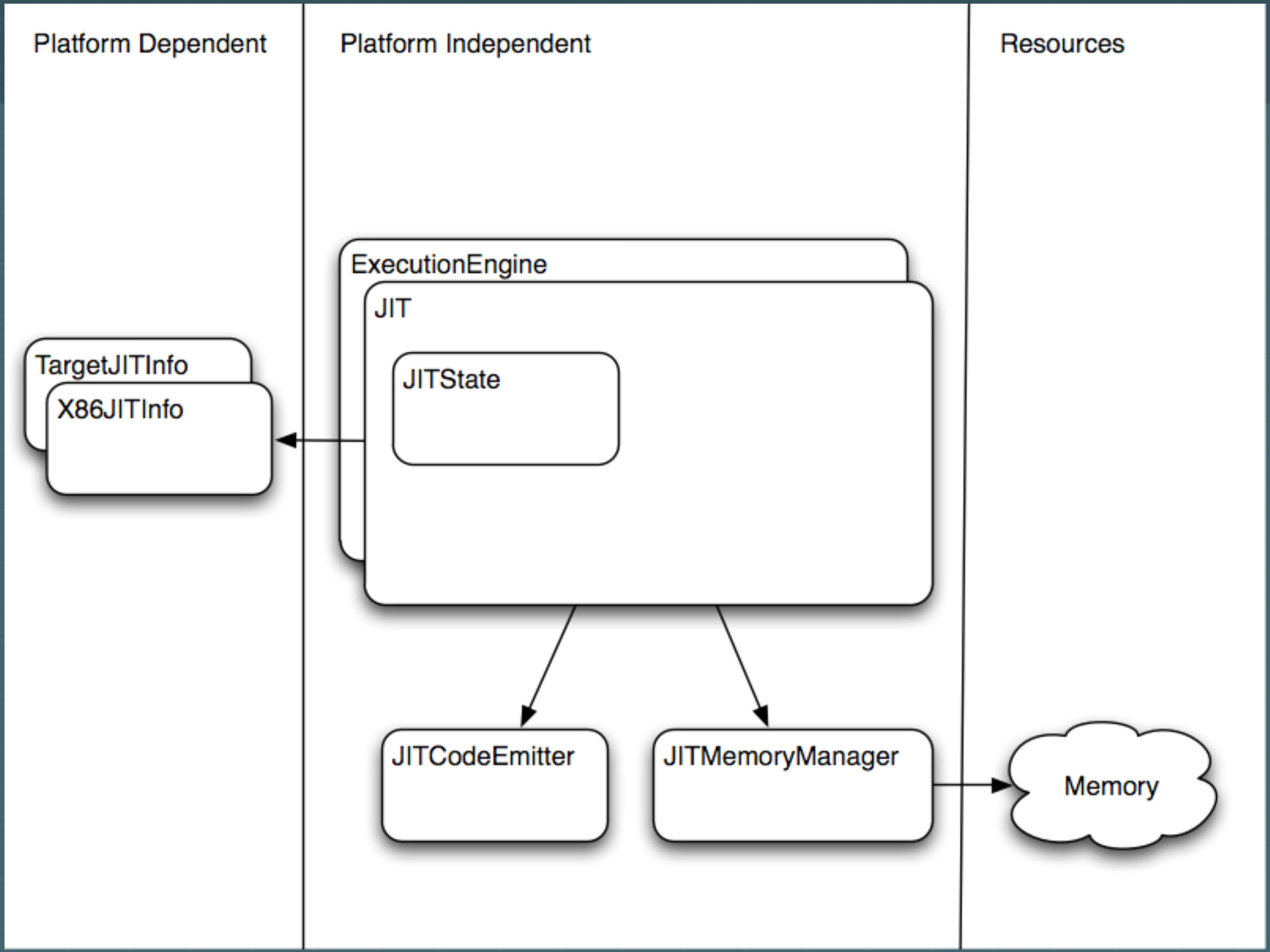
LLVM JIT



Platform Dependent
Platform Independent
Resources
ExecutionEngine
JIT
JITState
TargetJITInfo
X86JITInfo
JITCodeEmitter
JITMemoryManager
Memory

LLVM Attack Scenarios

- Bitcode injection.
  - Portable shellcode!
- Bitcode parser flaws
  - Shouldn't be trusted, but will probably be
- Poor emission
  - Incorrect code being emitted
- Liberal Memory Protections
  - Common vector in general
- Mistranslated instruction set

JITs and Security

- Compiling traditional executables is *typ* y developers
- Code compilation is a trust boundary
  - You've accepted your vendor's code and binary
  - But now your compiling *my untrusted code*

Incorrect Code Emission

- JITs don't always produce perfect code
  - Its impossible
- Compiler bugs are often caught during development and testing
- What can happen when the JIT emits incorrect code?

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Incorrect Code Emission

- Java x64 JIT *bug* patched on June 18th, 2011
- Unintended code emission:

addq %rsp,0xffffff2b ; shift the stack pointer!

popfq ; pop 64 bits from stack+0xffffff2b ; load the lower 32 bits into RFLAGS

Intended code emission:

addq (%rsp),0xffffff2b ; add 0xffffff2b to the value at %rsp
popfq ; pop 64 bits from stack, load ; the lower 32 bits into RFLAGS

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Incorrect Code Emission

- There are many examples of this
  - 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!

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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 it should be debated by the security research community

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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

- Publicized by Dion's talk
- 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
- Only 2 JIT engines randomize *VirtualAlloc*
  - V8, IE9
  - Does it matter on 32 bit?

JIT Spray

- JIT Spray in Firefox through JaegerMonkey
  - 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 into 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**

Memory Protections

- Nearly all JITs we surveyed produce RWX pages
  - Breaks DEP / W^X
  - Breaks assumption behind 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

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Memory Protections

- RWX pages can be repurposed for different things
  - Array index read/write
    - Point into JIT page
      - Write raw shell code, trigger JavaScript
      - Read pointers to a DLL that may be mapped beyond your reach
  - Overflows
    - Heap overflow in adjacent RW page
  - ROP
    - No need to find that VirtualAlloc stub

gaJITs

- ROP Gadgets are small sequences of code found in an existing DLL or .text
  - Combine them to get arbitrary code execution
- gaJITs: Predictable instructions on JIT pages at predictable 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

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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 inputs to generate them
  - Requires a specific gadget-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 creates 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!

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JIT Feng Shui + gaJITs

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

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JIT Protections

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

Emission Randomization

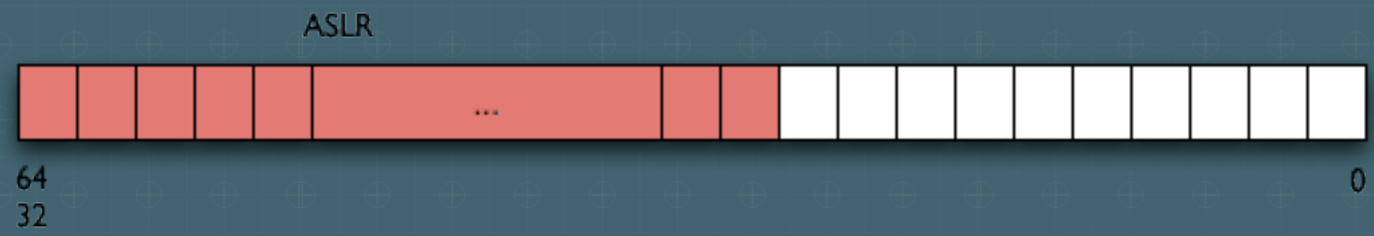
- Emitting code at runtime allows for randomizing addresses
  - High 22 bits (54 on 64 bit [fact check]) get randomized due to ASLR, or opting into a random address
  - Low ~3 bits get randomized due to NOP insertion
  - The middle bits get optimized within code region

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

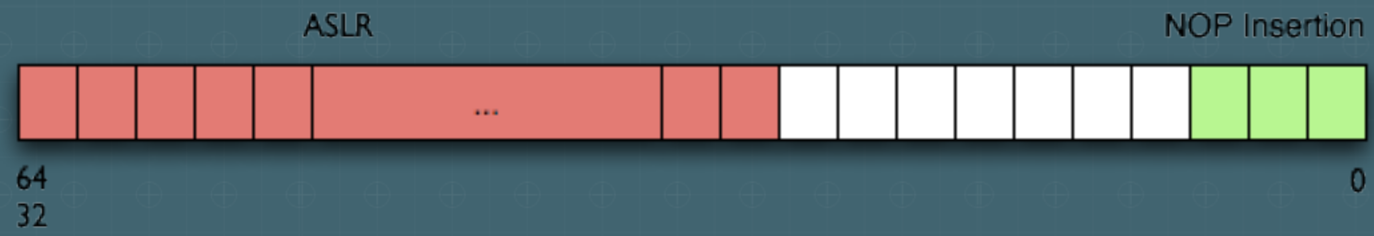
Randomization



Randomization

- Intra-page offsets (bottom 10 bits) are still predictable
- Since you're emitting code, you can shift each function emitted by inserting NOPs

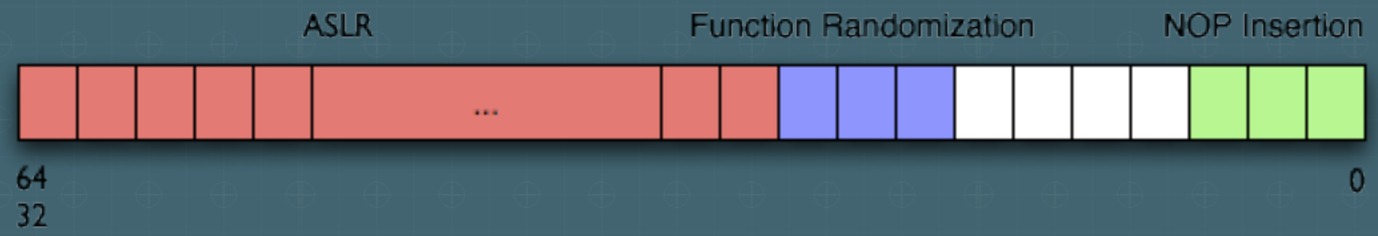
Randomization



Randomization

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

Randomization



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
  - Trigger JavaScript to get code execution
    - Blind execution
  - No need to gain EIP or overwrite a function pointer

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 allows 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 awhile, now they use constant blinding

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Constant Blinding

- XOR all untrusted immediate values by a secret cookie
- Generate a random value at startup
    - untrusted immediate ^ 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

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

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 the 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, code, 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
  - Outputs locations of 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)
  - Targets the JIT and interpreter only
    - DOM bugs are boring

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rubyfuzz

- Ruby fuzzer 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 framework Hoke
  - Generated test cases external to the Ruby implementation

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 constructs

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fuzzer(s)

- JavaScript Grammar fuzzer for Firefox JITs
- Describe JavaScript in flat text files
  - types, methods, properties, keywords, operators
- Parse text files and serialize into Ruby OpenStruct
- Iterate over the grammar
  - Fast Paths
  - Inline Caches
  - C++ Stubs
- Hundreds of millions of iterations through ./js

fuzzer(s)

- A note on fuzzing for info leaks
    - Fuzzing should be fast
    - Instrumentation is slow
- Differential fuzzing for info leaks
    - Two JavaScript implementations
        - d8 (V8) / js (Mozilla)
        - Feed them the same testcase
        - Record the output
            - What is the expected output type/value?
- Can be generalized to multiple implementations of any language

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A bug our fuzzer found

- Our fuzzer found a critical bug in SpiderMonkey

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

  - Info Leak: read arbitrary data from *current*
  - Code Execution: call a method on *current* object

Demo?

Questions

?

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