haha v8 engine go brrrrr

Syed Faraz Abrar

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whoami

Cyber Security Undergraduate @ Curtin University

Security Researcher @ elttam

Currently focusing on Chrome

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TL;DR

- Background information on browsers and sandboxing
- Internals of a couple of V8 components
- Analysis of a vulnerability for each of them
  - Focusing on bug hunting, not exploitation
- Tips on approaching V8 research

Browsers

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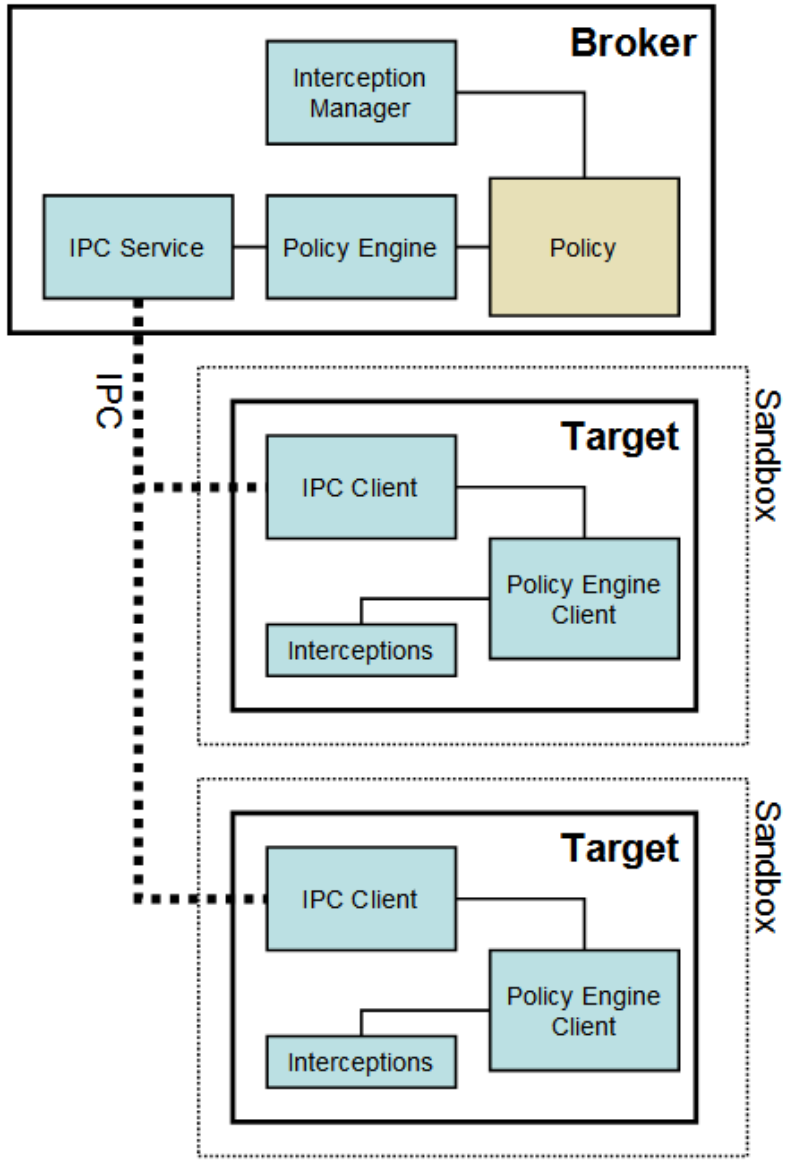

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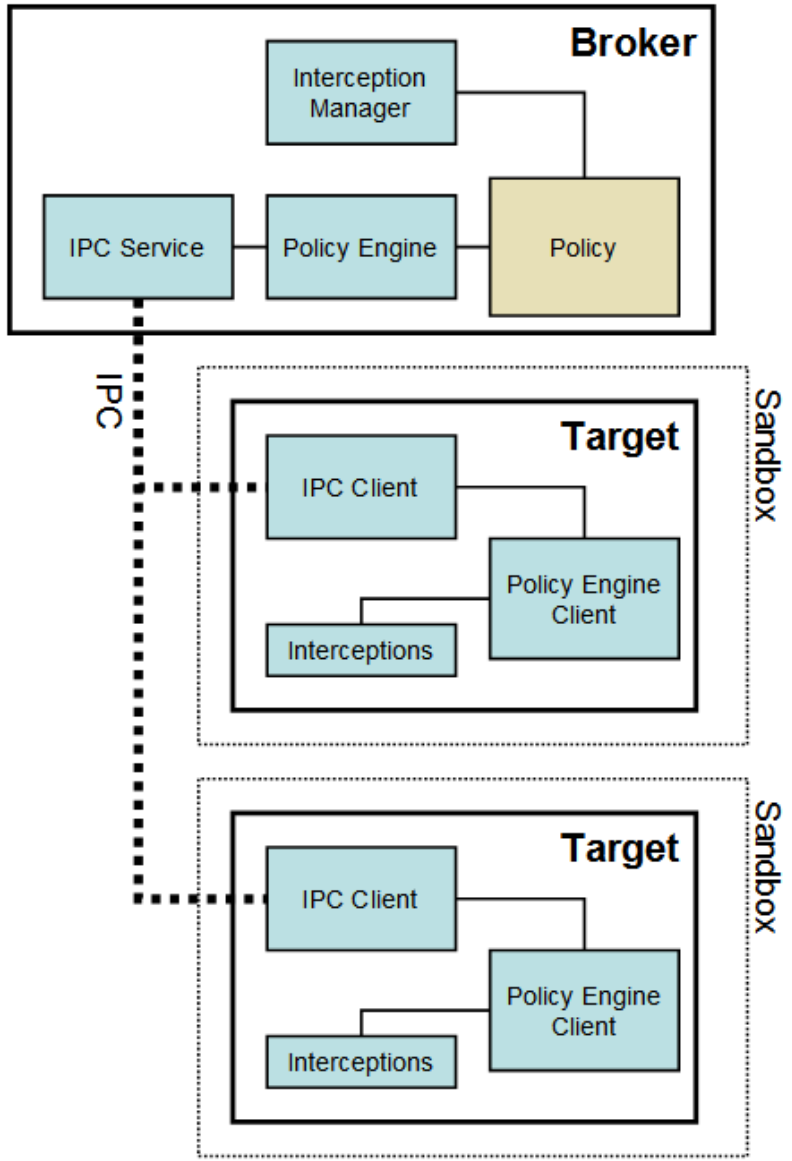

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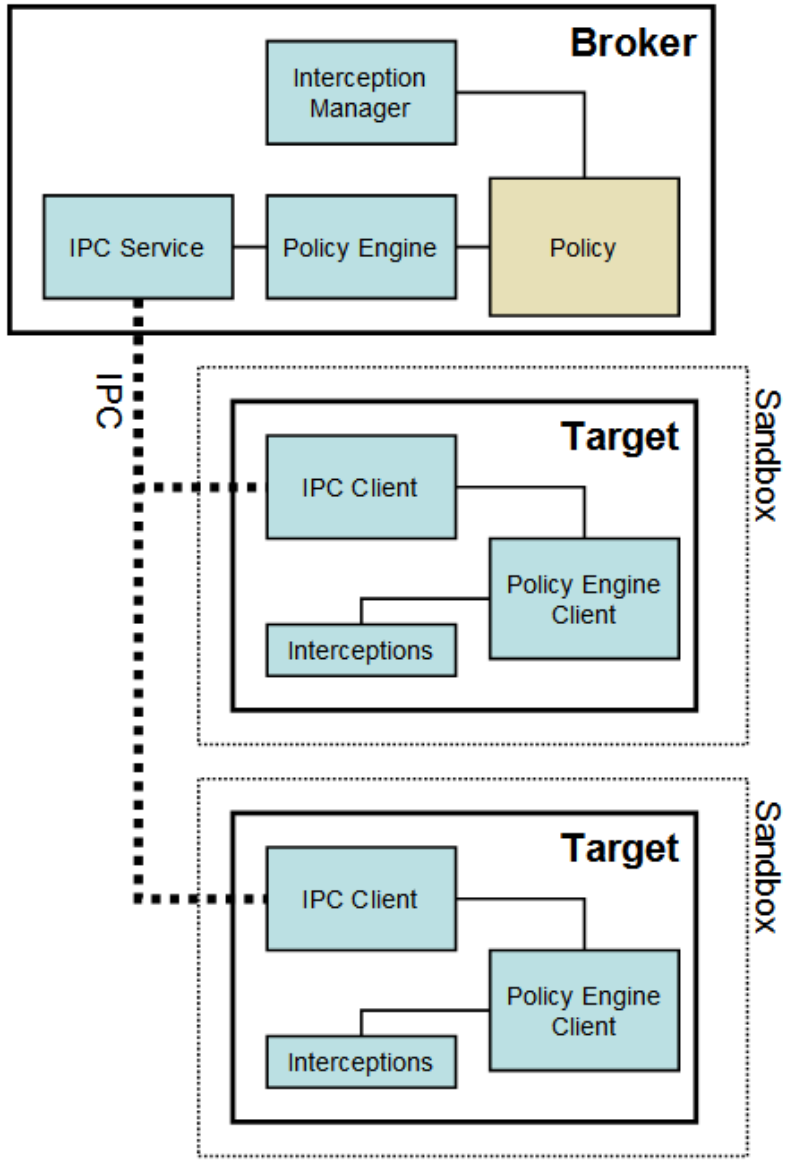

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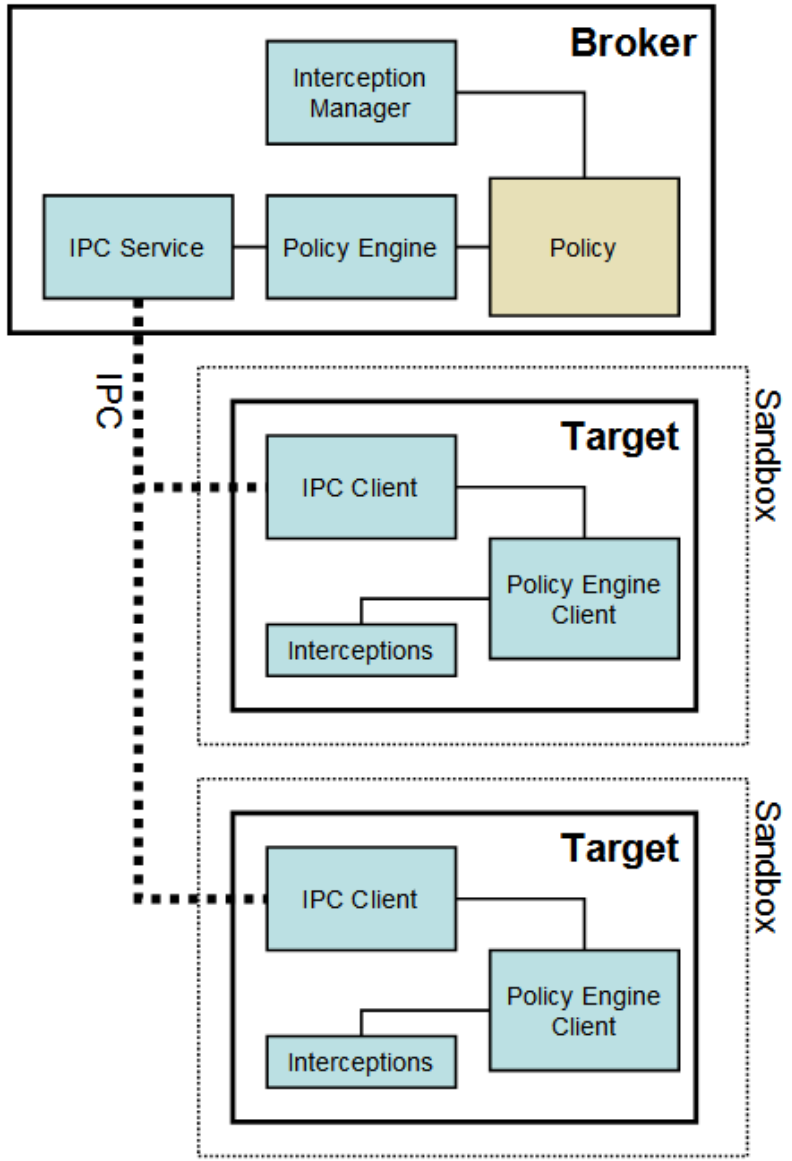

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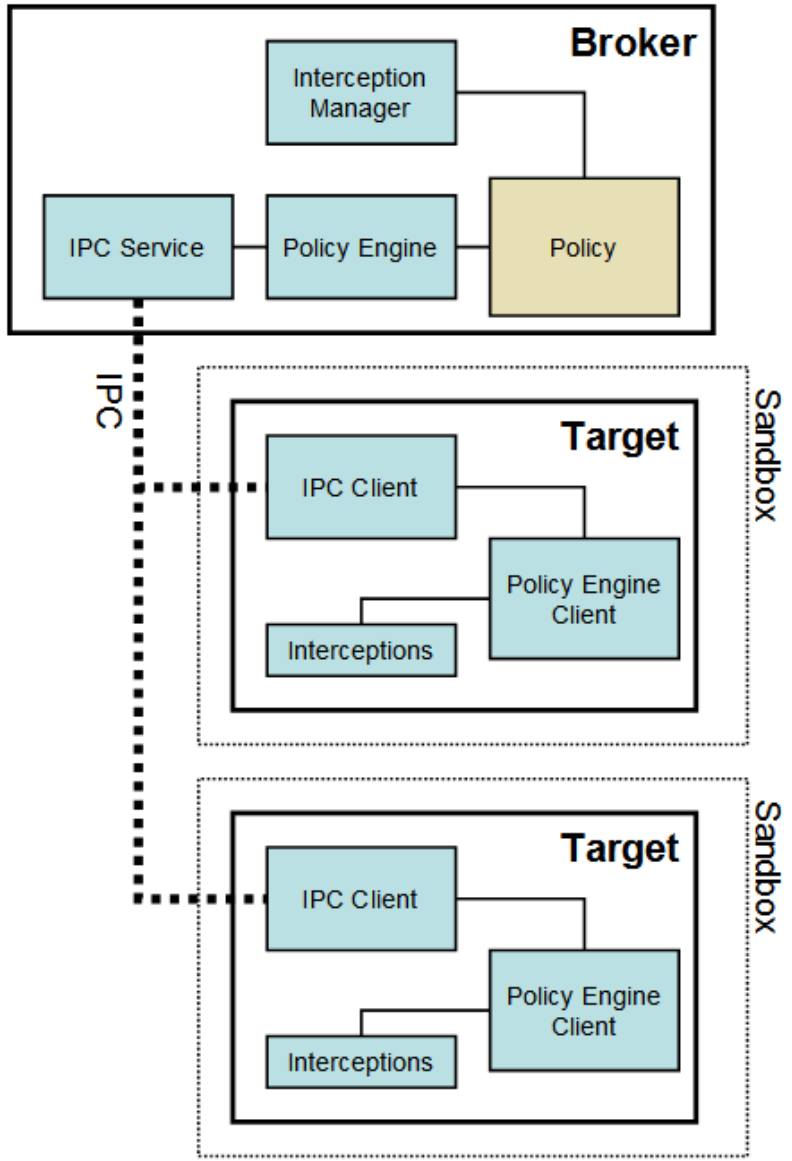

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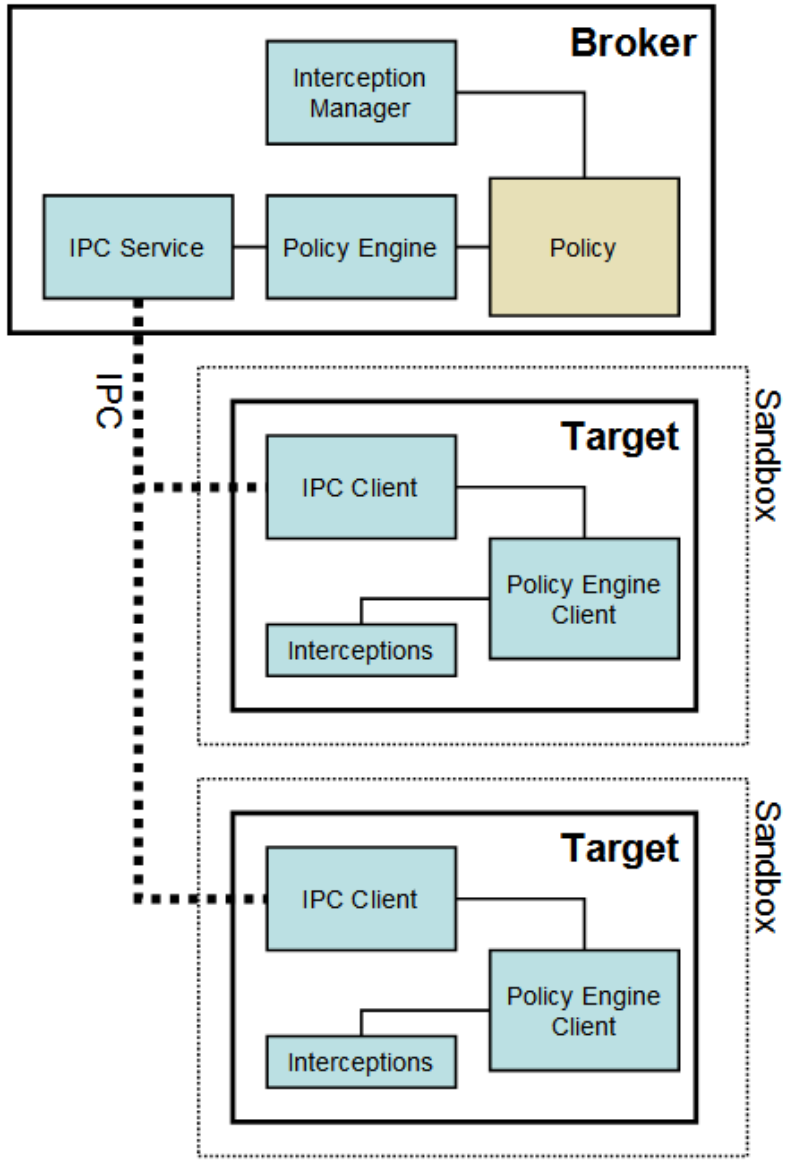

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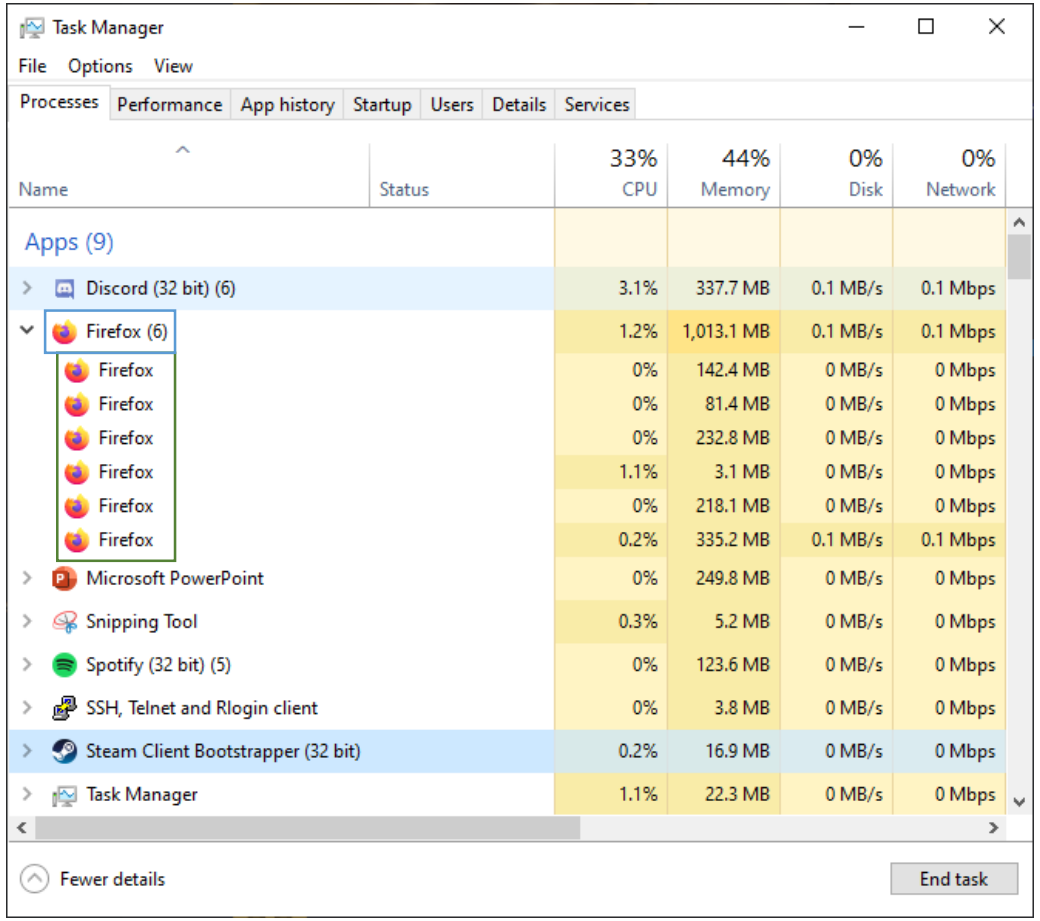
Multiprocess Architecture



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The *Browser* process intercepts all system calls made by the sandboxed processes and handles them.

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The enormous complexity of V8 means it contains entirely new and unique vulnerability classes.

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The *base address* is added to pointers prior to dereferencing.

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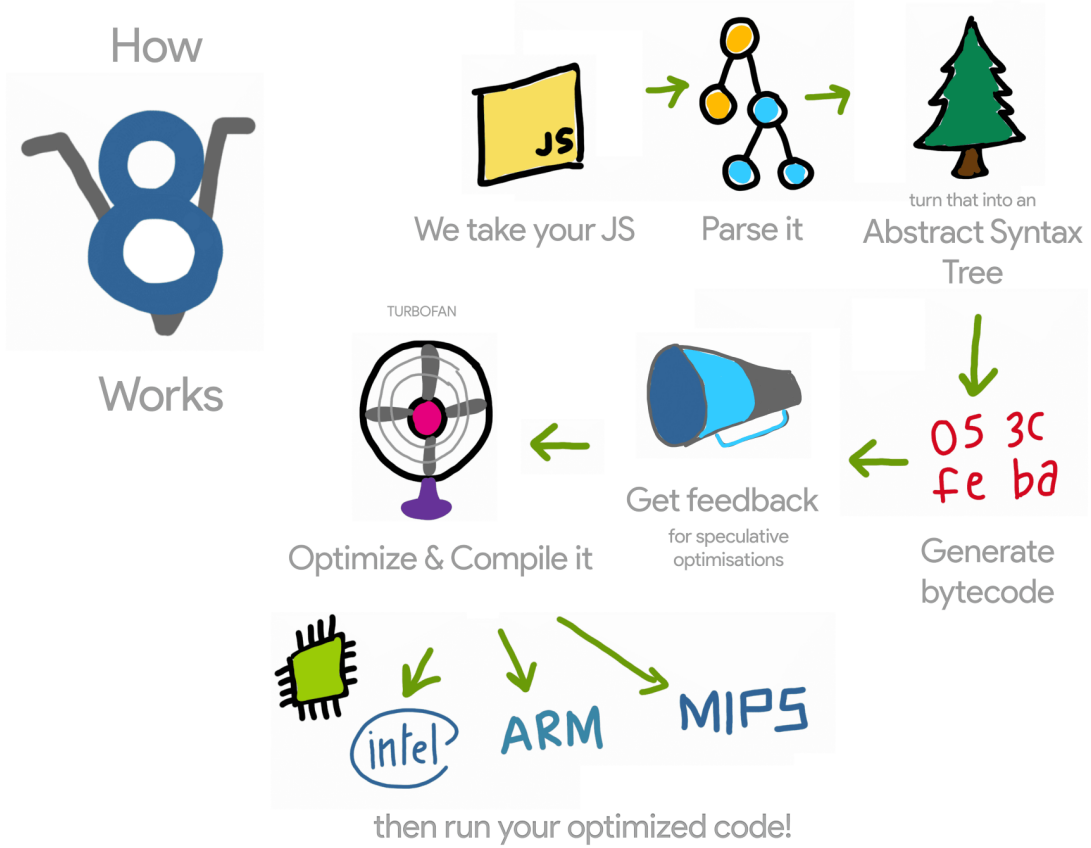
`v8/src/objects/objects.h`

```
// Formats of Object::ptr_:
//  Smi:        [31 bit signed int] 0
//  HeapObject: [32 bit direct pointer] (4 byte aligned) | 01
```


V8 Pipeline



By @addyosmani

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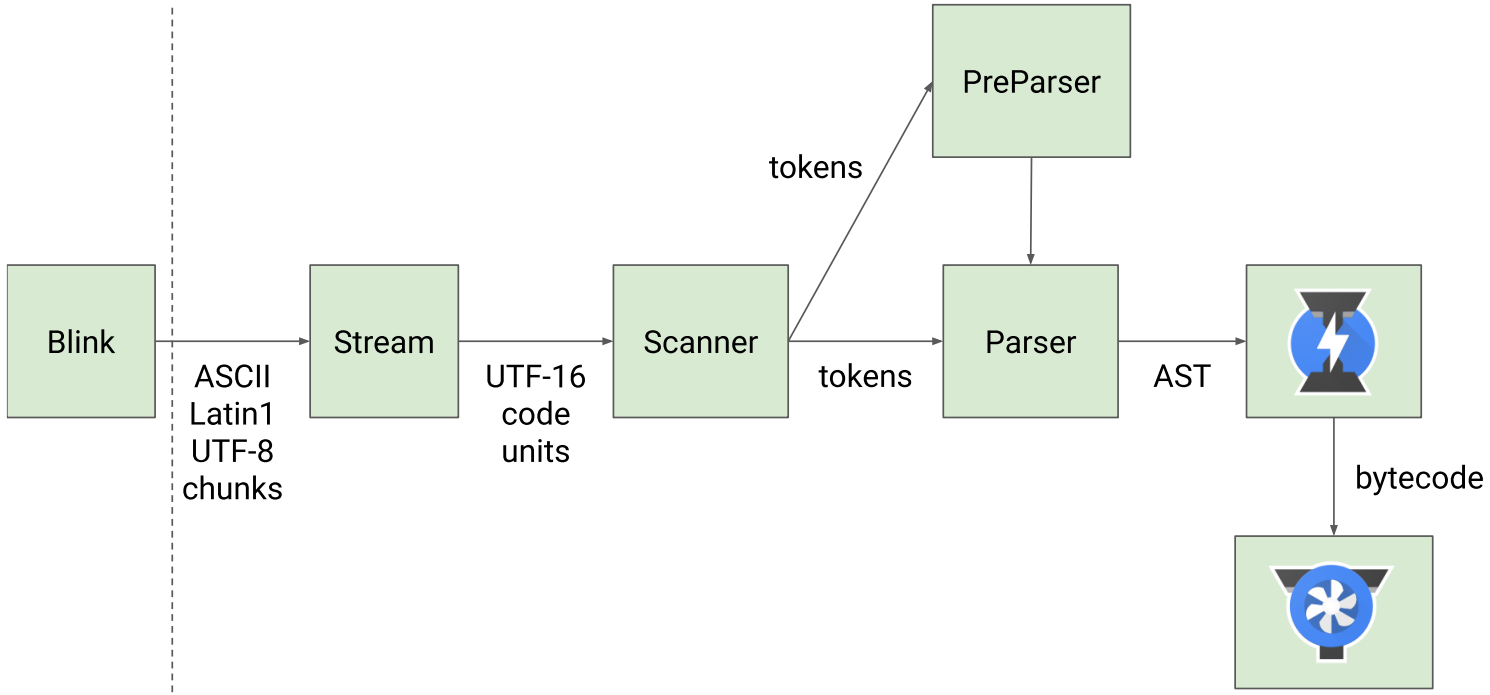

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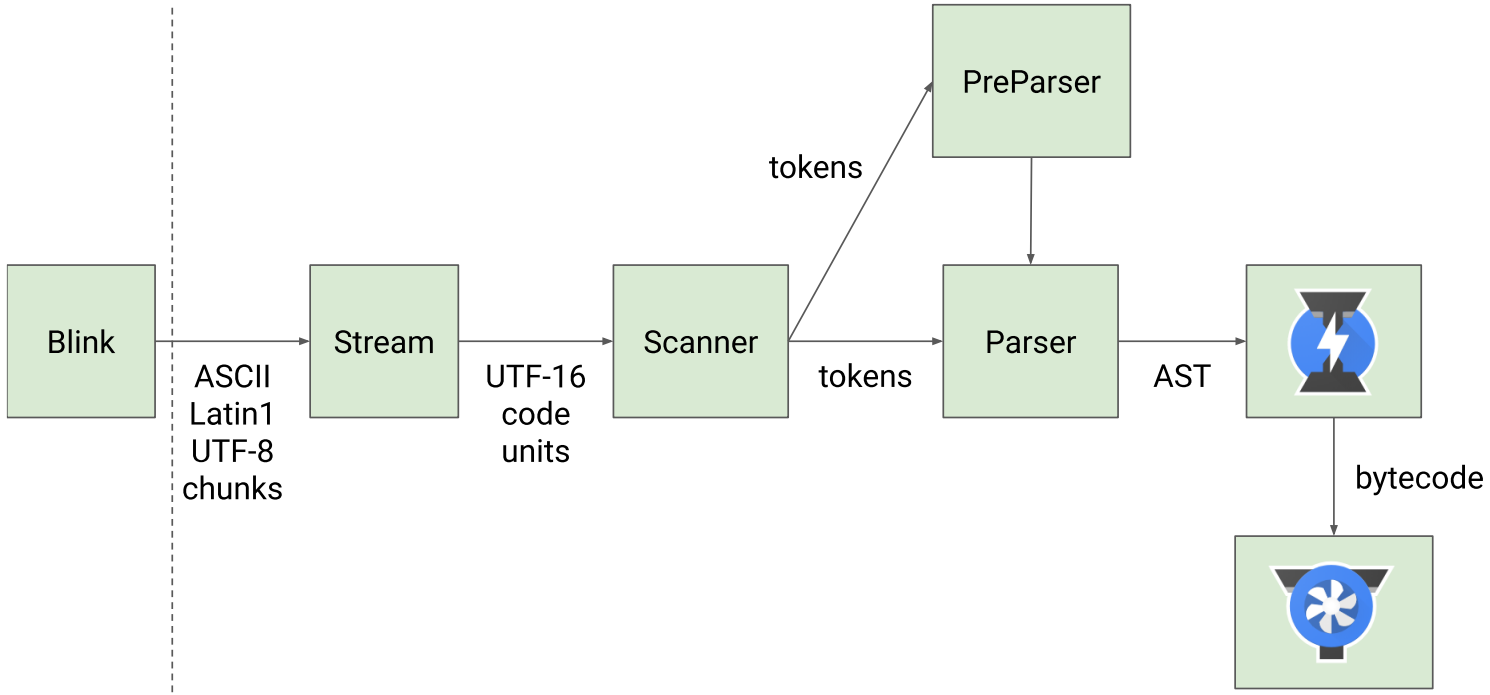

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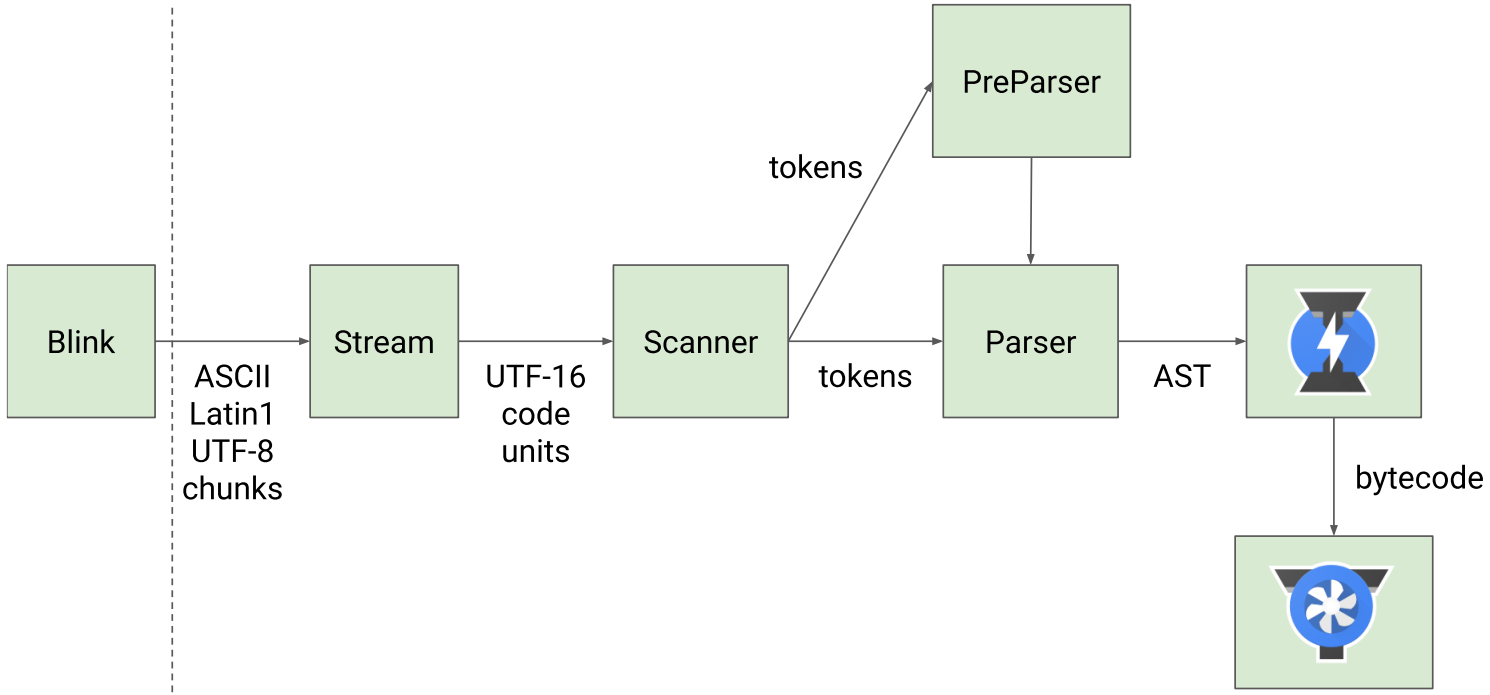

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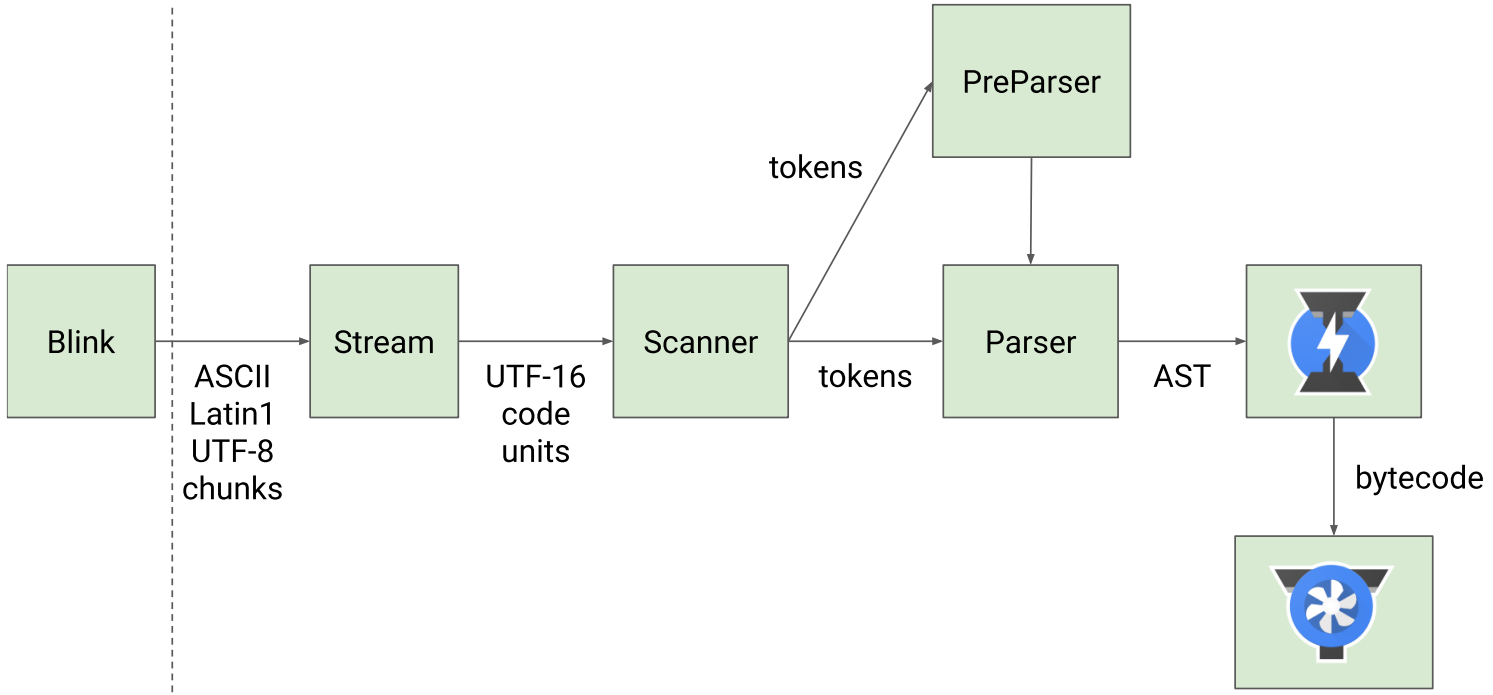
The **Parser** simply the code into an *Abstract Syntax Tree* (AST). The **Parser** might also parse functions that were *Preparsed* previously if they are now required to run.



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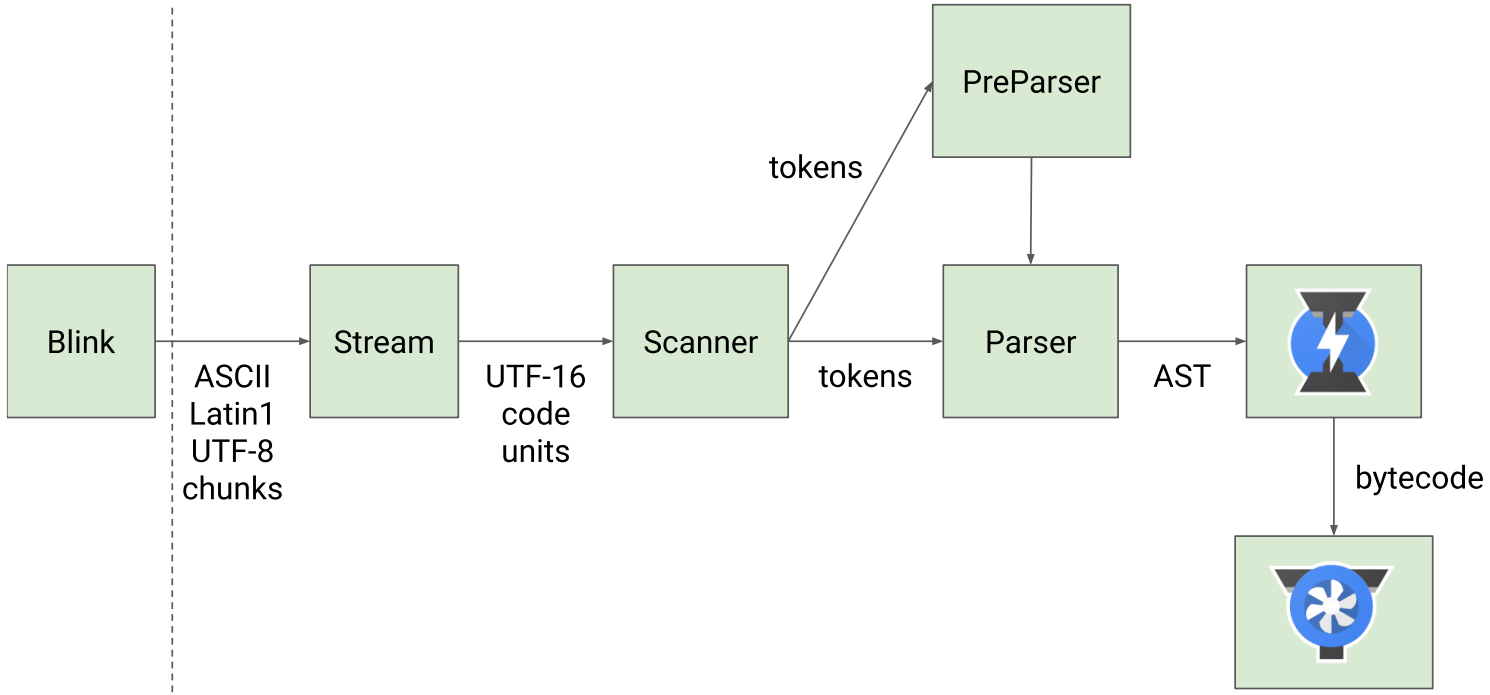
The AST is then passed into **Ignition**, which is V8's bytecode compiler / interpreter.



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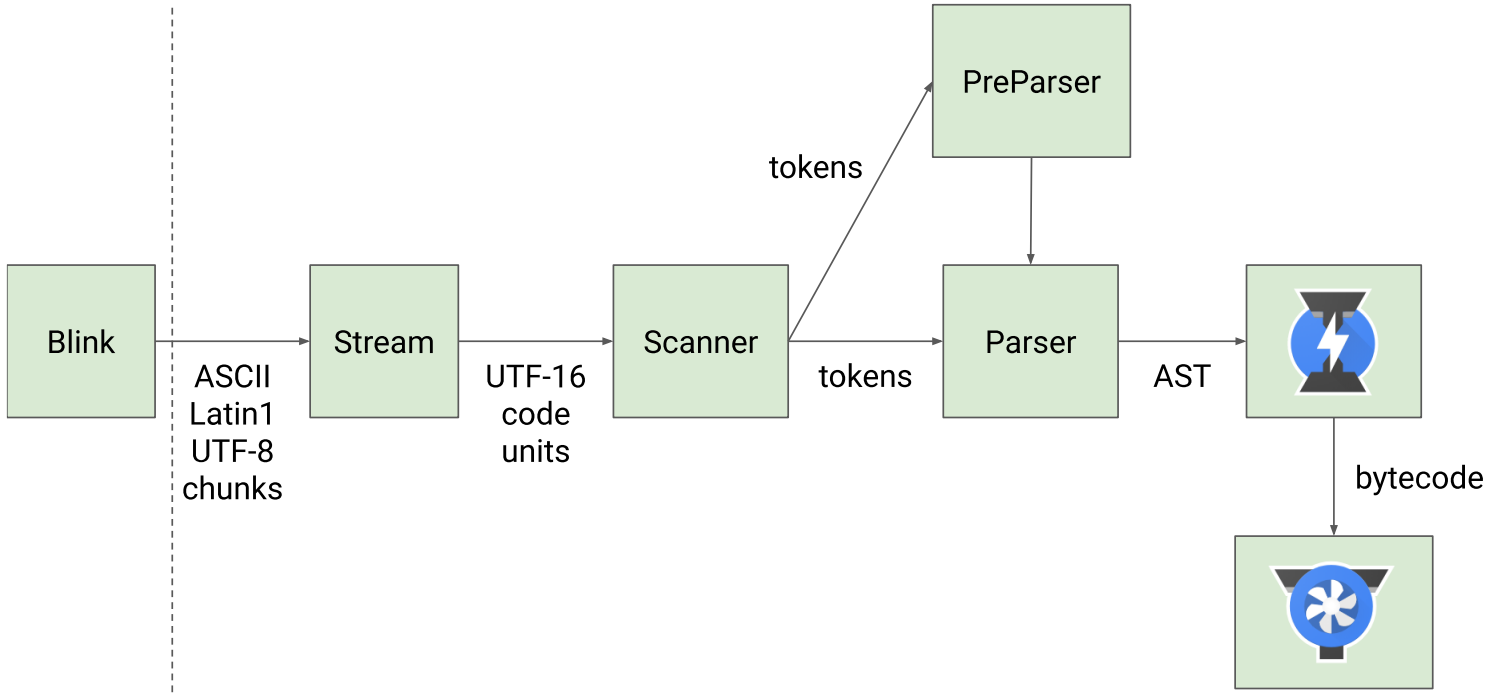

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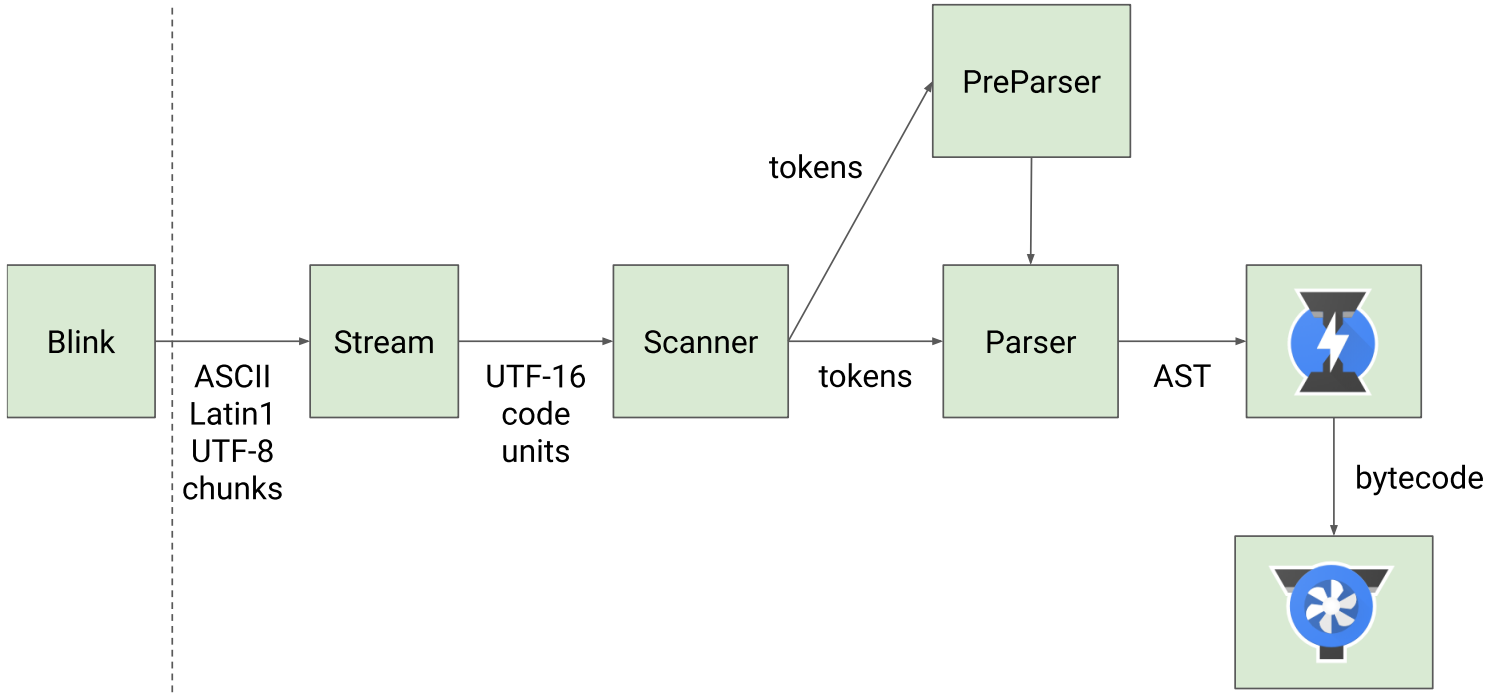
The Ignition *compiler* first compiles the AST into bytecode.

Finally, the Ignition *interpreter* interprets and executes this bytecode.



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Integer overflow within the *Scanner* found by Dimitry Fourny of Bluefrostsecurity.

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The `Scanner::Scan` method starts off by calling `Scanner::ScanSingleToken` to read in a single token.

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The `Scanner::Scan` method starts off by calling `Scanner::ScanSingleToken` to read in a single token.

Let's take a String as an example. We get the following call stack:

```
Scanner::Scan -> Scanner::ScanSingleToken ->
Scanner::ScanString -> Scanner::AddLiteralChar
-> Scanner::LiteralBuffer::AddChar ->
Scanner::LiteralBuffer::AddTwoByteChar
```


CVE-2019-5790 – LiteralBuffer Integer Overflow

```
void Scanner::LiteralBuffer::AddTwoByteChar(uc32 code_unit) {
  DCHECK(!is_one_byte());
  if (position_ >= backing_store_.length()) ExpandBuffer();
  if (code_unit <=
      static_cast(unibrow::Utf16::kMaxNonSurrogateCharCode)) {
    *reinterpret_cast<uint16_t*>(&backing_store_[position_]) = code_unit;
    position_ += kUC16Size;
  } else {
    *reinterpret_cast<uint16_t*>(&backing_store_[position_]) =
        unibrow::Utf16::LeadSurrogate(code_unit);
    position_ += kUC16Size;
    if (position_ >= backing_store_.length()) ExpandBuffer();
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  }
}
```

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CVE-2019-5790 – LiteralBuffer Integer Overflow

```
void Scanner::LiteralBuffer::ExpandBuffer() {
  Vector new_store = Vector::New(NewCapacity(kInitialCapacity));
  MemCopy(new_store.start(), backing_store_.start(), position_);
  backing_store_.Dispose();
  backing_store_ = new_store;
}
```

`kInitialCapacity = 16;`

```
int Scanner::LiteralBuffer::NewCapacity(int min_capacity) {
  int capacity = Max(min_capacity, backing_store_.length());
  int new_capacity = Min(capacity * kGrowthFactor, capacity + kMaxGrowth);
  return new_capacity;
}
```

`kGrowthFactor = 4; kMaxGrowth = 1024 * 1024;`

What if `(capacity * kGrowthFactor)` overflows and becomes less than `(capacity + kMaxGrowth)`?

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CVE-2019-5790 – LiteralBuffer Integer Overflow

```
int length() const {
  DCHECK_GE(std::numeric_limits<int>::max(), length_); // max length check
  return static_cast<int>(length_);
}
```

A `Vector` cannot have a size greater than $2^{31}-1$.

Proof of Concept:

```
let s = String.fromCharCode(0x4141).repeat(0x10000001) + "A";
s = "'"+s+"'";
eval(s);
```

```
capacity = 2 * 0x10000001 = 0x20000002
capacity * kGrowthFactory = 0x20000002 * 4 = 0x80000008
capacity + kMaxGrowth = 0x20000002 + (1024 * 1024) = 0x20100002
```

32-bit signed integer max value = $2^{31}-1$ = 0x7FFFFFFF

The first calculation overflows and yields a smaller value than the original capacity. This will in turn result in a heap overflow when the `MemCopy` is called later on.

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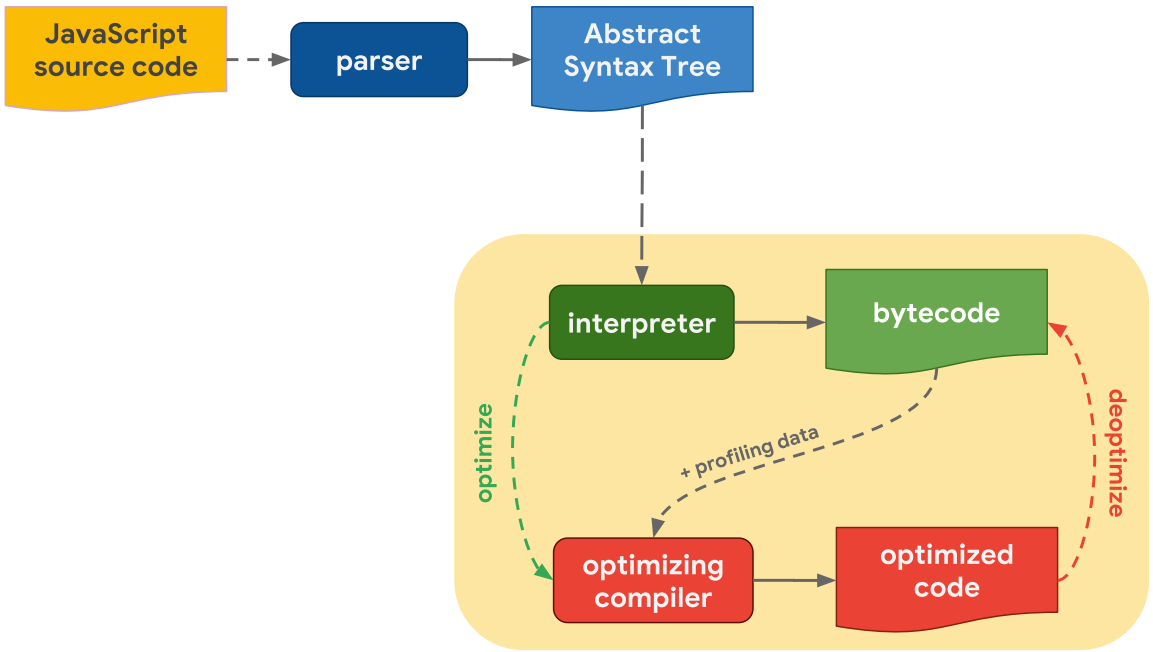
Ignition is V8's fast low-level register-based interpreter.



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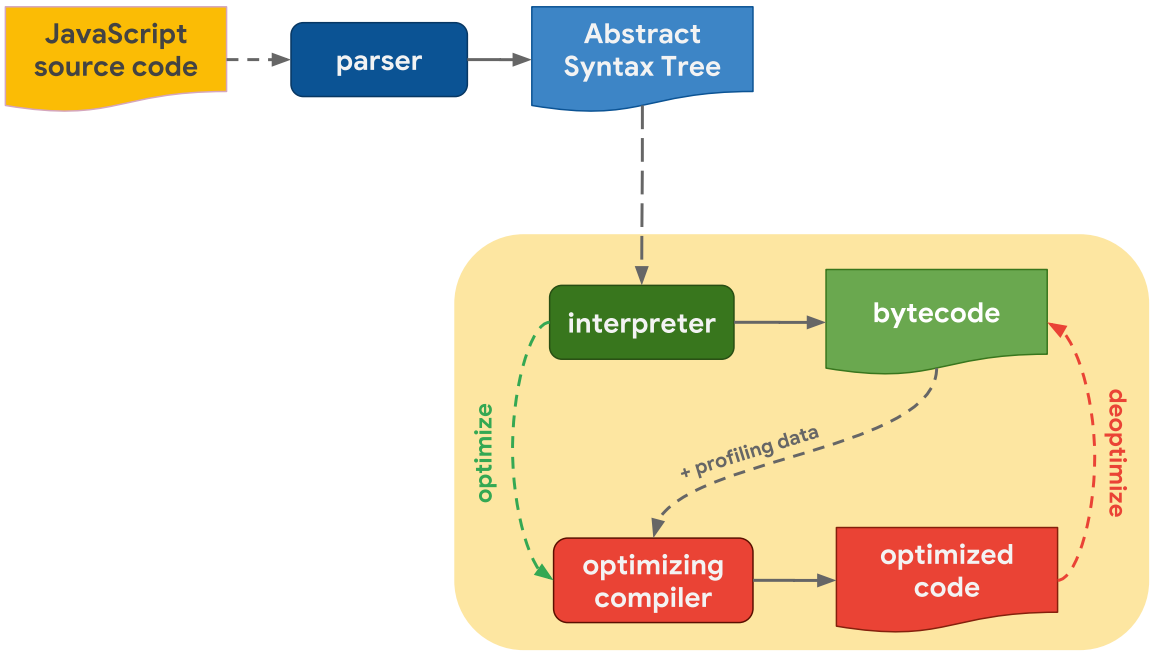

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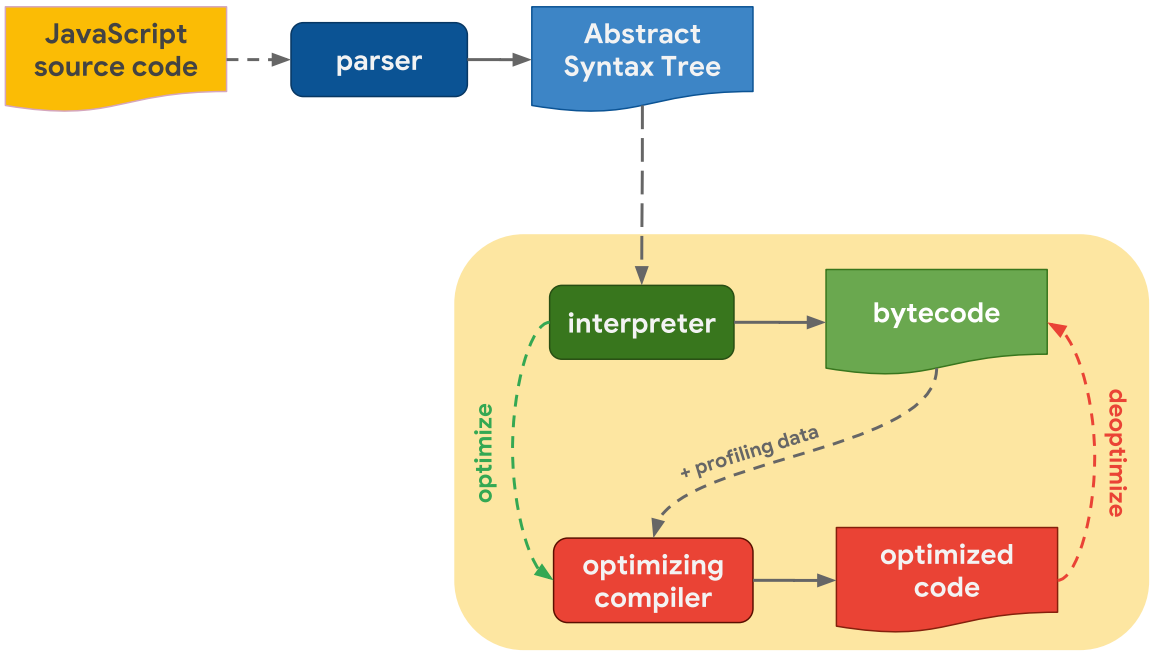

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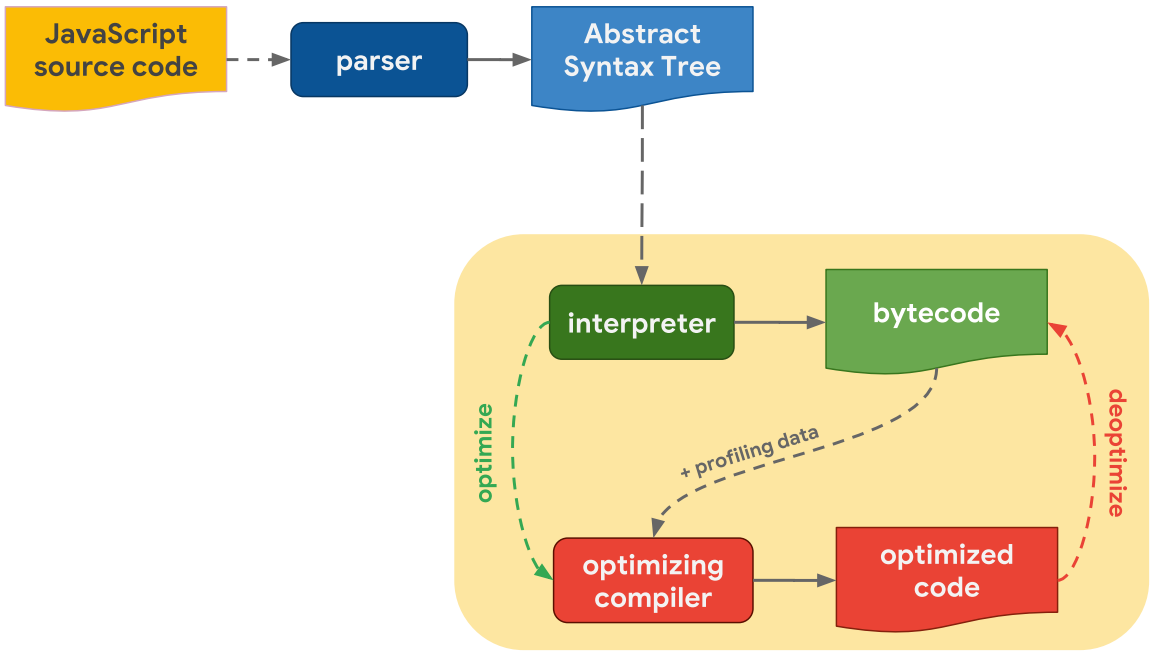
A special register known as the **accumulator** register is used for calculations and return values (similar to RAX in x86).



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Bytecode Execution

```
function add(x, y) {
  return x + y;
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console.log(add(1, 2));
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```
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[generated bytecode for function: add]
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Frame size 0
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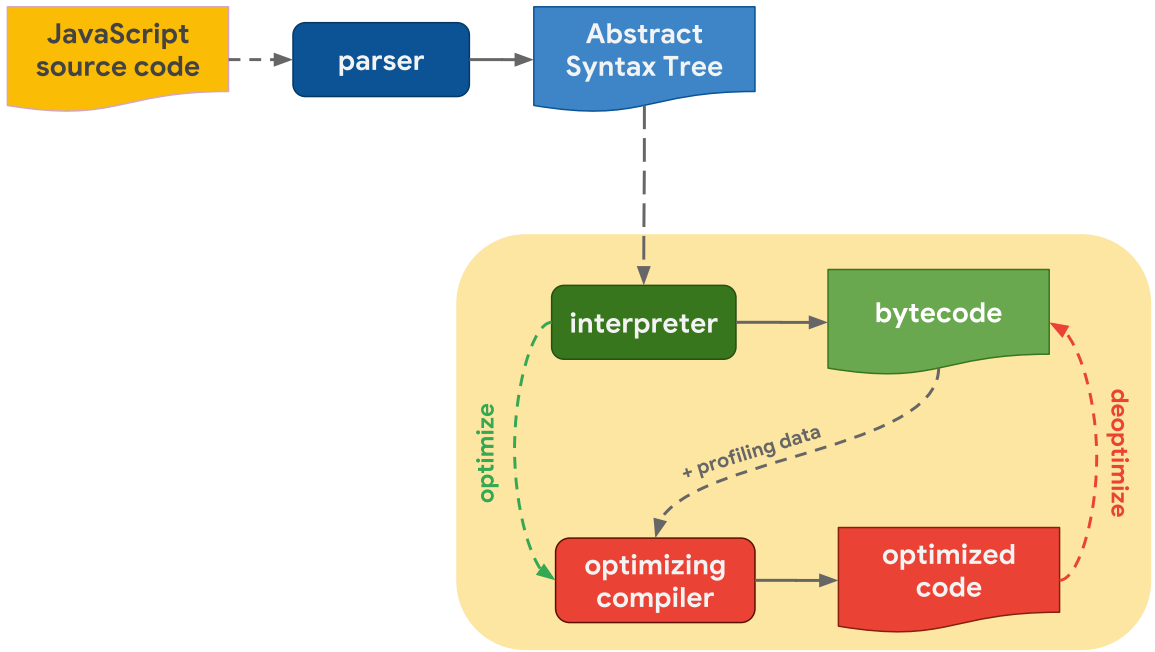

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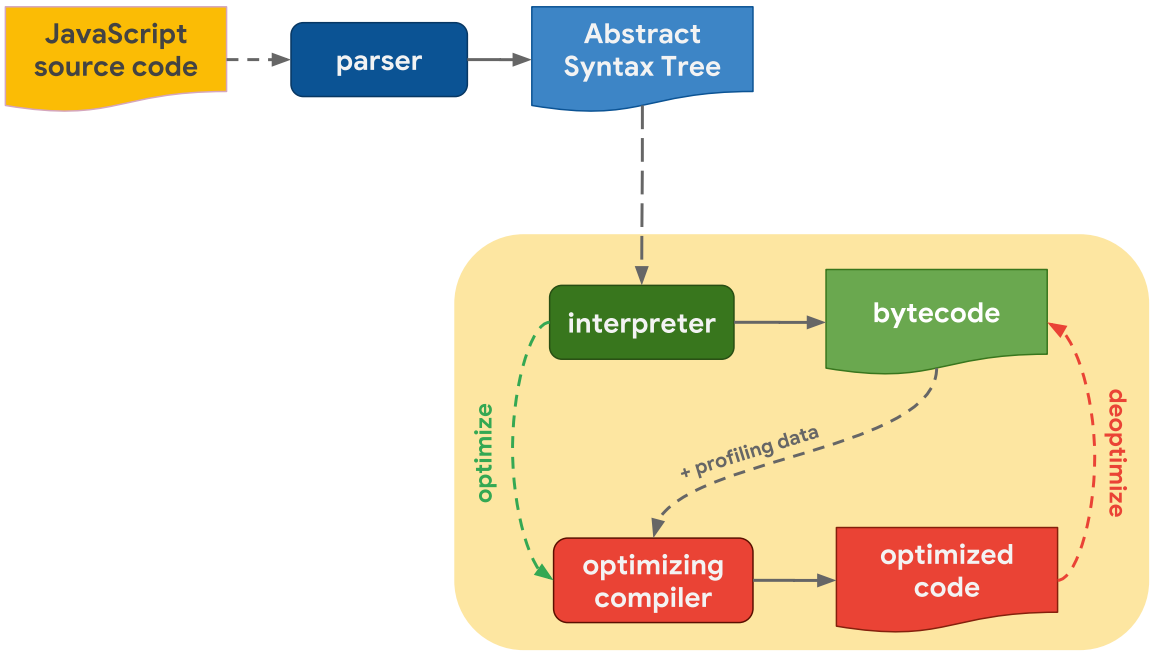

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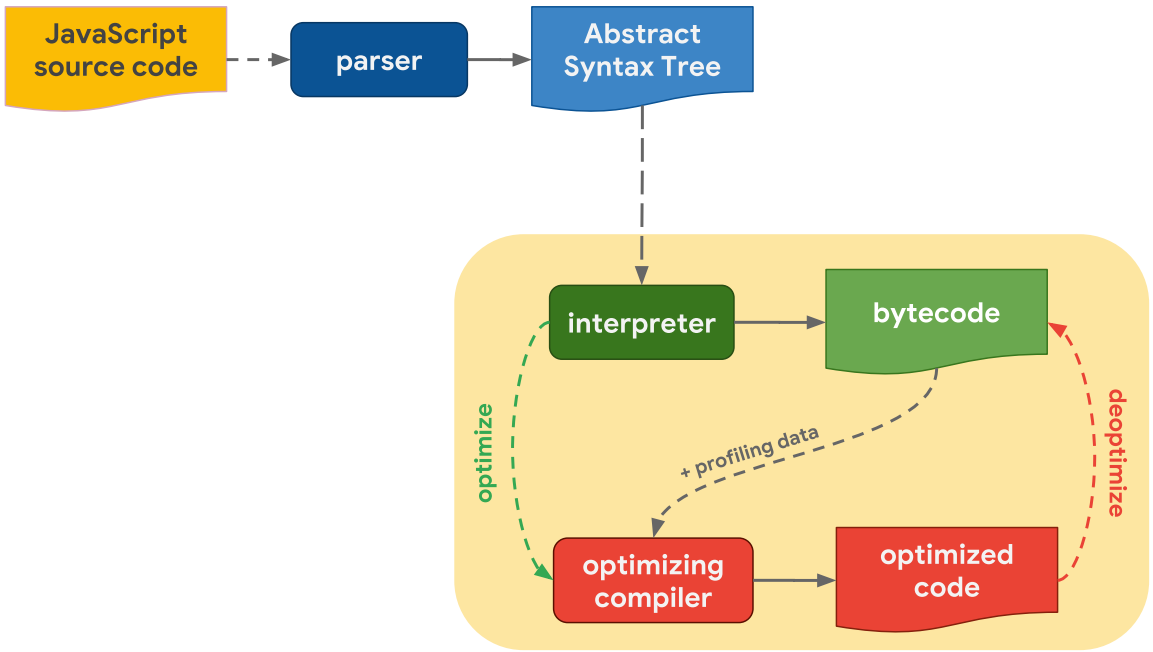

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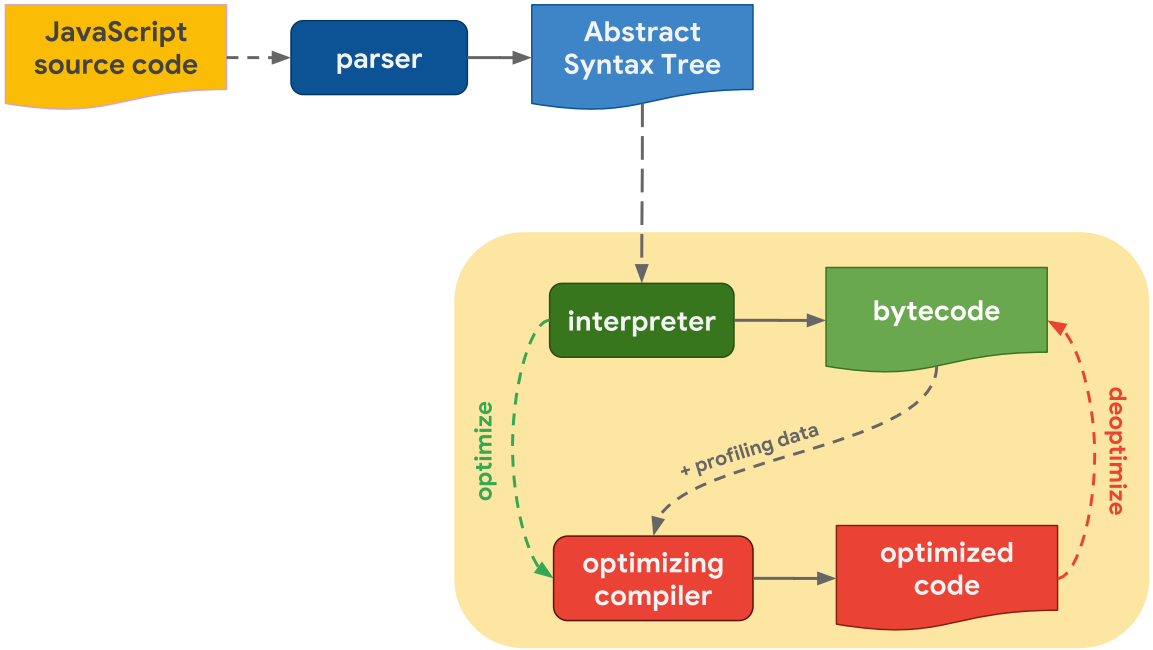
It uses these speculations as assumptions to produce highly optimized machine code.

If at any point these assumptions fail to hold true, the code is deoptimized and execution goes back to **Ignition**.



https://mathiasbynens.be/notes/shapes-ics

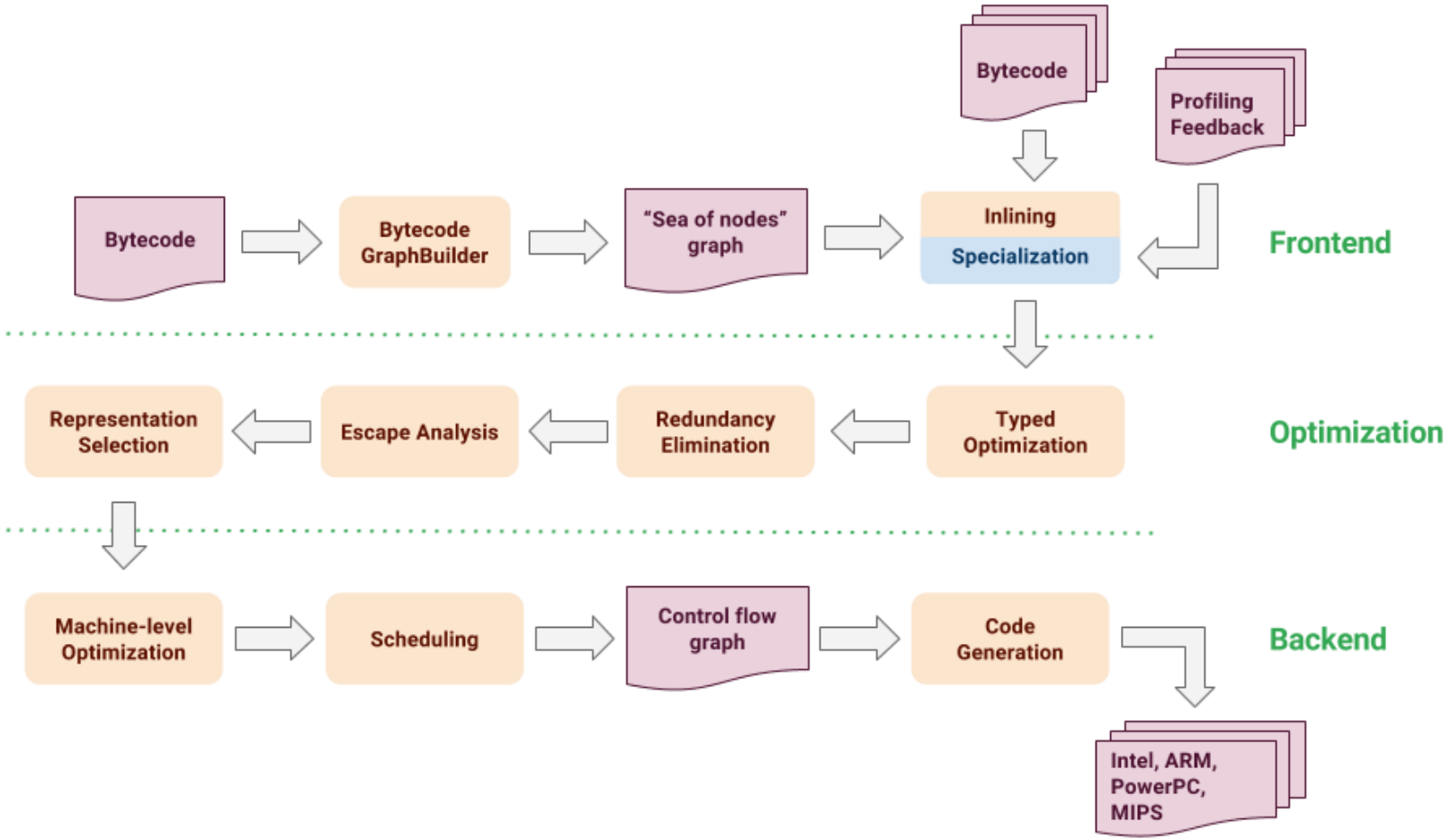
Speculative Optimization

```
function add(x, y) {
    return x + y;
}

for (var i = 0; i < 10000; i++) {
    add(1, 2);
}

add(1.1, 2.2);
```

```
add(1,2); // BinaryOp of SignedSmall
add(1,2); // Stored in Feedback Vector
…
add(1,2); // Optimized for Smis
…
add(1.1, 2.2); // Deoptimize to interpreter
```

@farazsth98

Speculative Optimization



@farazsth98

https://ponyfoo.com/articles/an-introduction-to-speculative-optimization-in-v8

Shapes

Shapes (a.k.a *HiddenClasses*) are used to store information about objects, specifically how their properties are to be accessed.

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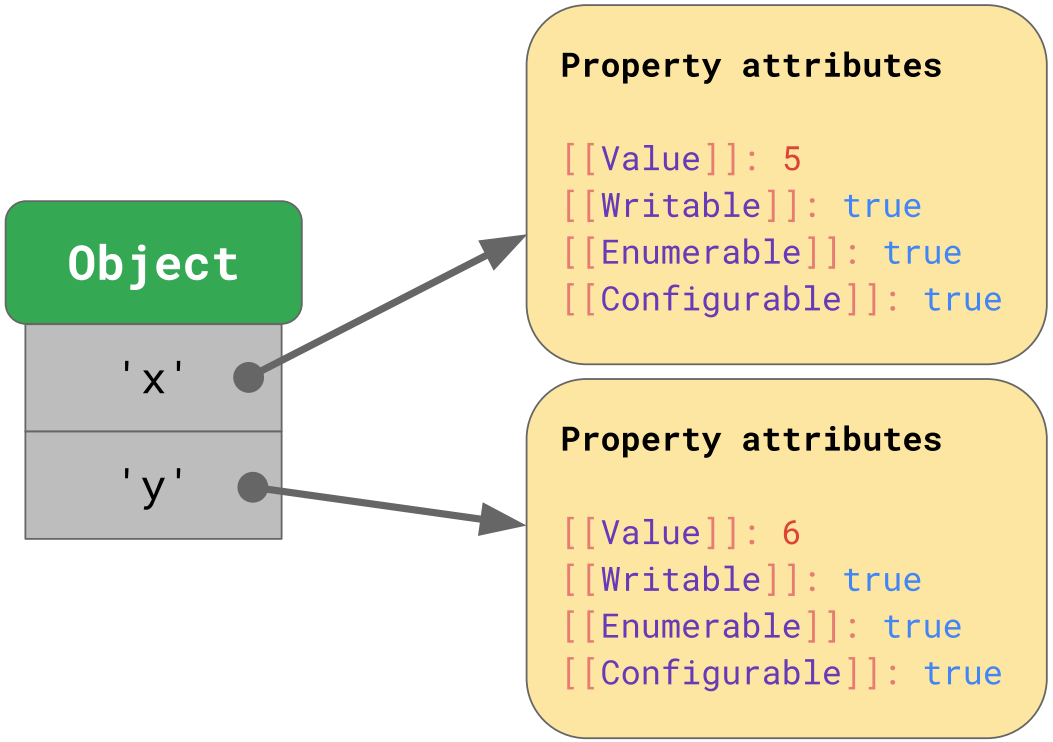
They also track *ElementsKinds* for arrays.

Shapes are created on-demand as needed, and shared between objects as much as possible.

Shapes

```
object = {
  x: 5,
  y: 6,
};
```



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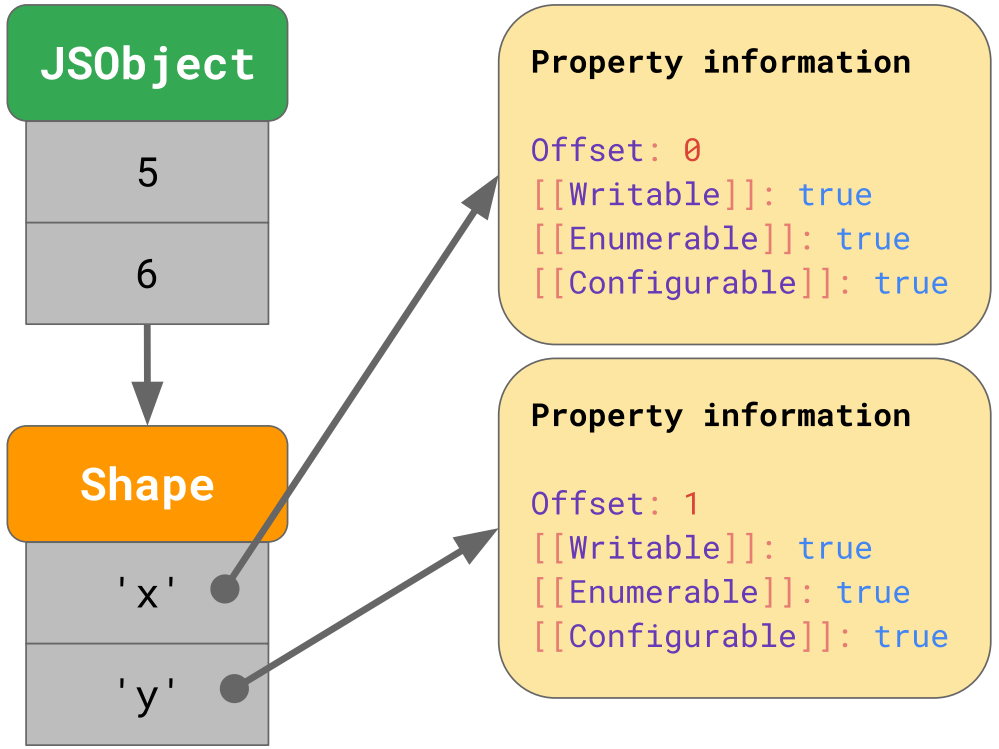

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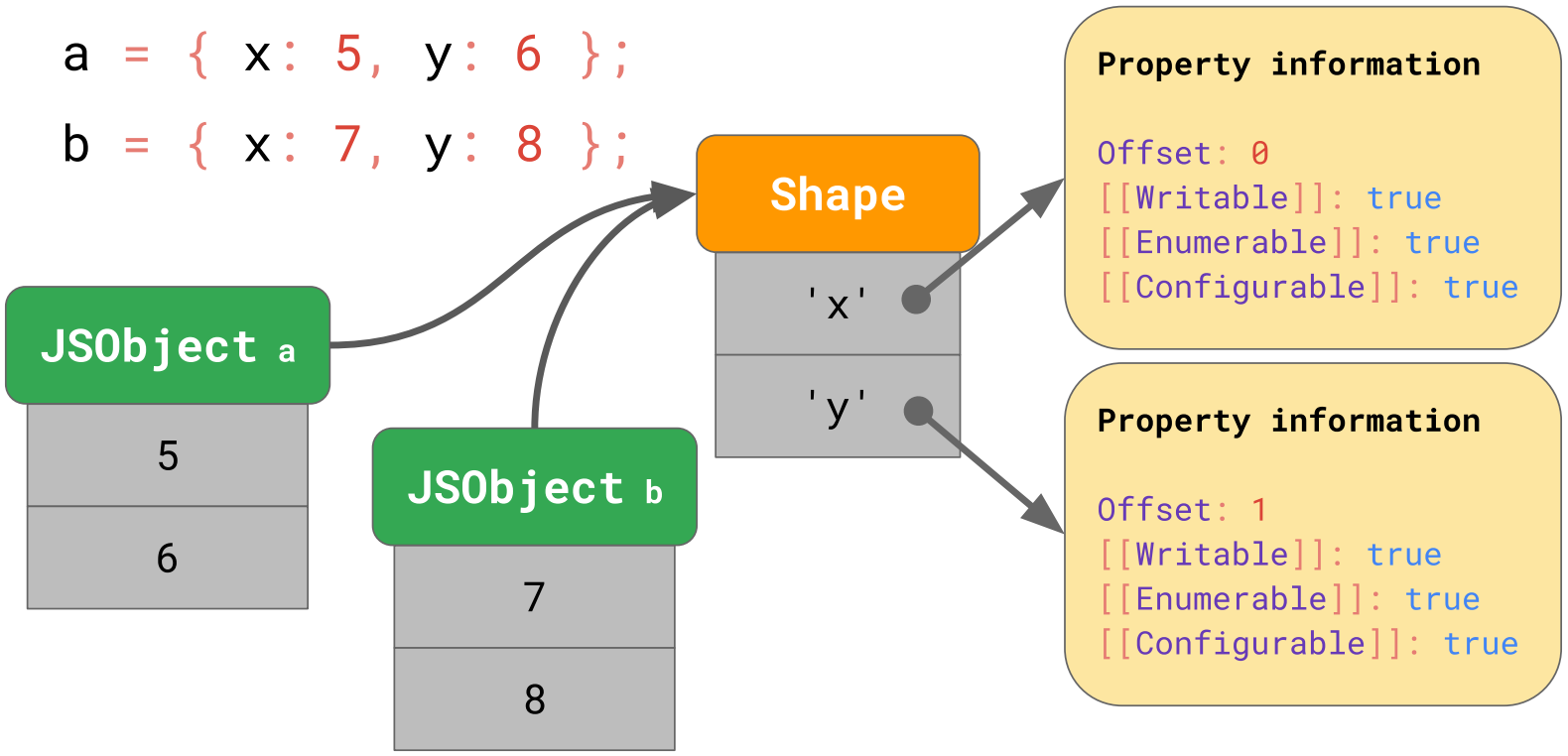
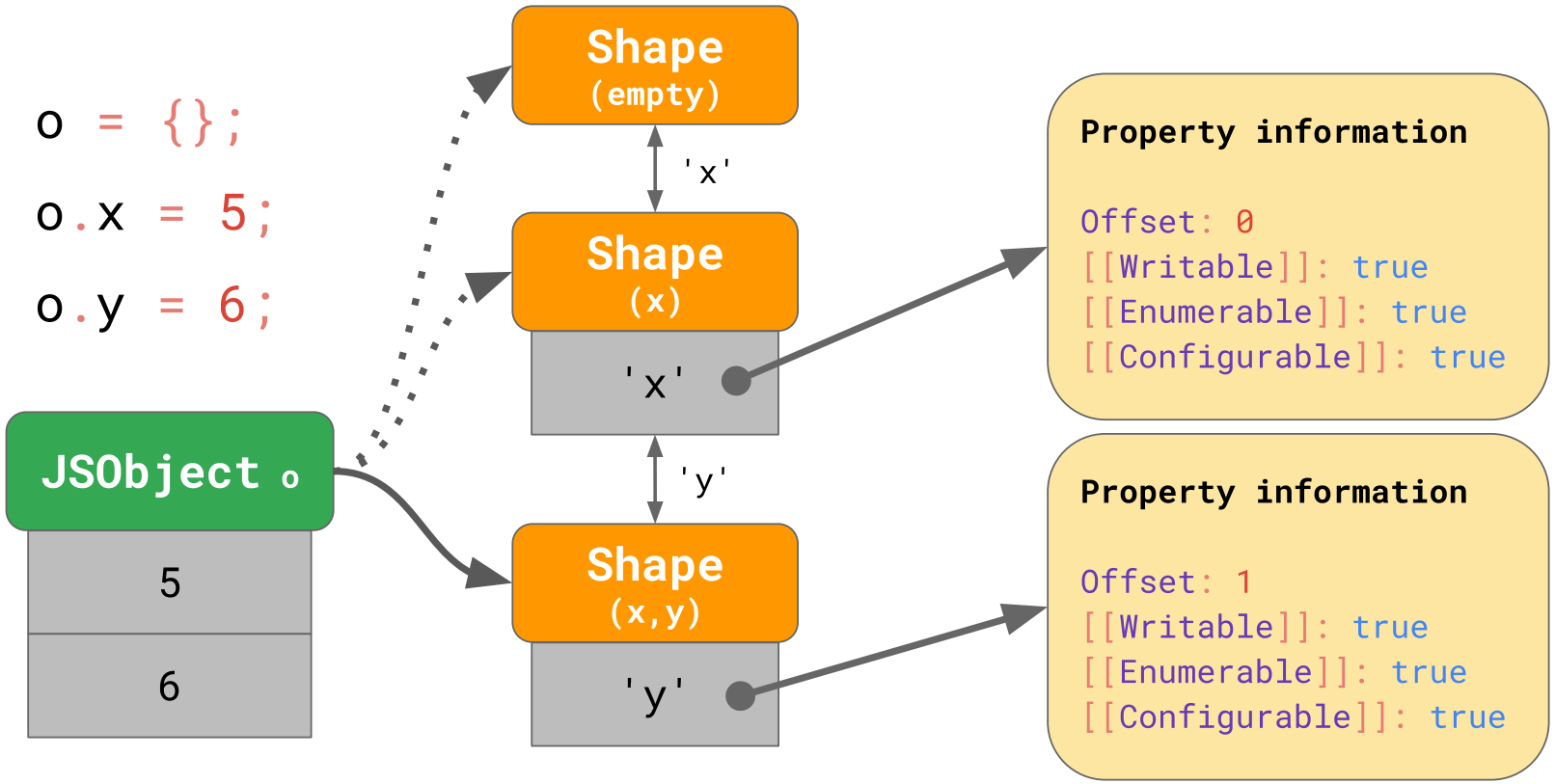

a = { x: 5, y: 6 };
b = { x: 7, y: 8 };
Shape
'x'
'y'
JSObject a
5
6
JSObject b
7
8
Property information
Offset: 0
[[Writable]]: true
[[Enumerable]]: true
[[Configurable]]: true
Property information
Offset: 1
[[Writable]]: true
[[Enumerable]]: true
[[Configurable]]: true

Shapes


o = {};
o.x = 5;
o.y = 6;
JSObject o
5
6
Shape
(empty)
'x'
Shape
(x)
'x'
'y'
Shape
(x,y)
'y'
Property information
Offset: 0
[[Writable]]: true
[[Enumerable]]: true
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Property information
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Shapes

```
a = {};
a.x = 5;
b = {};
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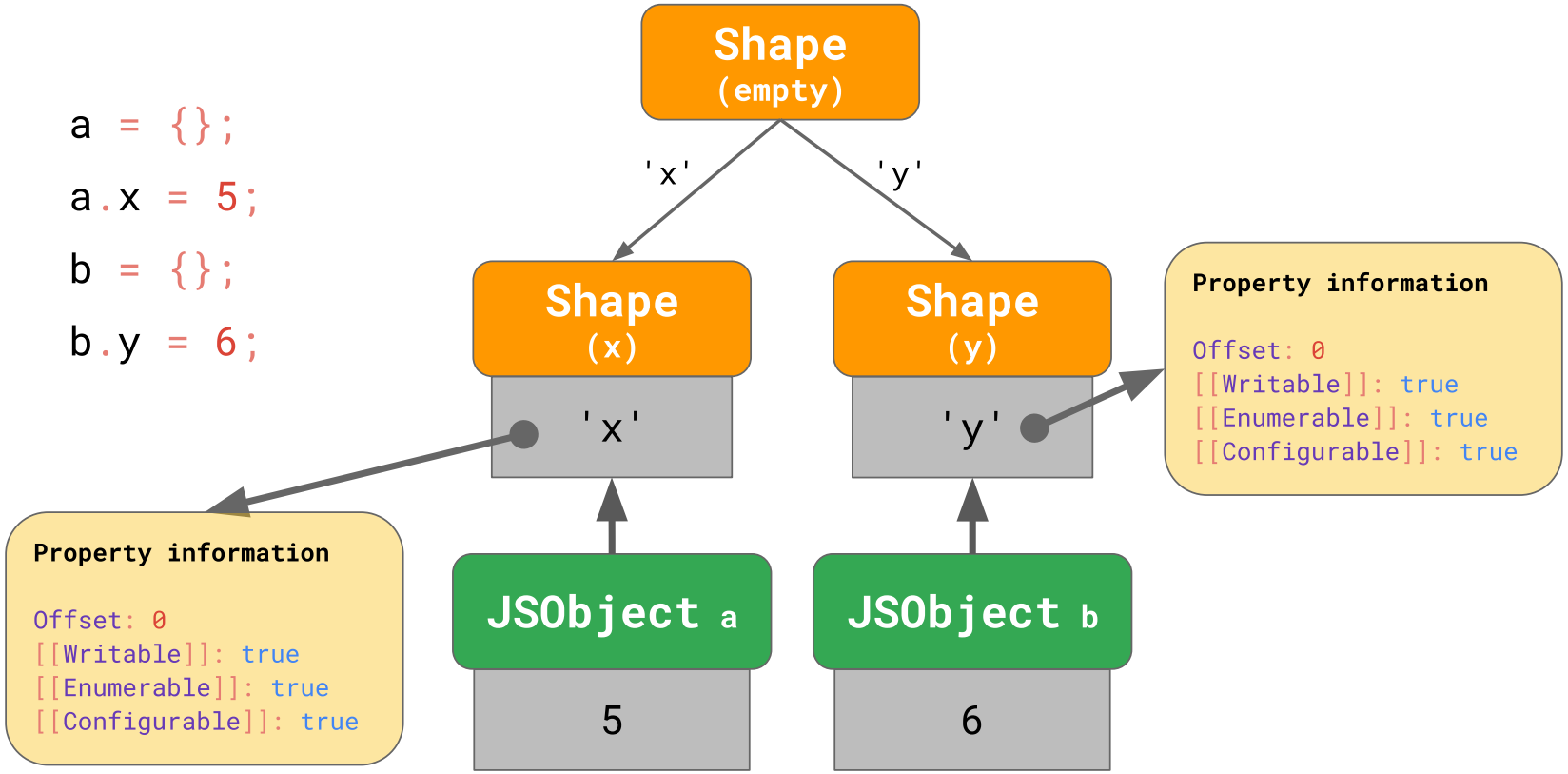
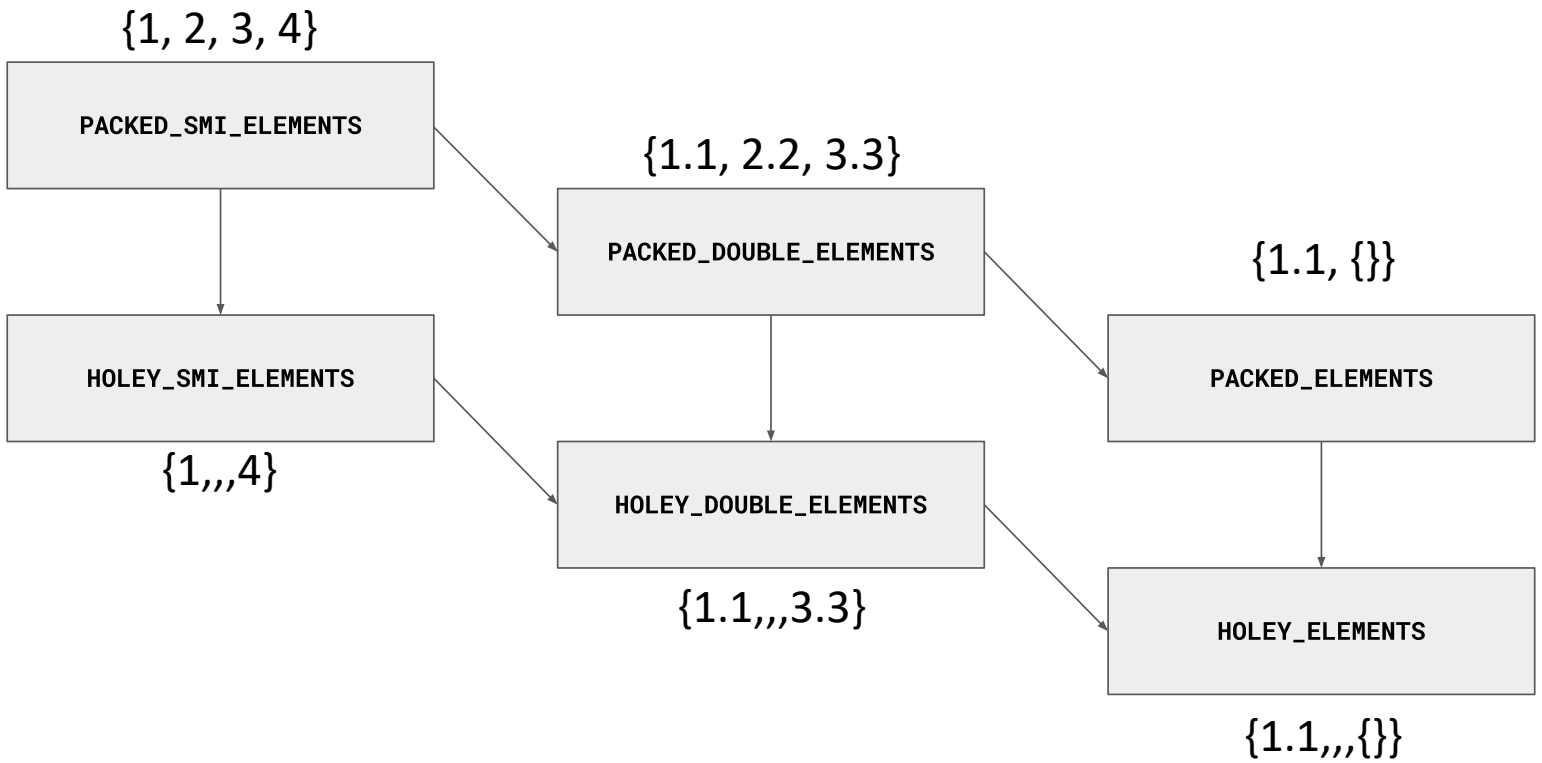


ElementsKind



@farazsth98

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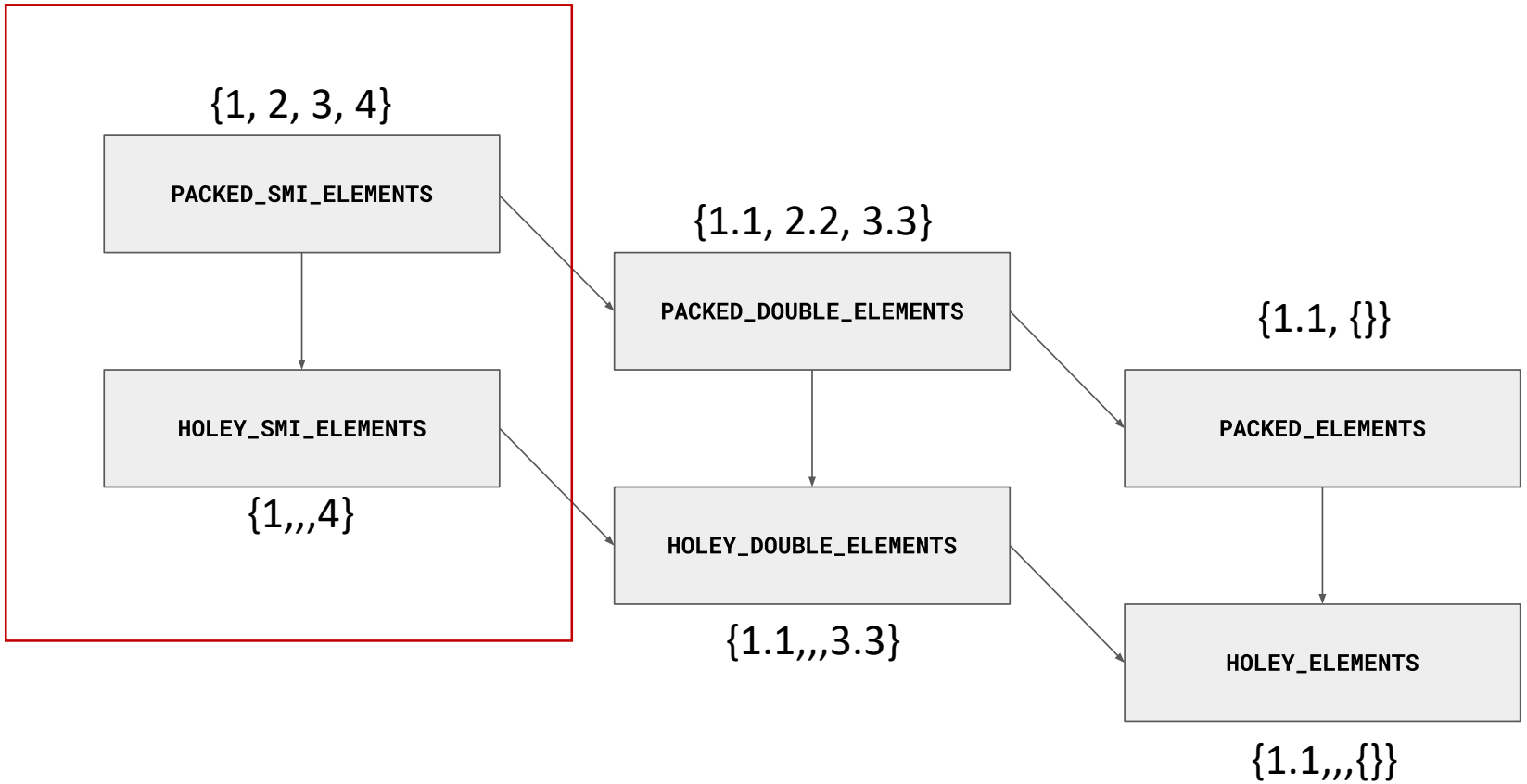

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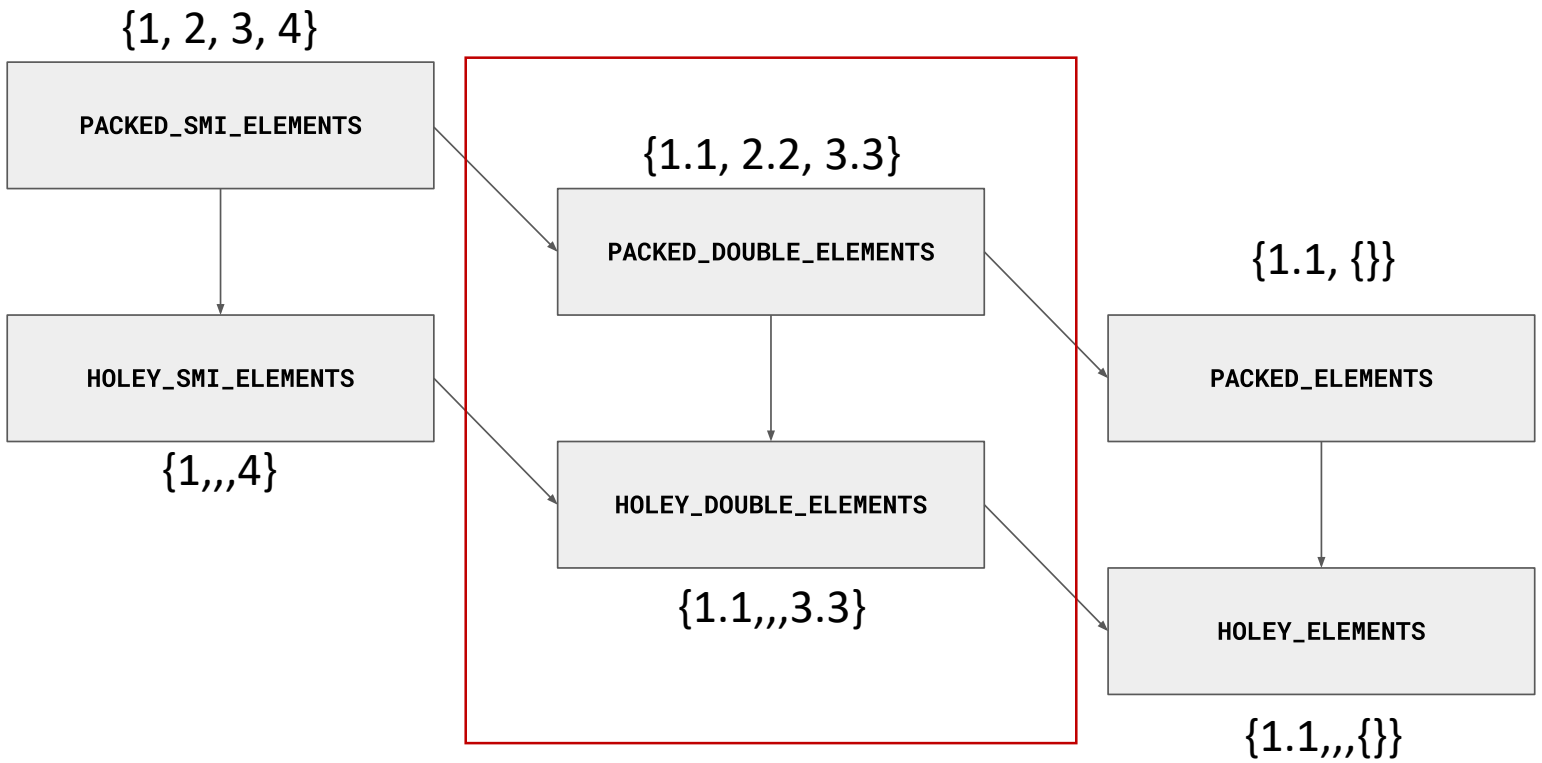


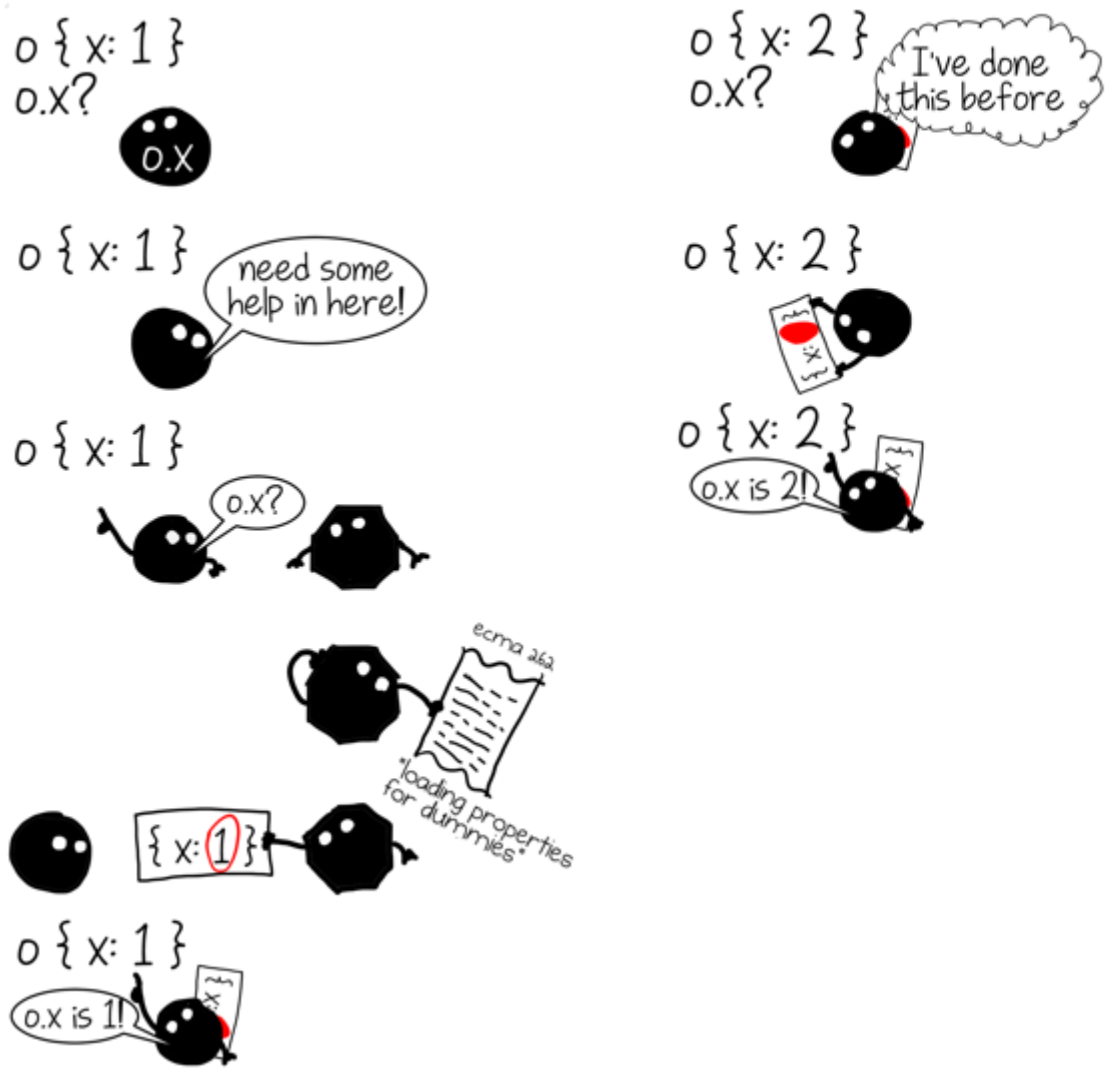
@farazsth98

Inline Caches

Inline Caches store information regarding property loads and stores.

Any time an object's property is accessed within a function, the information regarding this access is stored in the function's **Inline Cache**.

When optimized machine code is generated, the code speculates that the same object's property is accessed, and uses the information stored in the **Inline Cache** to access the property.



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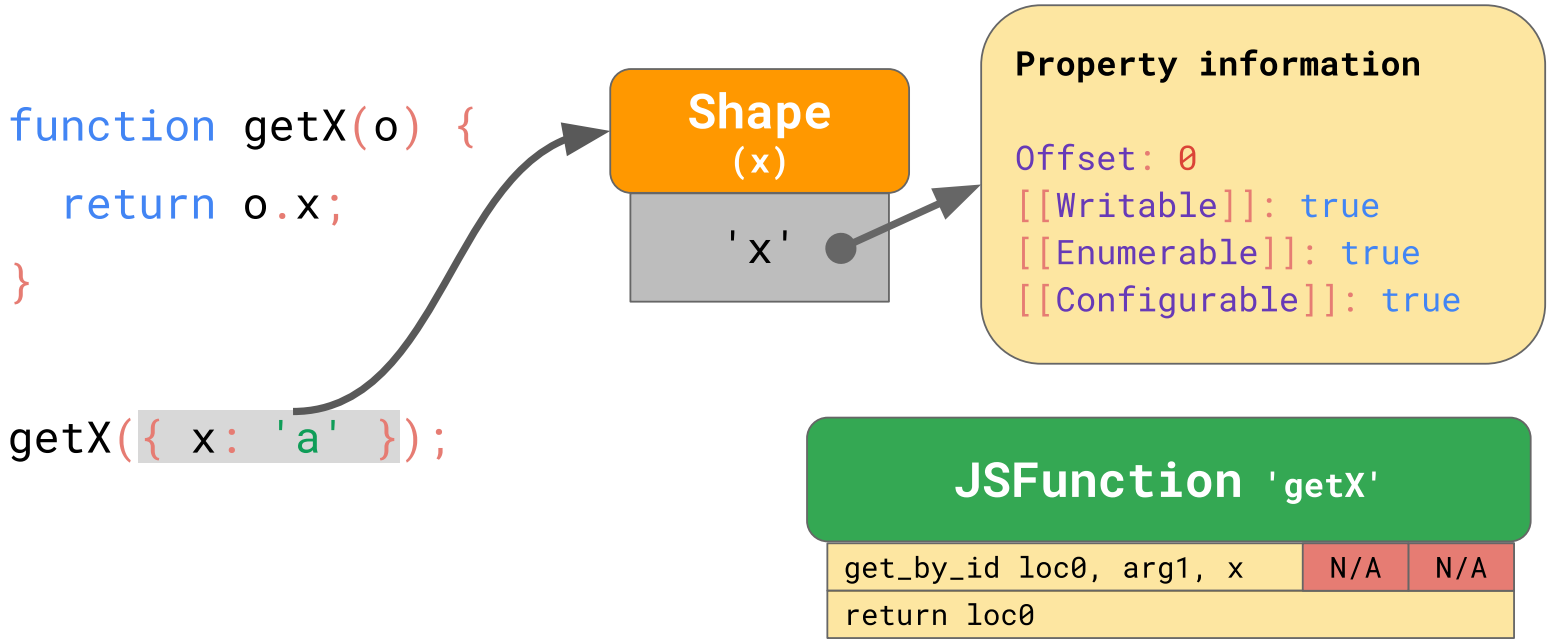
Inline Caches

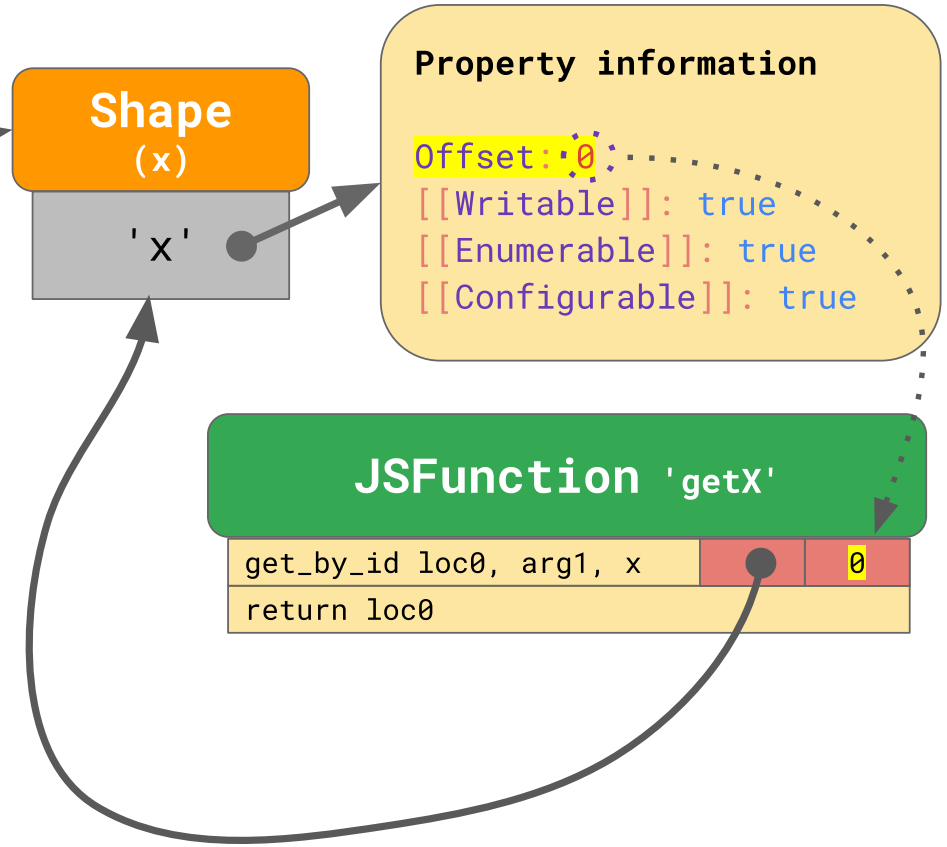


https://mathiasbynens.be/notes/shapes-ics

Inline Caches

```
function getX(o) {
  return o.x;
}

getX({ x: 'a' });
```



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Chromium Issue 944062 – Failing to insert Map checks in `Array.indexOf` and `Array.includes`

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Some more background information regarding **TurboFan** required.

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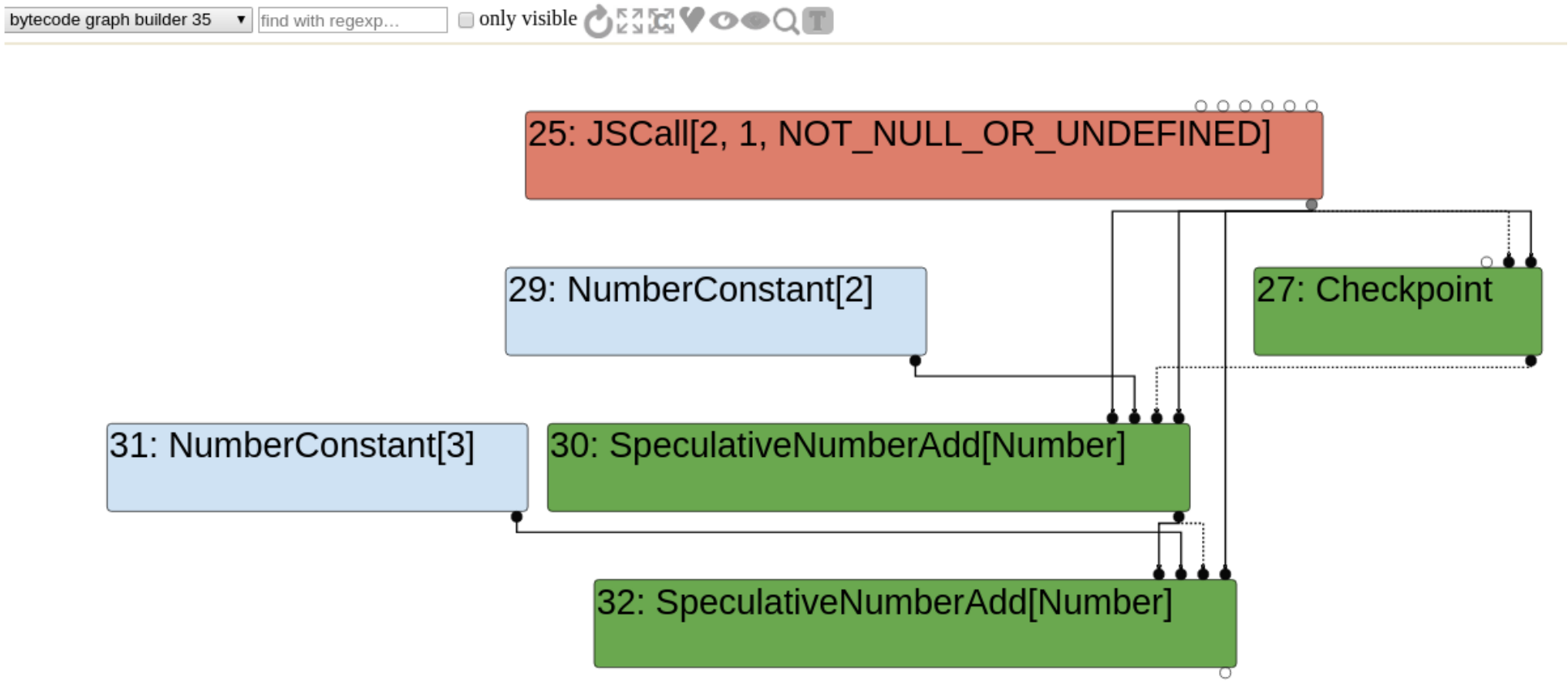
At the end, this “sea of nodes” graph is *lowered* down to machine code for a specific architecture.

Chromium Issue 944062 – Failing to insert Map checks in `Array.indexOf` and `Array.includes`



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If this is done incorrectly, *type confusions* might ensue between two objects that have different *Maps*.

@farazsth98

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The vulnerable code was in `JSCallReducer::ReduceArrayIndexOfIncludes`.

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  SearchVariant search_variant, Node* node) {
CallParameters const& p = CallParametersOf(node->op());
if (p.speculation_mode() == SpeculationMode::kDisallowSpeculation)
{
  return NoChange();
}

Node* receiver = NodeProperties::GetValueInput(node, 1);
Node* effect = NodeProperties::GetEffectInput(node);
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ZoneHandleSet<Map> receiver_maps;
NodeProperties::InferReceiverMapsResult result =
    NodeProperties::InferReceiverMaps(broker(), receiver, effect,
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if (result == NodeProperties::kNoReceiverMaps) return NoChange();

[...] // Continue with optimizing the function
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At the end, the function bails out to the interpreter if the map is not known.

Otherwise, it continues on and optimizes the function.

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[...] // Continue with optimizing the function
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```
enum InferReceiverMapsResult {
kNoReceiverMaps,         // No receiver maps inferred.
kReliableReceiverMaps,   // Receiver maps can be trusted.
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`kUnreliableReceiverMaps` tells the compiler that although the map has been inferred, it is unreliable as it could have possibly been changed by side-effects of other operations.

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`kUnreliableReceiverMaps` tells the compiler that although the map has been inferred, it is unreliable as it could have possibly been changed by side-effects of other operations.

If this happens, the caller *must* guard against possible map changes with a runtime check. One way to do this is by inserting a `CheckMaps` node into the graph.

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Chromium Issue 944062 – Failing to insert Map checks in `Array.indexOf` and `Array.includes`

The vulnerability occurs because the function fails to account for the case where the map that is inferred is unreliable.

Proof of concept:

```
function f(idx, arr) {
  // Transition to dictionary mode in the final invocation.
  arr.__defineSetter__(idx, ()=>{});
  // Will then read OOB.
  return arr.includes(1234);
}

f('', []);
f('', []);
%OptimizeFunctionOnNextCall(f);
f('1000000', []);
```

`__defineSetter__`, when called on an index, will immediately change the array's *ElementsKind* to `DICTIONARY_ELEMENTS`.

`%OptimizeFunctionOnNextCall` is a V8 native built-in function that causes TurboFan to compile the function that's called immediately after.

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Chromium Issue 944062 – Failing to insert Map checks in `Array.indexOf` and `Array.includes`

The patch:

```
+  // If we have unreliable maps, we need a map check.
+  if (result == NodeProperties::kUnreliableReceiverMaps) {
+    effect =
+        graph()->NewNode(simplified()->CheckMaps(CheckMapsFlag::kNone,
+                                                 receiver_maps, p.feedback()),
+                         receiver, effect, control);
+  }
+
```

Checks for `kUnreliableReceiverMaps` and inserts a `CheckMaps` node into the sea of nodes graph.

@farazsth98

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Watch some talks (like this one!) that explain some of the internals of V8.

Try your hand at an easy CTF challenge.

Pick a *very* detailed writeup / bug report and analyse it.

Slowly move onto lesser and lesser detailed bug reports.

Generalize older bugs into bug classes and look for similar ones.

Fuzz everything!

Useful links

https://chromereleases.googleblog.com/

https://bugs.chromium.org/p/chromium/issues/list

- `Security_Severity=High`
- `Security_Severity=Critical`
- `Component:Blink>Javascript`

https://source.chromium.org

Thanks to Thugcrowd for hosting this event!

Feel free to @ me on the discord and ask any questions

@farazsth98