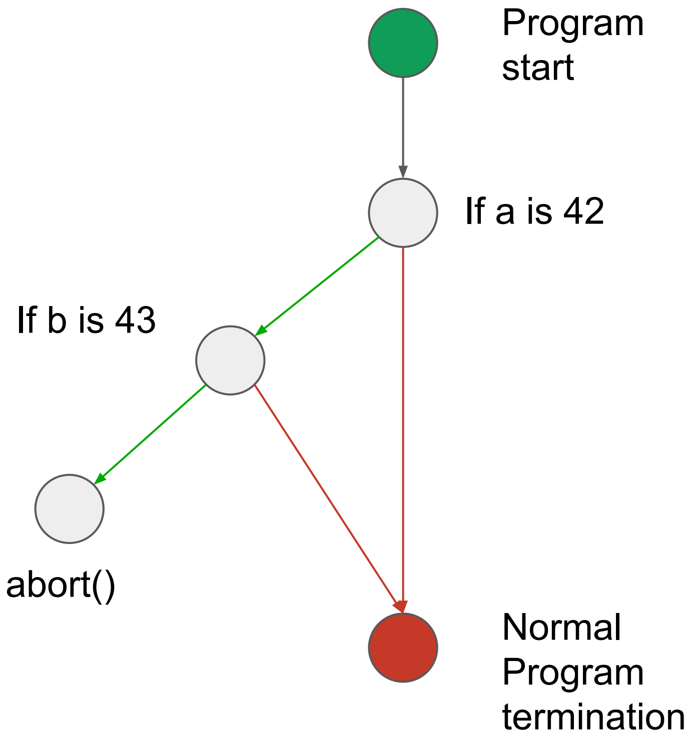
Advancements in JavaScript Engine Fuzzing

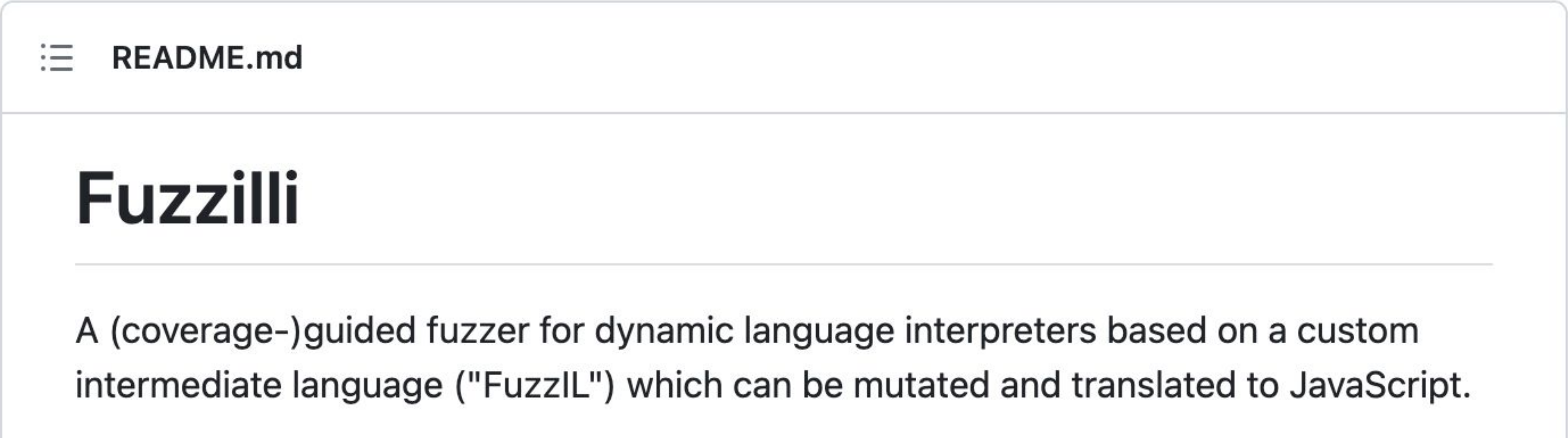
Finding cool bugs with little compute - HITCON'23

Carl Smith - V8 Security - Google

Code coverage guided fuzzing

```
int main() {
    int a = 0, b = 0;
    scanf("%d", &a);
    scanf("%d", &b);
    if (a == 42) {
        if (b == 43) {
            abort();
        }
    }
}
```





README.md

Fuzzilli

A (coverage-)guided fuzzer for dynamic language interpreters based on a custom intermediate language ("FuzzIL") which can be mutated and translated to JavaScript.

fuzzilli.io

Fuzzilli Recap

```
v0 <- BeginPlainFunction -> v1
    v2 <- CreateArray [v1, v1, v1]
    v3 <- LoadInt ‘1’
    v4 <- CallMethod ‘slice’, v2, [v3]
    Return v4
EndPlainFunction
v5 <- LoadFloat ‘13.37’
v6 <- CallFunction v0, [v5]
```

Fuzzilli Recap

```
v0 <- BeginPlainFunction -> v1
    v2 <- CreateArray [v1, v1, v1]
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    v4 <- CallMethod ‘slice’, v2, [v3]
    Return v4
EndPlainFunction
v5 <- LoadFloat ‘13.37’
v6 <- CallFunction v0, [v5]
```

Mutate

```
v0 <- BeginPlainFunction -> v1
    v2 <- CreateArray [v1, v1, v1]
    v4 <- LoadInt ‘100’
    SetProperty v2, ‘length’, v4
    v5 <- CallMethod ‘slice’, v2, [v1]
    Return v5
EndPlainFunction
v6 <- LoadFloat ‘42.0’
v7 <- CallFunction v0, [v5]
```

Splicing

Program 1

```
...

v21 <- BeginPlainFunction -> v22, v23

  ...


EndPlainFunction

...
```

Program 2

```
v0 <- BeginPlainFunction -> v1

    v2 <- CreateArray [v1, v1, v1]

    v3 <- LoadInt ‘1’

    v4 <- CallMethod ‘slice’, v2, [v3]

    Return v4

EndPlainFunction

v5 <- LoadFloat ‘13.37’

V6 <- CallFunction v0, [v5]
```

Splicing

Program 1

```
...
v21 <- BeginPlainFunction -> v22, v23
  ...
  v35 <- CreateArray [v23, v23, v23]
  v36 <- LoadInt ‘1’
  v37 <- CallMethod ‘slice’ v35, [v36]
  Return v37
EndPlainFunction
...
```

Program 2

```
v0 <- BeginPlainFunction -> v1
    v2 <- CreateArray [v1, v1, v1]
    v3 <- LoadInt ‘1’
    v4 <- CallMethod ‘slice’, v2, [v3]
    Return v4
EndPlainFunction
v5 <- LoadFloat ‘13.37’
V6 <- CallFunction v0, [v5]
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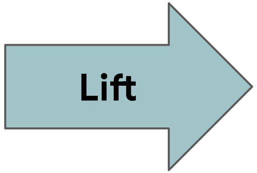
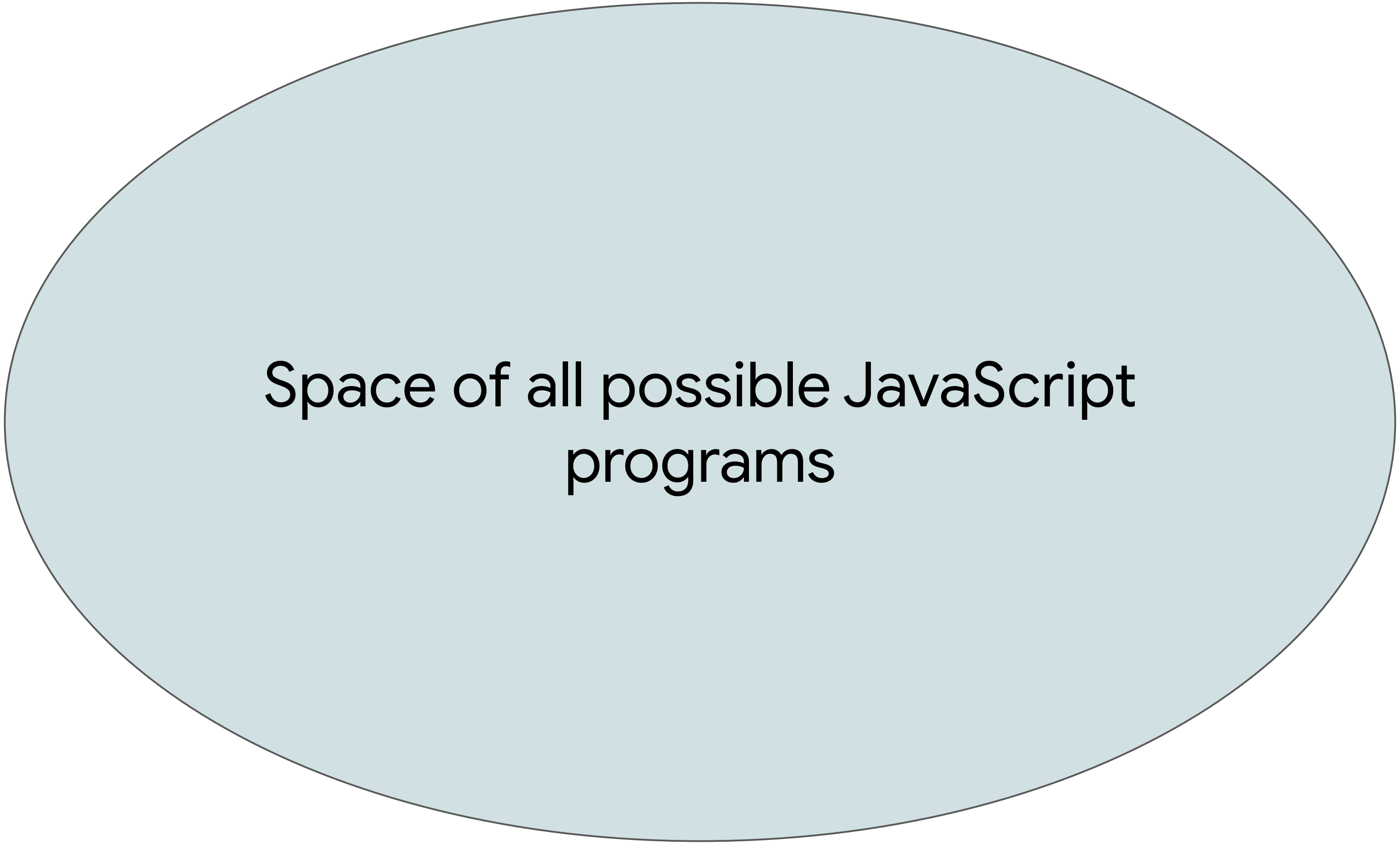
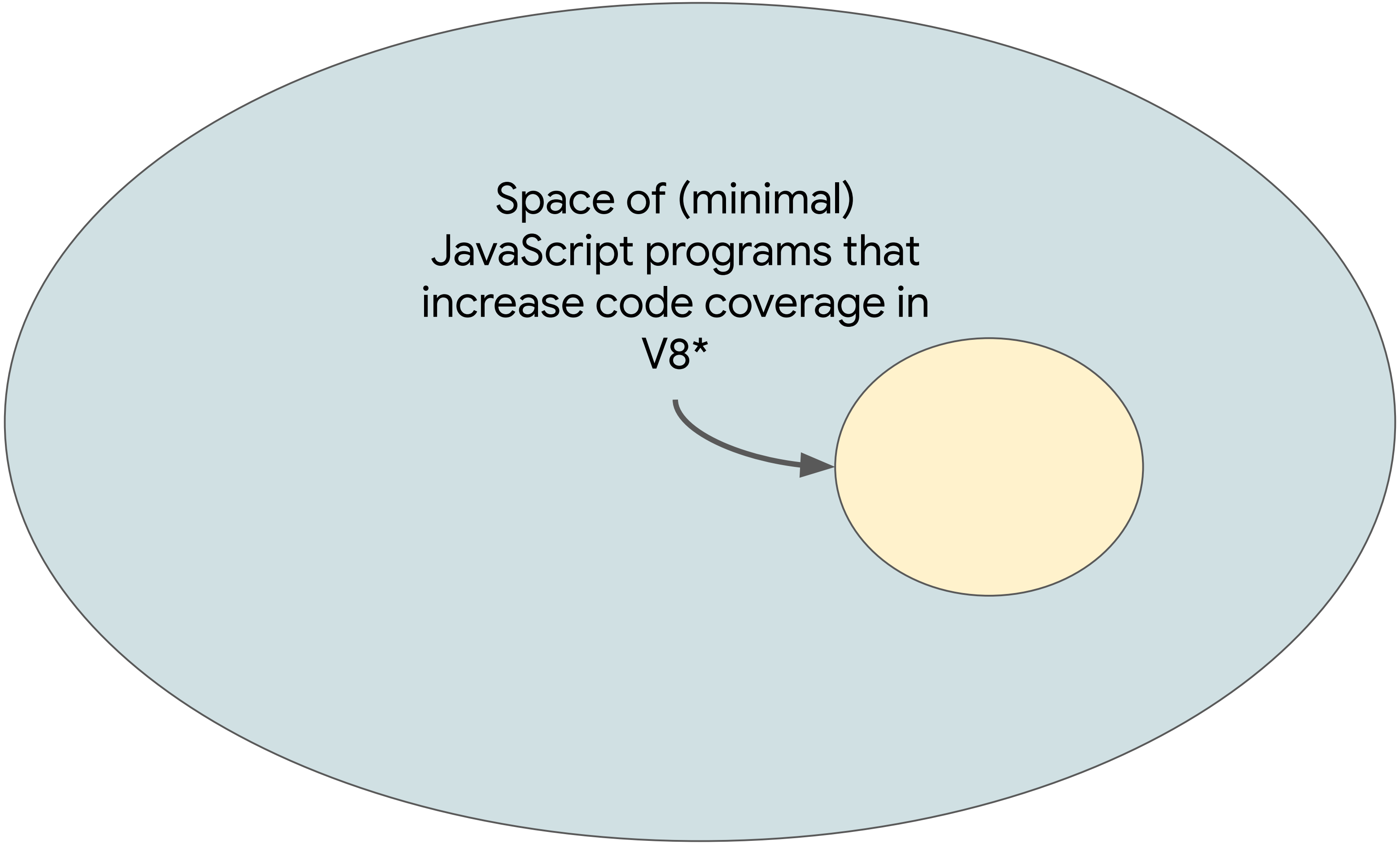

Lift

```
function f0(v1) {
    const v2 = [v1, v1, v1];
    return v2.slice(1);
}
f0(13.37);
```

This finds bugs, but not enough…

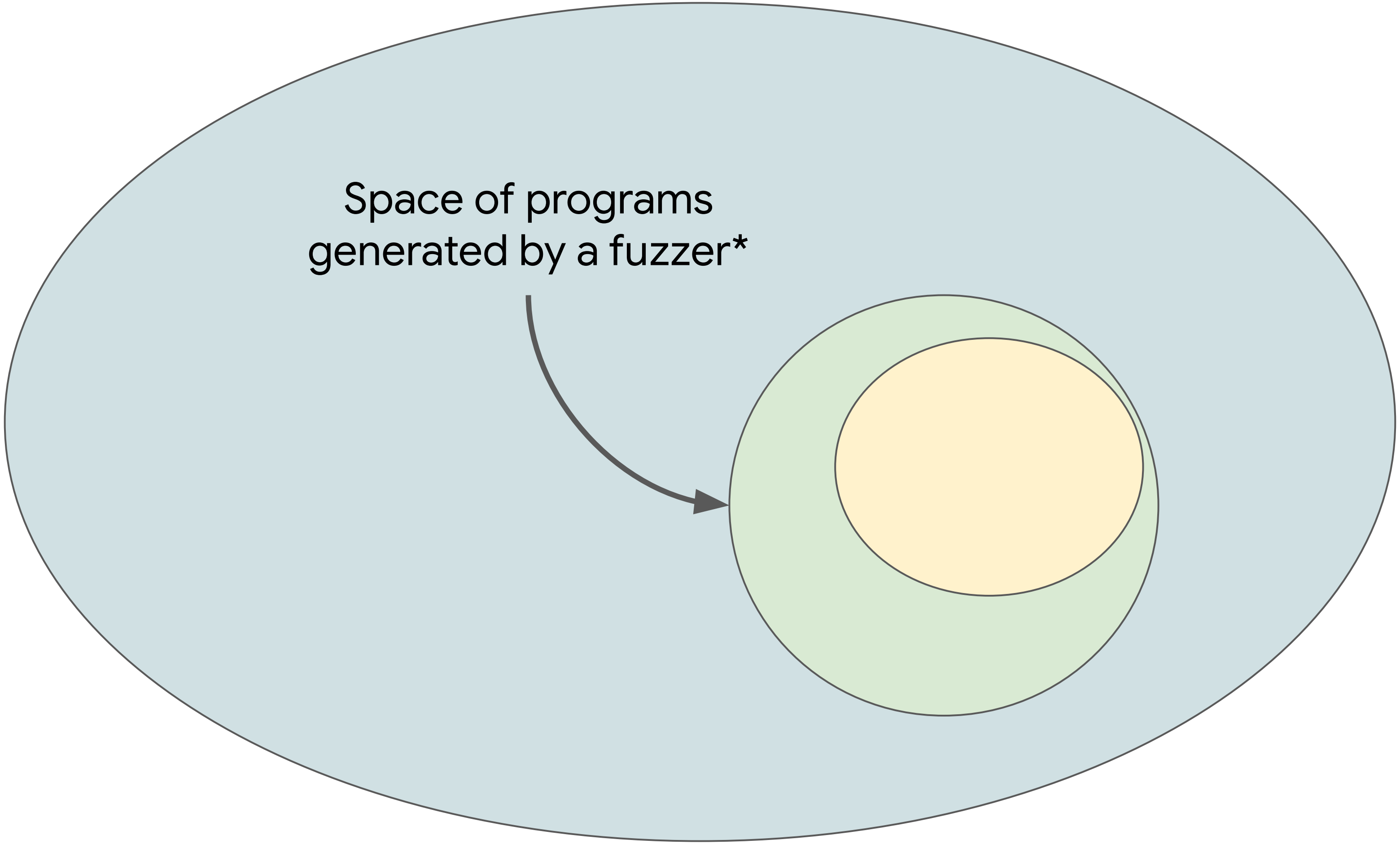


Space of all possible JavaScript programs

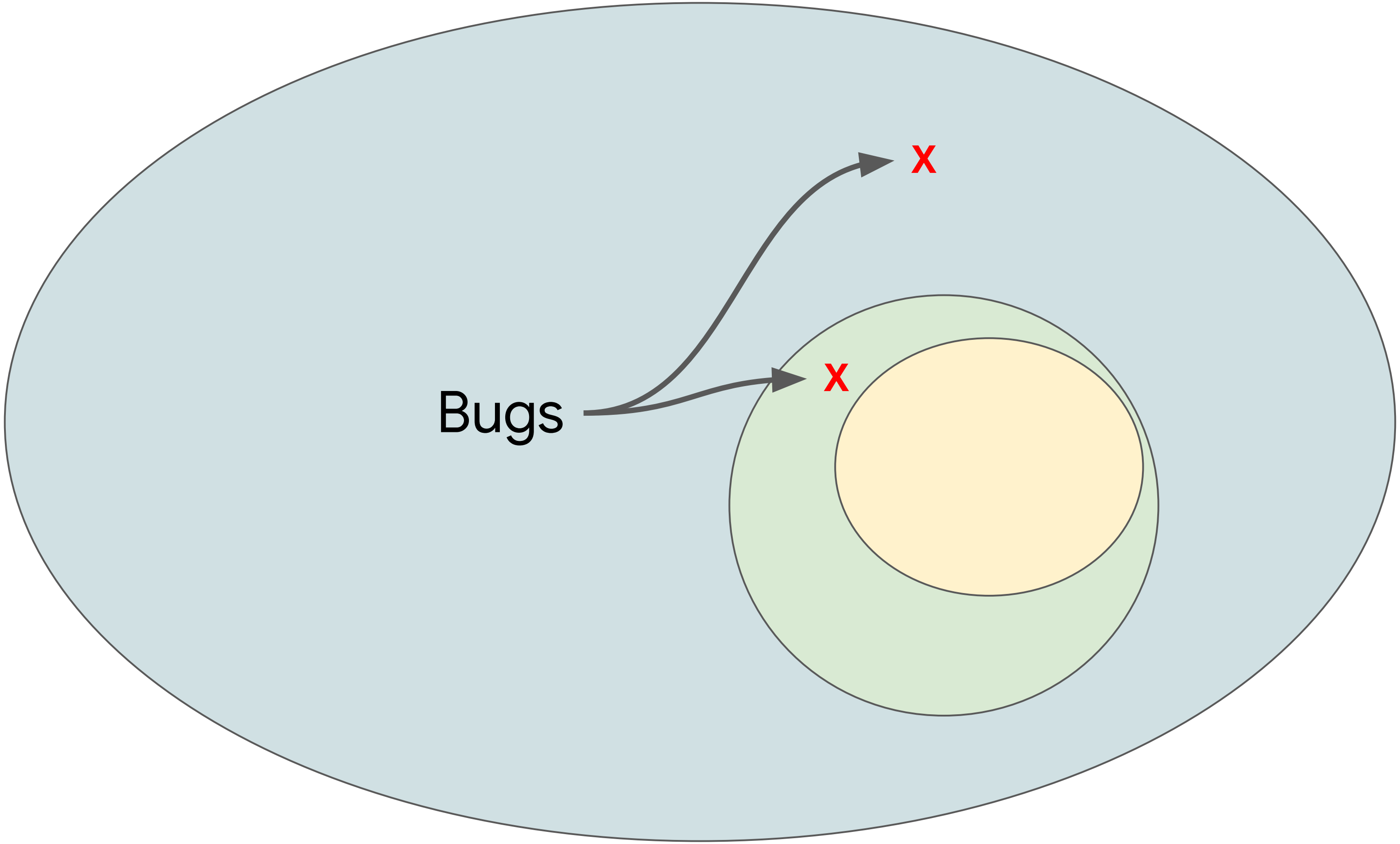


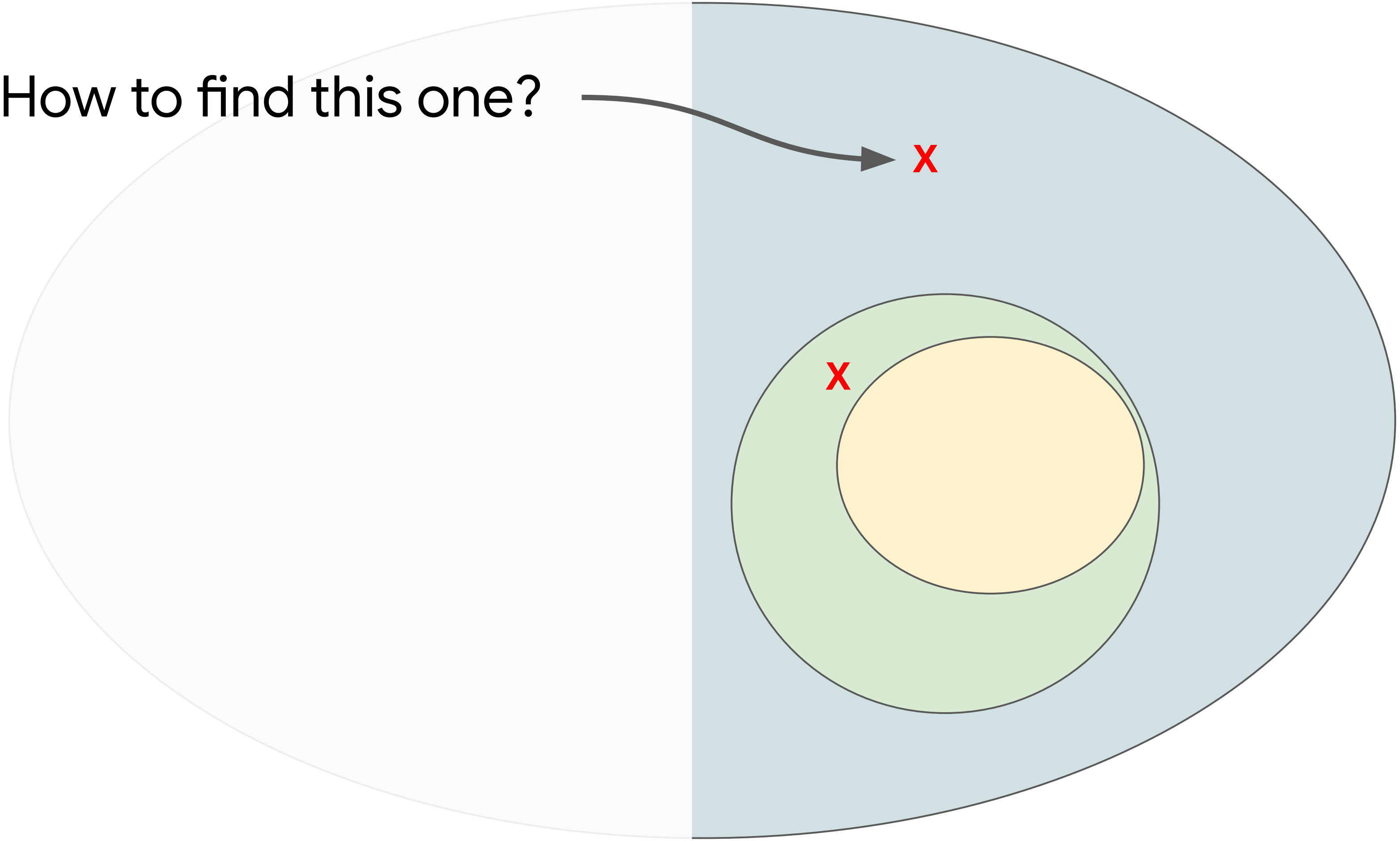
Space of (minimal) JavaScript programs that increase code coverage in V8*

* *much* smaller in reality. Also every fuzzing run will cover different parts



* Basically, one mutation away from the corpus


Bugs
X
X



How to find this one?

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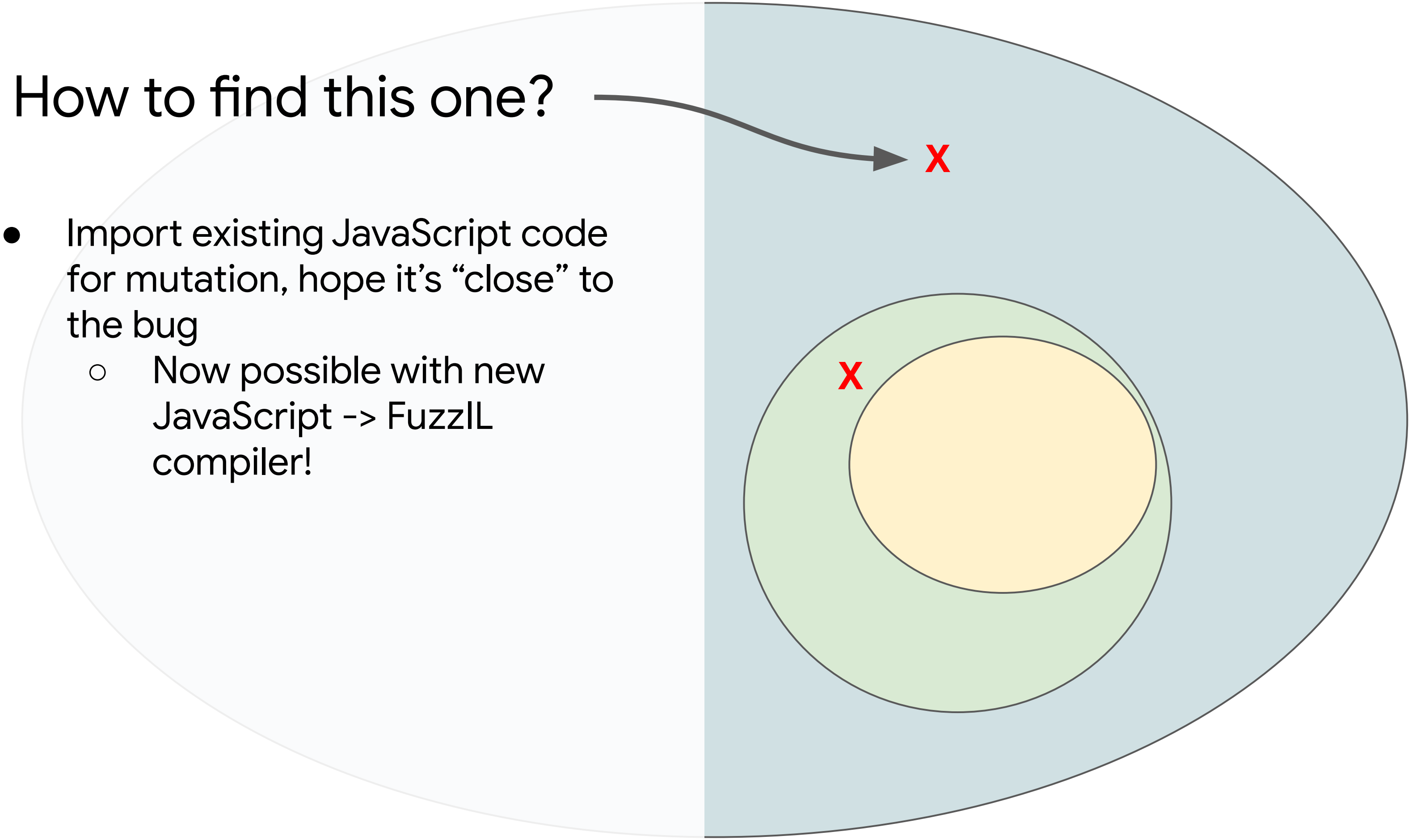
- Import existing JavaScript code for mutation, hope it’s “close” to the bug
  - Now possible with new JavaScript -> FuzzIL compiler!



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- Use different feedback
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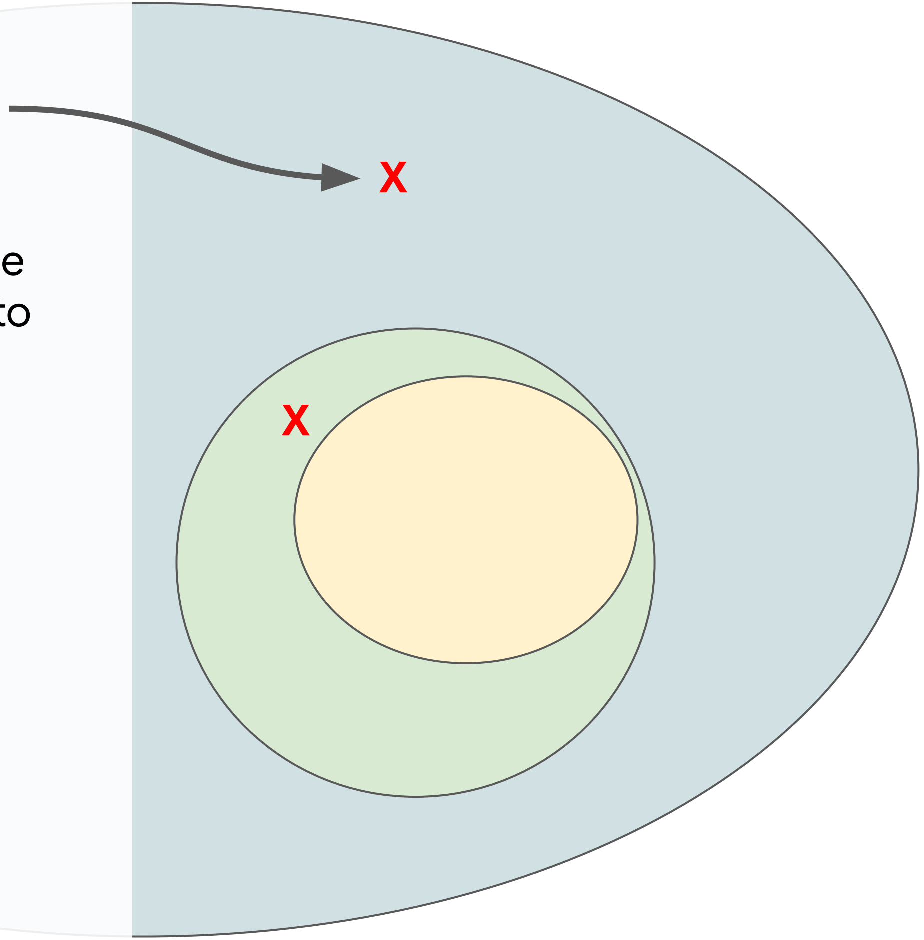

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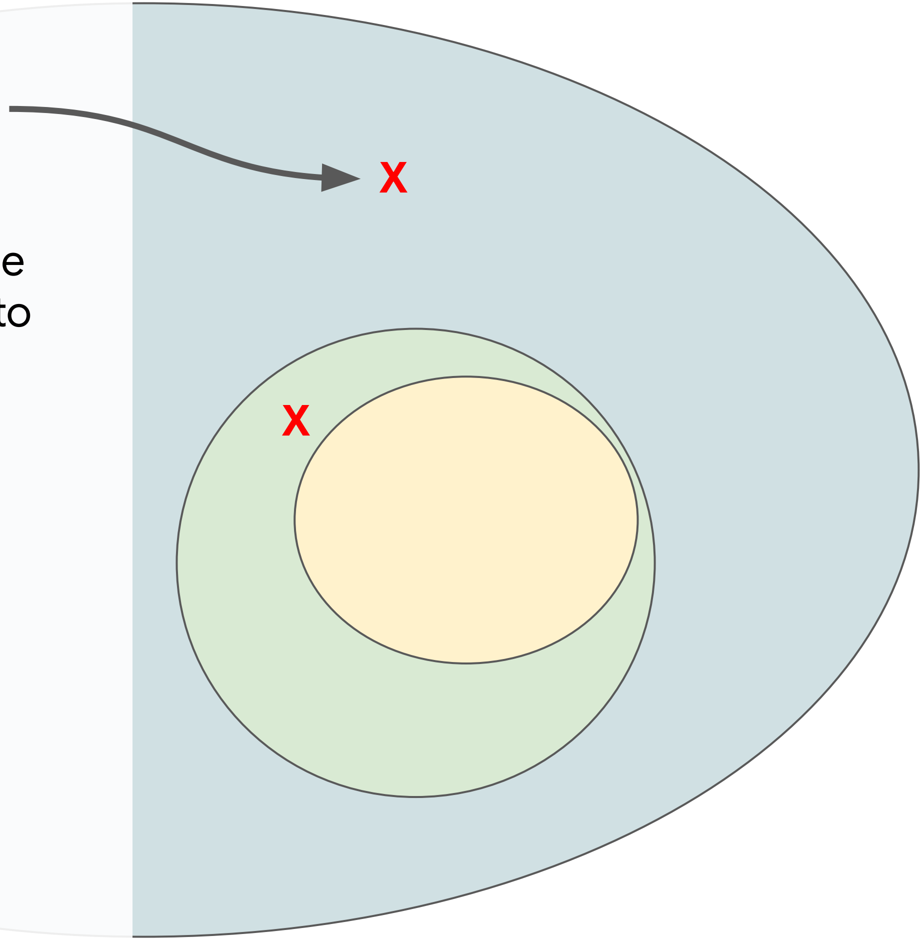

- Import existing JavaScript code for mutation, hope it's "close" to the bug
  - Now possible with new JavaScript -> FuzzIL compiler!
- Use different feedback
  - Future research topic?
- Use specialized mutators
  - To "hint" fuzzer towards known bug patterns

CVE-2016-4622

```
let a = [];
for (let i = 0; i < 100; i++) a.push(i + 0.123);
let evil = { valueOf() {
    a.length = 0; return 10;
}};
// Triggers valueOf callback of evil and unexpectedly
// shrinks the Array, leading to an OOB access
let b = a.slice(0, evil);

// b = [0.123,1.123,2.12199579146e-313,0,0,0,0,0,0,0
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```

Fuzzer is rewarded for finding these *individually*, but **not for combining** them!

Code Coverage Feedback

Sample 1:

```
let a = [];

for (let i = 0; i < 100; i++)
a.push(i + 0.123);

let evil = { valueOf() {

    return 10;

}};
```

Sample 2:

```
let a = [1, 2, 3];

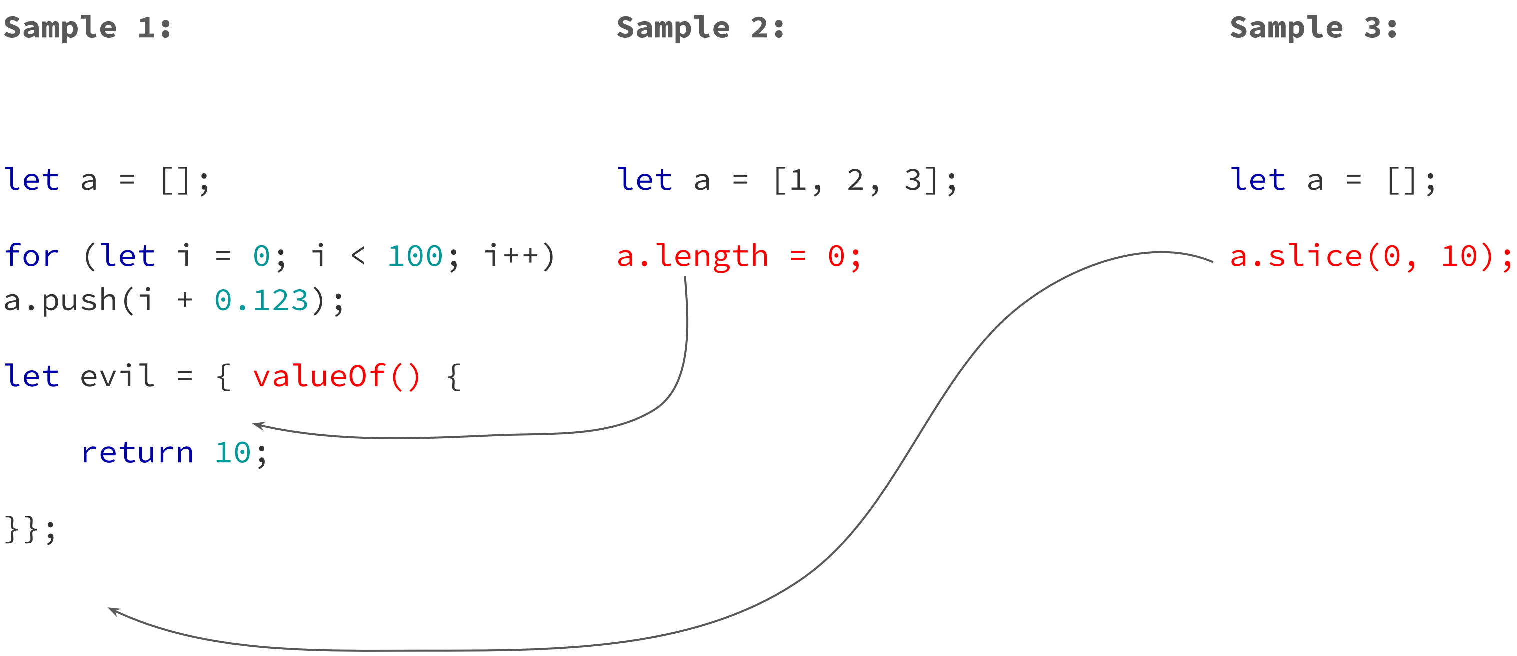
a.length = 0;
```

Sample 3:

```
let a = [];

a.slice(0, 10);
```

Code Coverage Feedback



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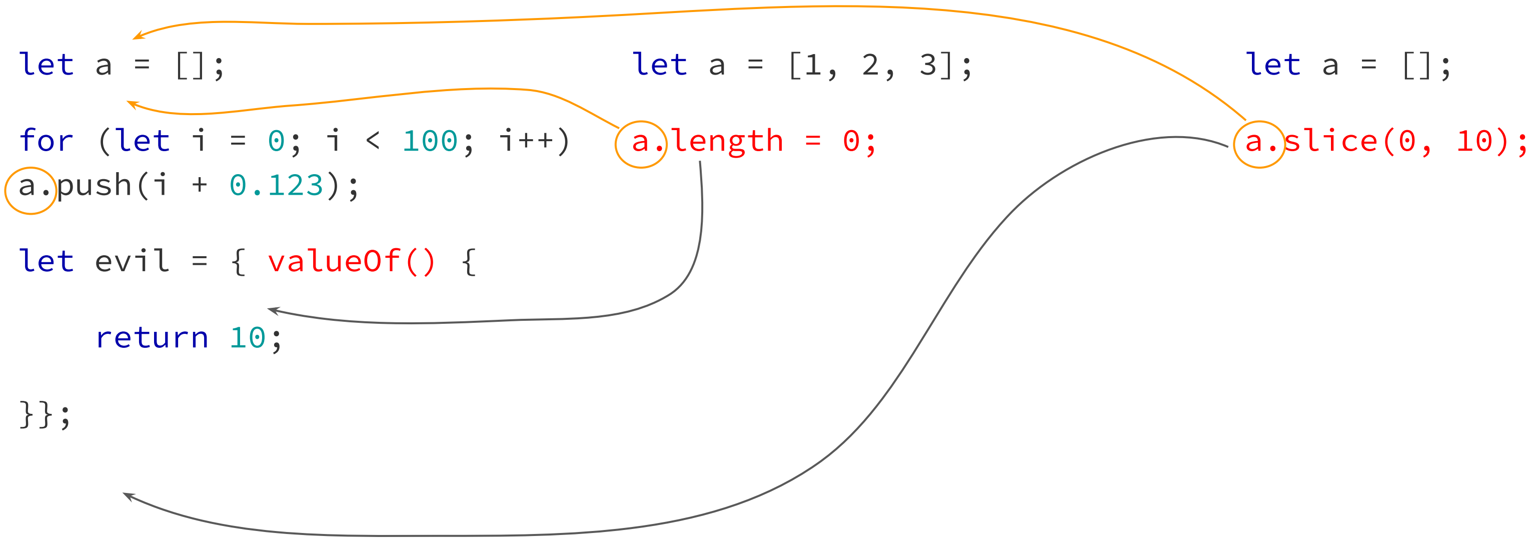

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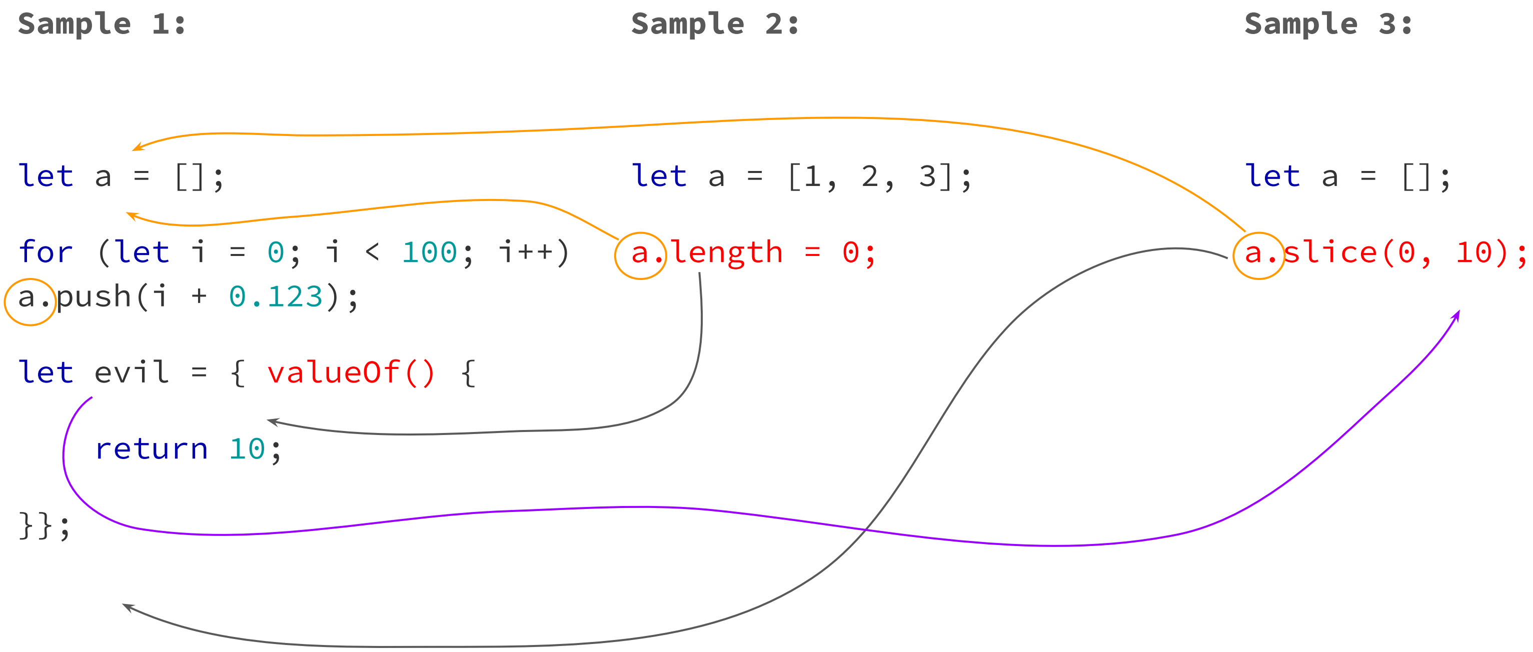

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let a = [1, 2, 3];

a.length = 0;
```

Sample 3:

```
let a = [];

a.slice(0, 10);
```

Probing Mutator

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```
let v1 = {};
// How is v1 being used?
builtin_func(v1);
```

Probing Part 1: Intermediate Program

```
let v1 = {};
// How is v1 being used?
// Let’s find out!
probe(v1);
builtin_func(v1);
```

Probing Part 1: Intermediate Program

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let v1 = {};

// How is v1 being used?

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probe(v1);

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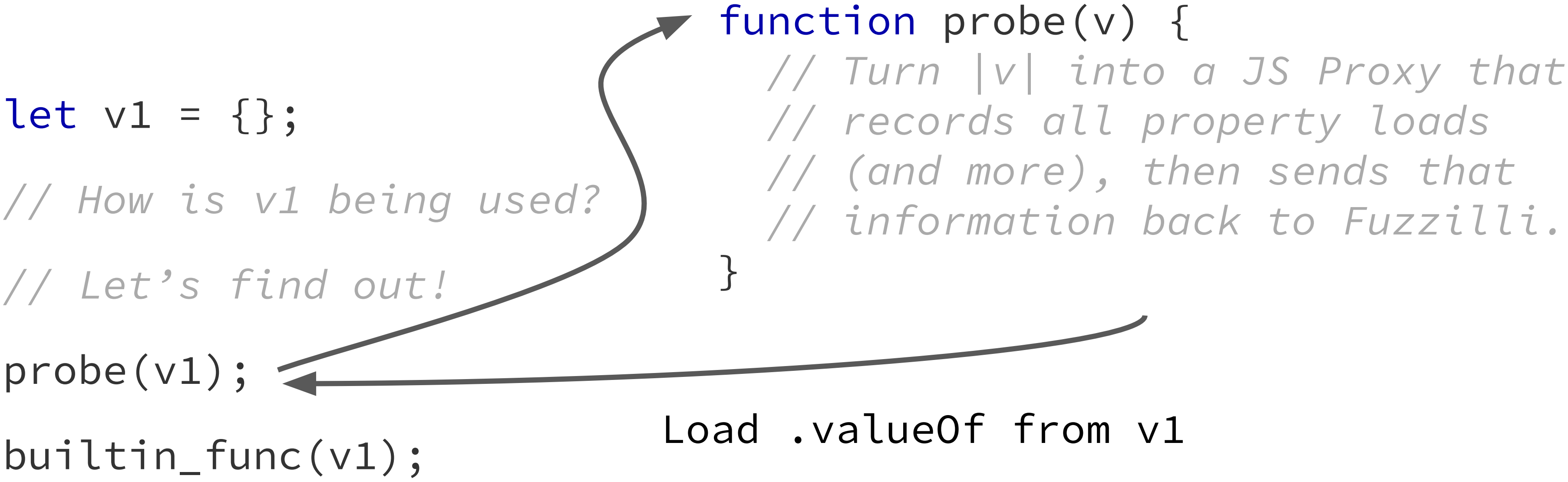
```

```
function probe(v) {
  // Turn |v| into a JS Proxy that
  // records all property loads
  // (and more), then sends that
  // information back to Fuzzilli.
}
```

Probing Part 1: Intermediate Program



```
let v1 = {};

// How is v1 being used?

// Let’s find out!

probe(v1);

builtin_func(v1);
```

```
function probe(v) {
  // Turn |v| into a JS Proxy that
  // records all property loads
  // (and more), then sends that
  // information back to Fuzzilli.
}
```

Load .valueOf from v1

Probing Part 2: Final Program

```
let v1 = {};
function v2() {
    ...;
}
v1.valueOf = v2;
builtin_func(v1);
```

crbug.com/1381064 (and a couple other, similar bugs)

```
const v8 = new ArrayBuffer(1050, {"maxByteLength":6623679});
const v10 = new Uint8ClampedArray(v8);
function v11() {
    const v15 = v8.resize();
}
v10[Symbol.toPrimitive] = v11;
// Triggers toPrimitive conversion and unexpectedly shrinks the
// ArrayBuffer, leading to a (harmless) OOB access.
v10[916] = v10;
```

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const v8 = new ArrayBuffer(1050, {"maxByteLength":6623679});

const v10 = new Uint8ClampedArray(v8);

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}

v10[Symbol.toPrimitive] = v11;

// Triggers toPrimitive conversion and unexpectedly shrinks the

// ArrayBuffer, leading to a (harmless) OOB access.

v10[916] = v10;
```

Exploration

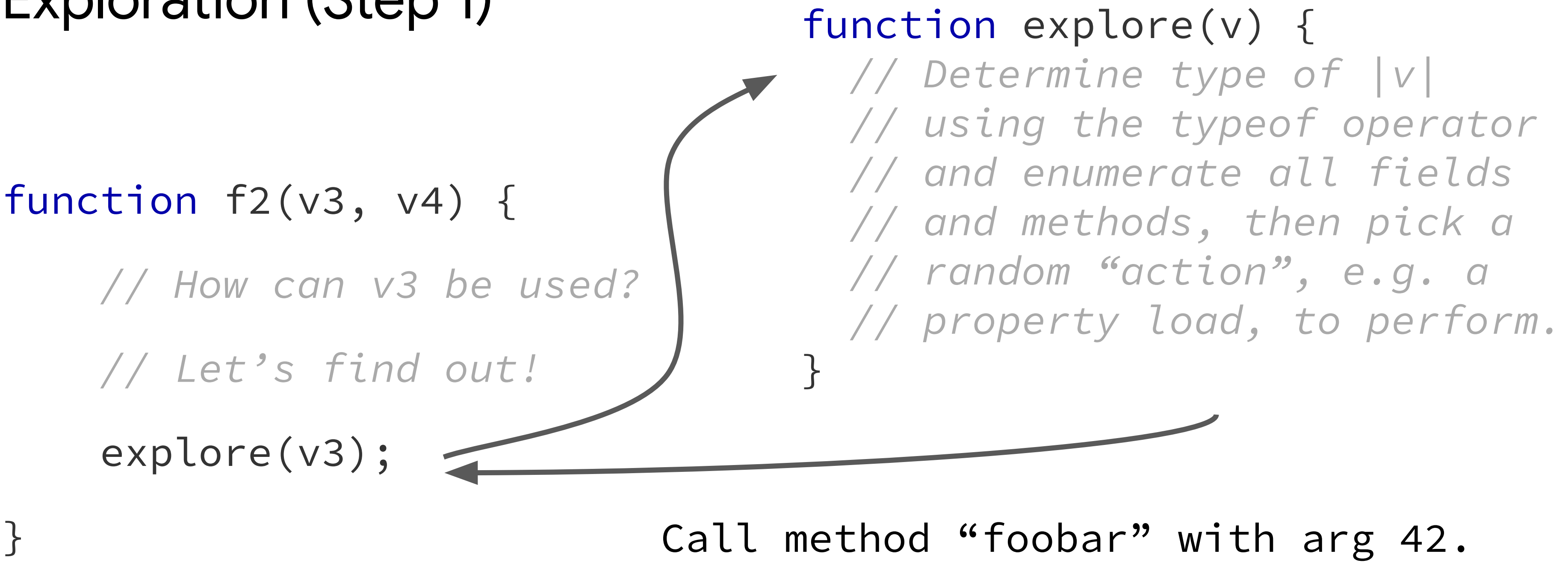
```
function f2(v3, v4) {
    // How can v3 be used?
}
```

Exploration (Step 1)

```
function f2(v3, v4) {

    // How can v3 be used?

    // Let’s find out!

    explore(v3);

}
```

```
function explore(v) {
  // Determine type of |v|
  // using the typeof operator
  // and enumerate all fields
  // and methods, then pick a
  // random “action”, e.g. a
  // property load, to perform.
}
```

Exploration (Step 1)



```
function f2(v3, v4) {

    // How can v3 be used?

    // Let’s find out!

    explore(v3);

}
```

```
function explore(v) {
  // Determine type of |v|
  // using the typeof operator
  // and enumerate all fields
  // and methods, then pick a
  // random “action”, e.g. a
  // property load, to perform.
}
```

Call method “foobar” with arg 42.

Exploration (Step 2)

```
function f2(v3, v4) {
    v3.foobar(42);
}
```

Example bug: crbug.com/1377775

```
const v19 = {};
v19.a = 42;
const v20 = [v19];
function v21(v23) {
    const v26 = v23.shift();
    const v27 = v23.at(1000000);        // .at is inlined by Turbofan but the type check
}                                       // is faulty, leading to a type confusion when
v19.__proto__ = v20;                    // v23 is not a JSArray.
for (let v39 = 0; v39 < 100; v39++) {
    const v43 = v21(v19);
    const v45 = v21(v20);
}
```

Probe vs Explore

Probe infers Arguments:

How do interact with this JavaScript API?

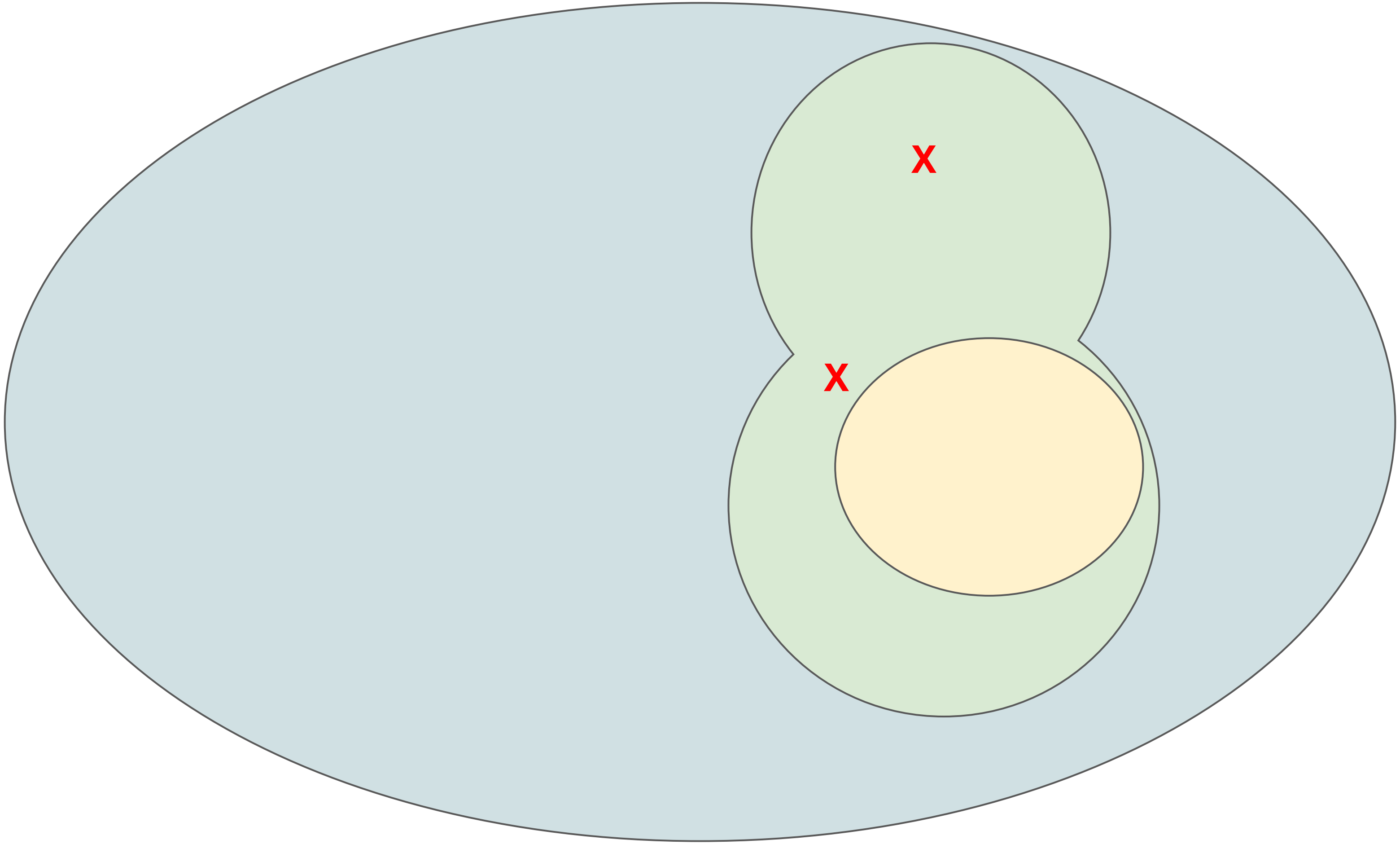
What do I need to pass to e.g. `new ArrayBuffer( {???} )`

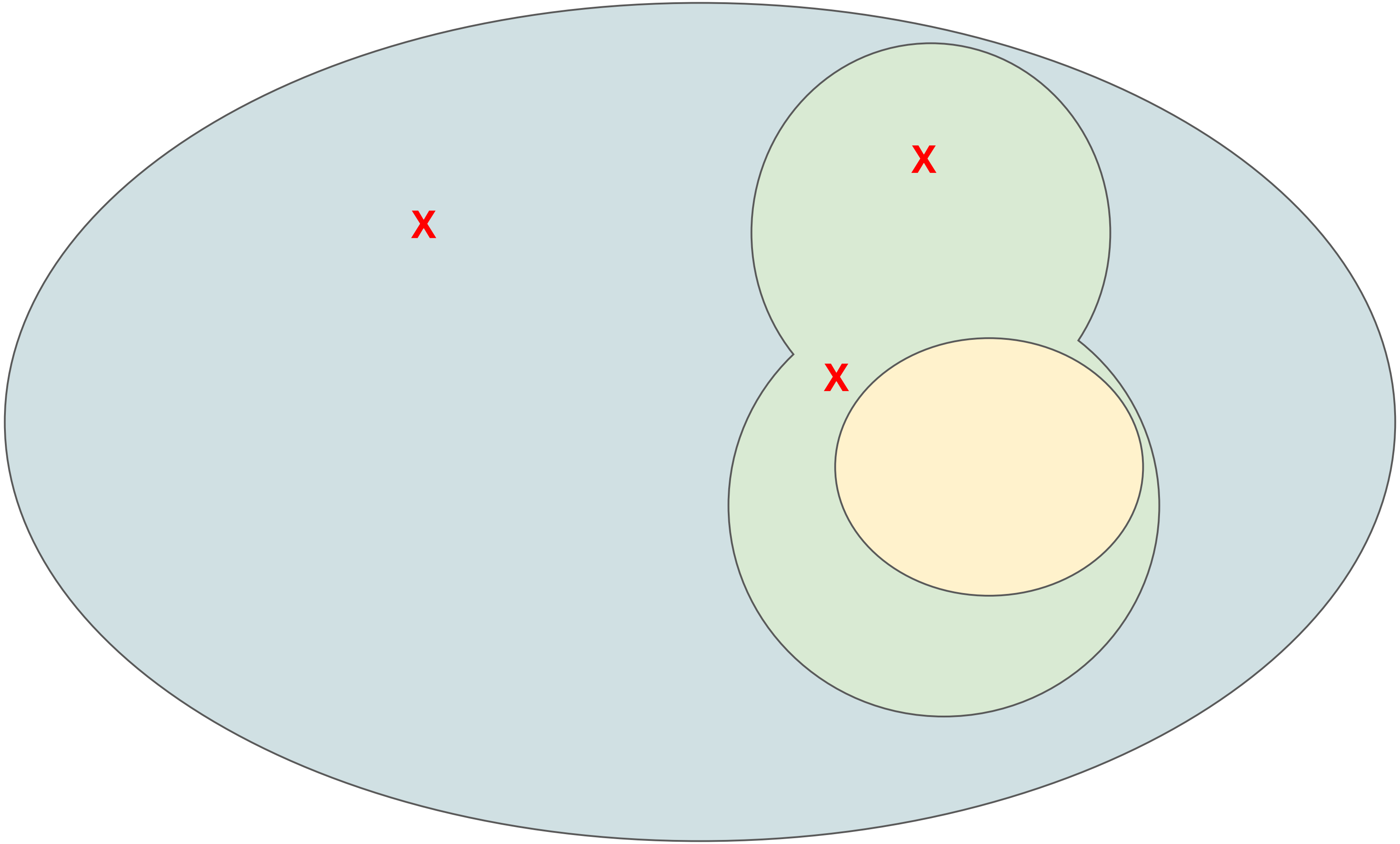
=> We can pass it maxByteLength: 1234

Explore infers return types of JavaScript APIs:

What can I do with the result of e.g. `new ArrayBuffer(...)`

=> We can call `.resize()`


X
X


X
X
X

Example bug: crbug.com/1377775

```
const v19 = {};                                   // Step 1
v19.a = 42;                                       // Step 2
const v20 = [v19];                                // Step 3
function v21(v23) {
    const v26 = v23.shift();                      // Step 4
    const v27 = v23.at(1000000);                  // Step 5
}
v19.__proto__ = v20;                              // Step 6
for (let v39 = 0; v39 < 10000; v39++) {           // Step 7
    const v43 = v21(v19);                         // Step 8
    const v45 = v21(v20);                         // Step 9
}
```

CVE-2022-3723 (V8 ITW)

```
function setInnerProperty(o) {
  o.inner.foo = {};
}
function makeObject() {
    var o = {
        inner: {
            ['foo']: 0
        }
    };
    setInnerProperty(o, ...arguments);
    return o;
}
makeObject();
gc();
makeObject();
gc();

let o = makeObject();
%HeapObjectVerify(o.inner);
```

https://googleprojectzero.github.io/0days-in-the-wild/0day-RCAs/2022/CVE-2022-3723.html

CVE-2022-3723 (V8 ITW)

```
function setInnerProperty(o) {                  // Step 1
  o.inner.foo = {};                             // Step 2-3
}
function makeObject() {                         // Step 4
    var o = {                                   // Step 5
        inner: {                                // Step 6
            ['foo']: 0                          // Step 7
        }
    };
    setInnerProperty(o, ...arguments);          // Step 8
    return o;
}
makeObject();                                   // Step 9
gc();                                           // Step 10
makeObject();                                   // Step 11
gc();                                           // Step 12

let o = makeObject();                           // Step 13
%HeapObjectVerify(o.inner);                     // Step 14
```

CVE-2022-3723 (V8 ITW)

```
function setInnerProperty(o) {                  // Step 1
  o.inner.foo = {};                             // Step 2-3
}
function makeObject() {                         // Step 4
    var o = {                                   // Step 5
        inner: {                                // Step 6
            ['foo']: 0                          // Step 7
        }
    };
    setInnerProperty(o, ...arguments);          // Step 8
    return o;
}
makeObject();                                   // Step 9
gc();                                           // Step 10
makeObject();                                   // Step 11
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let o = makeObject();                           // Step 13
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```
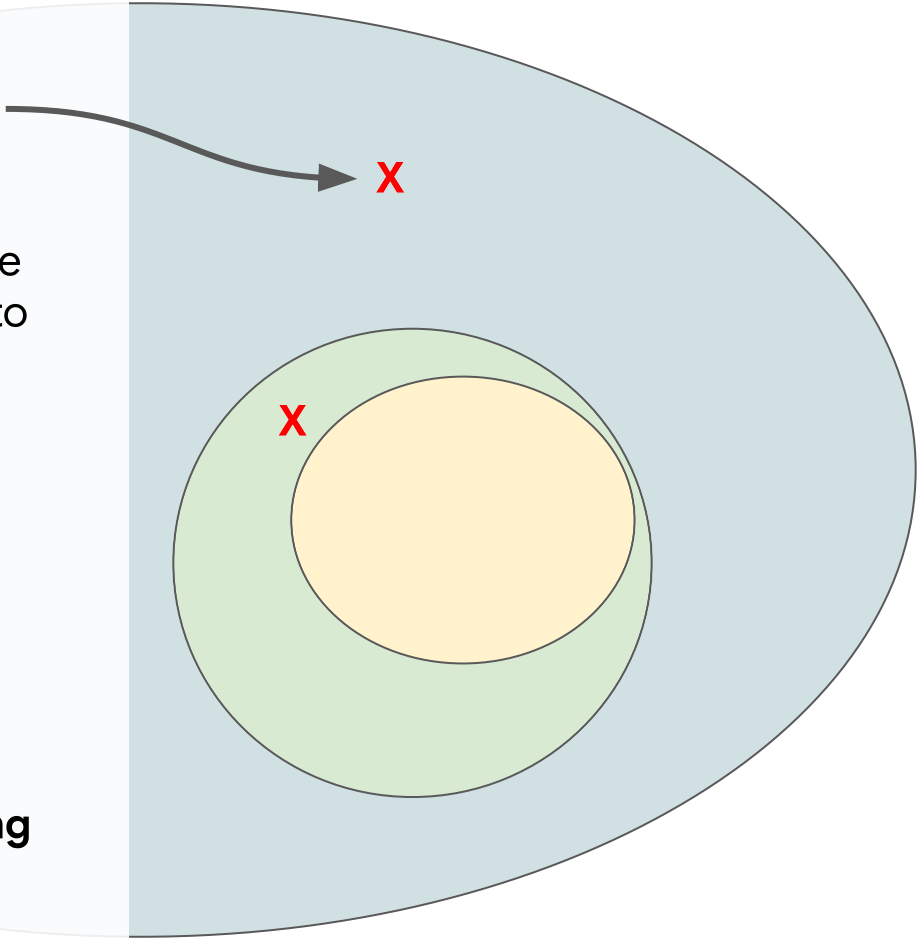

CVE-2022-3723 (V8 ITW)

```
function setProperty(o) {                       // Step 1
  o.foo = {};                                   // Step 2
}
function makeObject() {                         // Step 3
    var o = {                                   // Step 4
        ['foo']: 0                              // Step 5
    };
    setProperty(o, ...arguments);               // Step 6
    return o;
}
makeObject();                                   // Step 7
%GetObjectIntoInterestingState(o);              // Step 8
makeObject();                                   // Step 9
%HeapObjectVerify(o.inner);                     // Step 10
```

How to find this one?



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  - Now possible with new JavaScript -> FuzzIL compiler!
- Use different feedback
  - Future research topic?
- Use specialized mutators
  - To "hint" fuzzer towards known bug patterns
- **Use "human-assisted" fuzzing**
  - Let the researcher guide the fuzzer

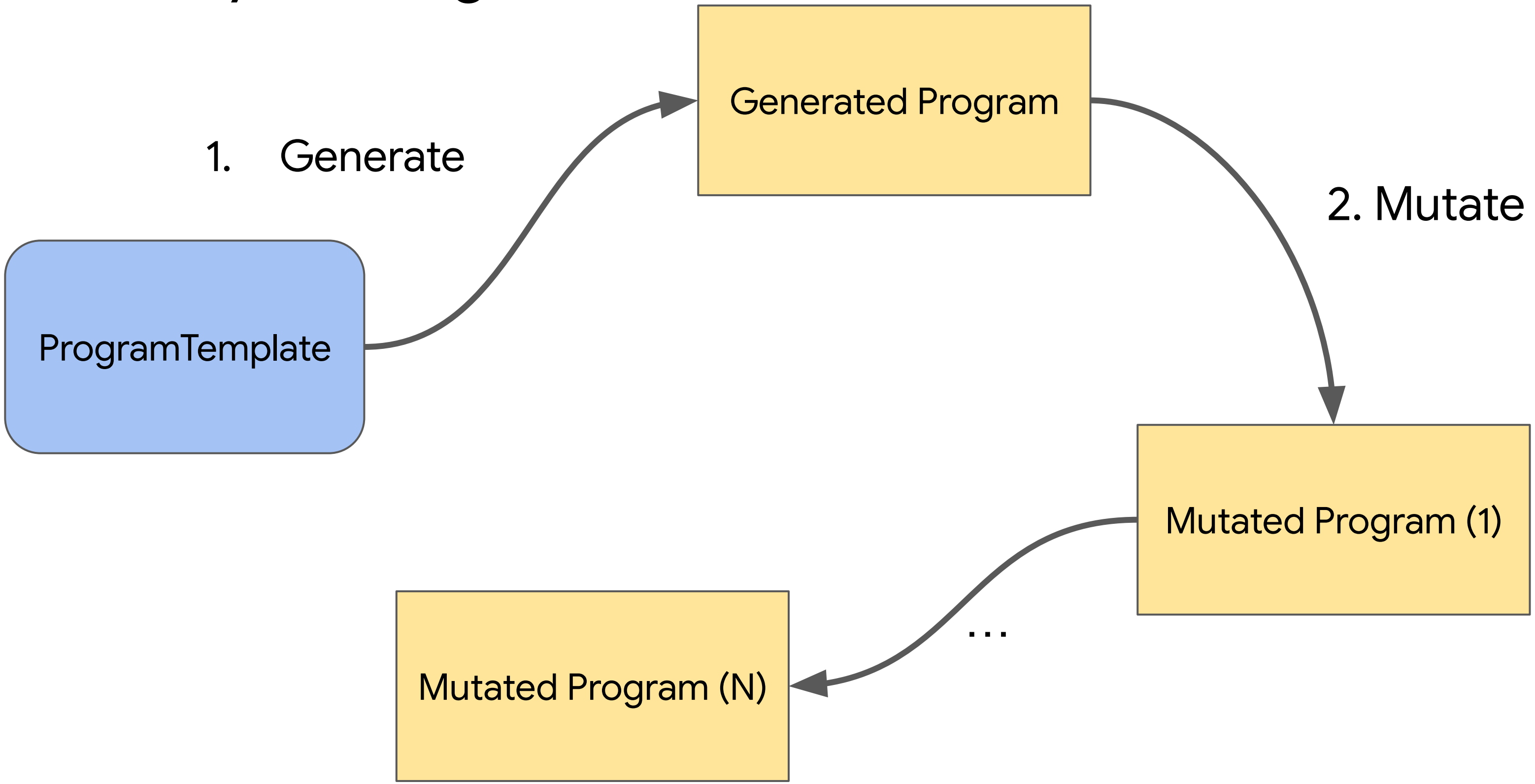
Code Shape ITW

```
function f1(...) {
    ...
}

function f2(...) {
    ...
}

...

%GetObjectIntoInterestingState(...);

...

for(let i = 0; i < 100; i++) {
    ...
}
```

“Hybrid” Fuzzing with ProgramTemplates

```
let f1 = b.buildPlainFunction(with: b.randomParameters()) {
    b.build(50)
}

b.getObjectIntoInterestingState(b.randomArguments())

b.buildRepeatLoop(n: 100) {
    let f = b.randomFunction()
    let args = b.randomArguments(forCalling: f)
    b.callFunction(, withArgs: args)
}
```

Fuzzilli’s HybridEngine



1. Generate

2. Mutate

RegExp Fuzzer in Fuzzilli

```
ProgramTemplate("RegExpFuzzerTemplate") { b in

    let f = b.buildPlainFunction(with: .parameters(n: 0)) {
        let pattern = probability(0.5) ? chooseUniform(from: b.fuzzer.environment.interestingRegExps) : b.randomString()
        let regExpVar = b.loadRegExp(pattern, RegExpFlags.random())

        let subjectVar: b.loadString(b.randomString())

        let symbol = b.loadBuiltin("Symbol")
        let resultVar = b.callMethod("exec", on: regExpVar, withArgs: [subjectVar])

        b.build(n: 7)

        b.doReturn(resultVar)
    }

    b.callFunction(f)
    b.callFunction(f)

    b.build(n: 15)
}
```

RegExp Fuzzer in Fuzzilli

crbug.com/1439691:

```
function f0() {
}
/(?!(a))\1/gudyi[Symbol.replace]("f\uD83D\uDCA9ba\u2603", f0);
```

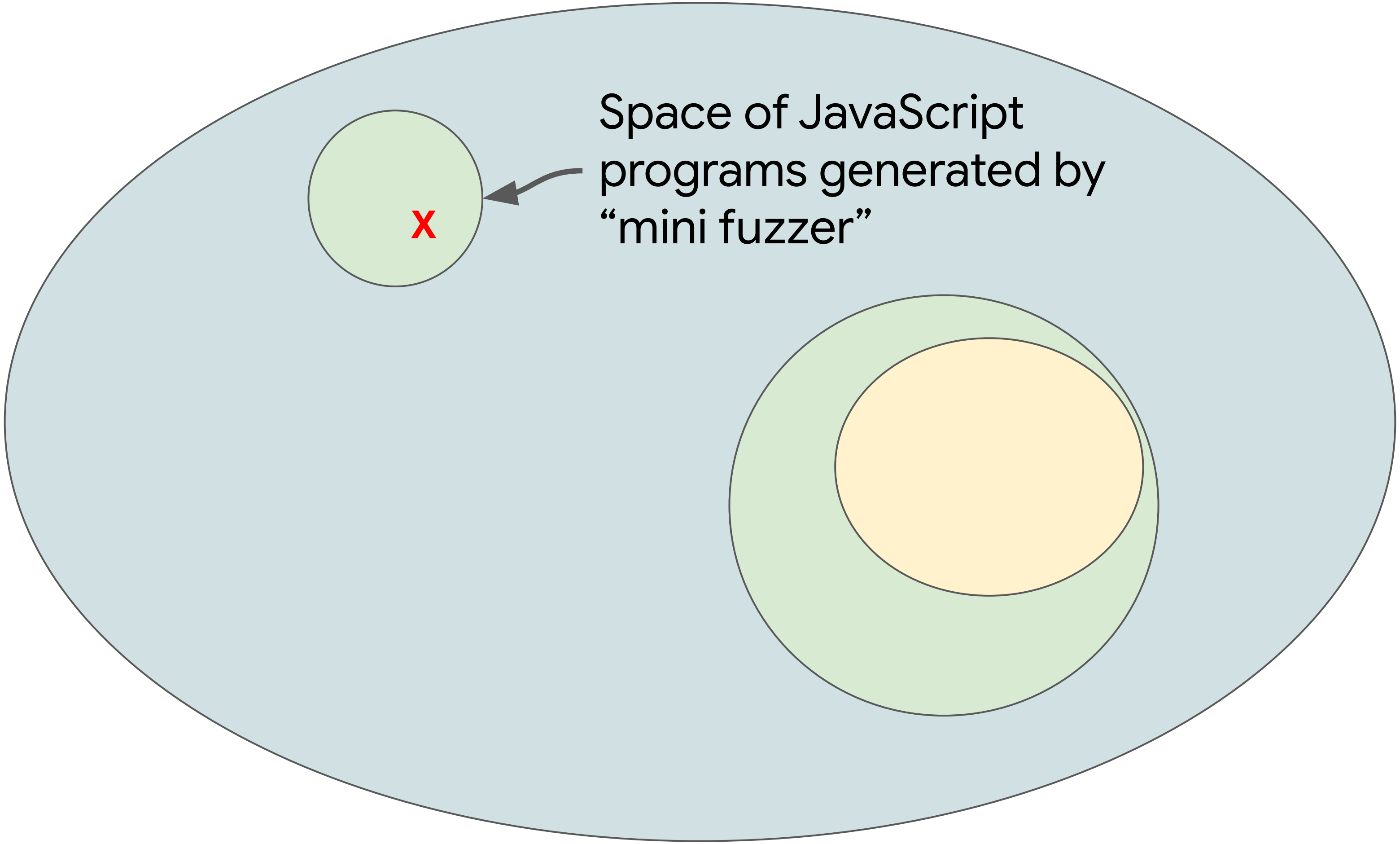
Serializer API Fuzzer

```
// Serialize a random object
let content = b.callMethod("serialize", on: serializer, withArgs: [b.randomVariable()])

// Mutate the contents
b.mutate(content)

// Deserialize the resulting buffer
let _ = b.callMethod("deserialize", on: serializer, withArgs: [content])

// Deserialized object is available in a variable now and can be used by following code
```

Serializer API Fuzzer

crbug.com/1364974:

```
const v4 = d8.serializer.serialize(-2147483648n);
const v5 = new Uint8Array(v4);
v5[3] = 1;
const v9 = d8.serializer.deserialize(v4);
~v9;
```



Space of JavaScript programs generated by “mini fuzzer”

Future for JavaScript Engine Fuzzing

- Combining samples with features is hard
- Code Coverage will bring out features into a diverse corpus!
- How do we combine them meaningfully?
    - New feedback mechanisms?
- It is hard to design a good feedback mechanism
    - Too fine grained? Every new program will be “interesting”
    - Too coarse grained? Feedback will not capture enough detail

Summary

- Key challenge: JavaScript “search space” is extremely large
- Coverage guided fuzzing only gets you so far
  - Can find some types of bugs, but will struggle with others
- Specific mutators can be used to target certain bug types
  - Fuzzilli’s new Probe- and Explore mutators have each found new bugs
- “Human-guided fuzzing” to target areas that researcher deems interesting
  - Can build “mini fuzzers” on top of Fuzzilli’s HybridEngine