Fuzzilli

(Guided-)fuzzing for JavaScript engines

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Motivation

Cool bugs in JS engine runtime implementations, JIT compilers, etc.

```javascript
var a = [1, 2, 3, 4, 5];
var i = {};
i.valueOf = function() {
    a.length = 1;
    return 5;
}
a.slice(0, i);
```

```javascript
function hax(o) {
    o.a;
    Object.create(o);
    return o.b;
}

for (let i = 0; i < 100000; i++) {
    let o = {a: 42};
    o.b = 43;
    hax(o);
}
```

CVE-2016-4622

CVE-2018-17463
How to fuzz JavaScript Engines?
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./js_shell < /dev/urandom
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./js_shell < /dev/urandom

::

::
Requirements

1. Valid syntax of produced samples
Syntactical Correctness

- Possible to achieve with grammar-based generative fuzzing
  - Example: domato
- Basic idea: formulate JavaScript language as context-free grammar
- Then apply random production rules

A.3 Statements

Statement[Yield, Await, Return] :
BlockStatement[Yield, ?Await, ?Return]
VariableStatement[Yield, Await]
EmptyStatement
ExpressionStatement[Yield, Await]
IfStatement[Yield, Await, ?Return]
BreakableStatement[Yield, Await, ?Return]
ContinueStatement[Yield, Await]
BreakStatement[Yield, Await]
[+Return] ReturnStatement[Yield, Await]
WithStatement[Yield, Await, ?Return]
LabelledStatement[Yield, Await, ?Return]
ThrowStatement[Yield, Await]
TryStatement[Yield, Await, ?Return]
DebuggerStatement

Excerpt from the ECMAScript grammar
...;
var v4 = new Array(42, v3, "foobar");
for (var v5 = 0; v5 < 1000; v5++) {
    v4 = v5 * 7;
    var v6 = v4.slice(v1, v1, v2);
}
...;

Script generated by grammar-based fuzzer
Exception: TypeError: v4.slice is not a function.
Grammar-based Fuzzing

...;
var v4 = new Array(42, v3, "foobar");
for (var v5 = 0; v5 < 1000; v5++) {
    v4 = v5 * 7;
    var v6 = v4.slice(v1, v1, v2);
}
...

Following code is never executed...

Exception: TypeError: v4.slice is not a function.
Solution: Try-Catch?

```javascript
...;
var v4 = new Array(42, v3, "foobar");
for(var v5 = 0; v5 < 1000; v5++) {
    v4 = v5 * 7;
    var v6 = v4.slice(v1, v1, v2);
}
...;
```

```javascript
...;
try {
    var v4 = new Array(42, v3, "foobar");
} catch(e) {}
for (var v5 = 0; v5 < 1000; v5++) {
    try {
        v4 = v5 * 7;
    } catch(e) {}
    try {
        var v6 = v4.slice(v1, v1, v2);
    } catch(e) {}
}
...;
```
Solution: Try-Catch?

...;
var v4 = new Array(42, v3, “foobar”);
for(var v5 = 0; v5 < 1000; v5++) {
    v4 = v5 * 7;
    var v6 = v4.slice(v1, v1, v2);
}

...;

try {
    var v4 = new Array(42, v3, “foobar”);
} catch(e) {}  
for (var v5 = 0; v5 < 1000; v5++) {
    try {
        v4 = v5 * 7;
    } catch(e) {}
    try {
        var v6 = v4.slice(v1, v1, v2);
    } catch(e) {}
}

...;

Two pretty different things for a JIT compiler...
Requirements

1. Valid syntax of produced samples
2. High degree of semantic correctness
Semantic correctness

- Harder to achieve than syntactical correctness
- Multiple options:
  a. Precise type tracking in generated code
  b. Generate JavaScript code
     “step-by-step”, validating after each step
  c. Use mutational approach, only keep semantically valid samples in corpus
  d. … ?

1. Take sample from corpus. Sample is guaranteed to be valid.
2. Mutate sample, small chance of making it invalid.
3. Potentially insert sample back into corpus, but only if it is valid.
Requirements

1. Valid syntax of produced samples
2. High degree of semantic correctness
3. Definition of sensible mutations of JavaScript code
Mutating Programs

- Mutations possible at different “levels”:
- Observation: relevant are mostly control and data flow of the programs
- Syntactic representations are largely irrelevant for execution

=> Mutate at “bytecode” level

<table>
<thead>
<tr>
<th>Source Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit and byte mutations</td>
</tr>
<tr>
<td>String insertions, replacements, ...</td>
</tr>
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<table>
<thead>
<tr>
<th>Syntax Tree (AST)</th>
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</thead>
<tbody>
<tr>
<td>Mutations of literals and identifiers</td>
</tr>
<tr>
<td>Subtree insertions, replacements, ...</td>
</tr>
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<table>
<thead>
<tr>
<th>Bytecode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutations of operands and “registers”</td>
</tr>
<tr>
<td>Instruction insertions, replacements, ...</td>
</tr>
</tbody>
</table>
FuzzIL

- Define custom intermediate language: “FuzzIL”
- Captures control and data flow
- Define mutations on the IL
- Translate IL to JavaScript for execution

; Example FuzzIL program
v0 ← LoadInt '0'
v1 ← LoadInt '10'
v2 ← LoadInt '1'
v3 ← Phi v0
BeginFor v0, '<', v1, '+', v2 → v4
    v6 ← BinaryOperation v3, '+', v4
    Copy v3, v6
EndFor
v7 ← LoadString 'Result: '
v8 ← BinaryOperation v7, '+', v3
v9 ← LoadGlobal 'console'
v10 ← CallMethod v9, 'log', [v8]
FuzzIL - Lifting

v0 ← LoadInt '0'
v1 ← LoadInt '10'
v2 ← LoadInt '1'
v3 ← Phi v0
BeginFor v0, '<', v1, '+', v2 → v4
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v10 ← CallMethod v9, ‘log’, [v8]

// Trivial lifting
const v0 = 0;
const v1 = 10;
const v2 = 1;
let v3 = v0;
for (let v4 = v0; v4 < v1; v4 = v4 + v2) {
    const v6 = v3 + v4;
    v3 = v6;
}
const v7 = "Result:"
const v8 = v7 + v3;
const v9 = console;
const v10 = v9.log(v8);
FuzzIL - Lifting

v0 <- LoadInt '0'
v1 <- LoadInt '10'
v2 <- LoadInt '1'
v3 <- Phi v0
BeginFor v0, '<', v1, '+', v2 -> v4
  v6 <- BinaryOperation v3, '+', v4
  Copy v3, v6
EndFor
v7 <- LoadString 'Result: '
v8 <- BinaryOperation v7, '+', v3
v9 <- LoadGlobal 'console'
v10 <- CallMethod v9, 'log', [v8]

// Trivial lifting
const v0 = 0;
const v1 = 10;
const v2 = 1;
let v3 = v0;
for (let v4 = v0; v4 < v1; v4 = v4 + v2) {
  const v6 = v3 + v4;
  v3 = v6;
}
const v7 = "Result: ";
const v8 = v7 + v3;
const v9 = console;
const v10 = v9.log(v8);

// Lifting with expression inlining
let v3 = 0;
for (let v4 = 0; v4 < 10; v4++) {
  v3 = v3 + v4;
}
console.log("Result:" + v3);
Mutating FuzzIL

v0 <- LoadGlobal 'print'
v1 <- LoadString 'Hello World'
v2 <- CallFunction v0, v1
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v2 <- CallFunction v0, v1

Input Mutator

Operation Mutator
Mutating FuzzIL

```plaintext
v0 <- LoadGlobal 'print'
v1 <- LoadString 'Hello World'
v2 <- CallFunction v0, v0

v0 <- LoadGlobal 'print'
v1 <- LoadString 'Hello World'
v2 <- CallFunction v0, v1

v0 <- LoadGlobal 'encodeURI'
v1 <- LoadString 'Hello World'
v2 <- CallFunction v0, v1

v0 <- LoadGlobal 'print'
v1 <- LoadString 'Hello World'
v2 <- LoadProperty v0, 'foo'
v3 <- CallFunction v0, v1
```
Mutating FuzzIL

Input Mutator

\( v0 \leftarrow \text{LoadGlobal } 'print' \)
\( v1 \leftarrow \text{LoadString } 'Hello World' \)
\( v2 \leftarrow \text{CallFunction } v0, v1 \)

Operation Mutator

\( v0 \leftarrow \text{LoadGlobal } 'print' \)
\( v1 \leftarrow \text{LoadString } 'Hello World' \)
\( v2 \leftarrow \text{CallFunction } v0, v1 \)

Splice Mutator

(Inserts existing code)

\( v0 \leftarrow \text{LoadGlobal } 'print' \)
\( v1 \leftarrow \text{LoadString } 'Hello World' \)
\( v2 \leftarrow \text{LoadGlobal } 'print' \)
\( v3 \leftarrow \text{CallFunction } v0, v1 \)

Insertion Mutator

(Generates new code)

\( v0 \leftarrow \text{LoadGlobal } 'encodeURI' \)
\( v1 \leftarrow \text{LoadString } 'Hello World' \)
\( v2 \leftarrow \text{CallFunction } v0, v1 \)

\( v0 \leftarrow \text{LoadGlobal } 'print' \)
\( v1 \leftarrow \text{LoadString } 'Hello World' \)
\( v2 \leftarrow \text{LoadProperty } v0, 'foo' \)
\( v3 \leftarrow \text{CallFunction } v0, v1 \)
Minimization

- Problem: mutations can only grow a program in size
- Solution: minimize programs before inserting them into the corpus
- Simple algorithm: remove one instruction (starting at end) and check if behaviour changed
- But very expensive…
  - Room for improvement here!

* E.g. doesn’t have any undefined variables now
Guided Fuzzing

- Have mutation-based fuzzer
  => Plug in a feedback system and keep “interesting” programs for future mutations

- Currently implemented:
  edge-coverage, similar to afl
  - For JIT, only coverage in the compiler though!

- Easily replaced by different metrics
  - Ideas anyone?
Algorithm

Take sample from corpus, mutate, execute.
Did it crash?

Yes -> Minimize and process crash
No -> Did it succeed? (no exception thrown)

Yes -> Minimize and insert into corpus
No -> Did it trigger new behaviour?

Yes -> Minimize and insert into corpus
No -> No

No -> No
Architecture

- 1 fuzzer instance per target process
  - No locking of e.g. corpus required
  - Simplifies code because program execution is synchronous
- Synchronization over IPC/network
- Programs can be imported from another instance, will be executed and compared against local corpus
Synchronization

Master

Worker

Some communication link (task queues, IPC, network, …)

Worker

Worker
Synchronization

“I found this interesting program!”
Synchronization

“I found this interesting program!”

“Thanks, let me execute that!”
<< executes and evaluates program >>
Synchronization

“Thanks, let me execute that!”
<< executes and evaluates program >>

“Indeed, that’s interesting!”
Synchronization

“We found this new interesting program”
Synchronization

Master

“We found this new interesting program”

Worker

<< execute and evaluate program >>

Worker

Worker
Synchronization

Roughly same procedure for crashes, but they aren’t sent downstream again.
Scaling…

- Distributed fuzzing over many machines by synchronizing with simple TCP-based protocol
- Easy setup with GCE and docker
- Kubernetes maybe?
Results

- Currently supported: JavaScriptCore, Spidermonkey, v8
- Some results from last year:
  - Numerous unique crashes (>50 or >100 or so…)
    - Many assertion failures in debug builds, misbehaviour but no security impact, nullptr derefs, crashes in HEAD but not (yet) RELEASE, etc. Analysis often tedious...
  - 2 CVEs in JavaScriptCore (CVE-2018-4299, CVE-2018-4359)
  - 1 CVE in Spidermonkey (CVE-2018-12386)
    - Cool register allocation bug, used in Hack2Win competition =)
- Now running on > 1 server
  - ...

Roadmap

● Next few weeks:
  ○ Clean up code
  ○ Put into review for release
  ○ Wait for current bugs to be fixed, probably ...

● Open source release!

● Afterwards:
  ○ Implement “compiler” JavaScript -> FuzzIL
  ○ Extend FuzzIL language features
  ○ Experiment with more generative approaches (“Hybrid-fuzzing”?)
  ○ Better type tracking/prediction
  ○ Play with different instrumentations, also custom ones
  ○ Much much more ...
Wrap-up

Summary:

● Guided fuzzing of JS engines by mutating a custom IL
● Fairly generic code mutation engine

Watch this space: https://github.com/googleprojectzero/fuzzilli

Looking for collaborators! :)