FuzzJIT: Oracle-enhanced Fuzzing for JavaScript Engine JIT Compiler

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Browser is vital in our daily life

- Web browsing
- Social media
- Online shopping
- Online banking
- Online collaboration
- ...
Browser can get compromised

- At Pwn2Own 2022, Manfred Paul successfully demonstrated 2 bugs on Mozilla Firefox, earning him $100,000.
- Manfred Paul successfully scored his second win on Apple Safari, earning him $50,000.
JavaScript engine powers browser

- Parse and validate JavaScript
- Execute JavaScript
- JIT compile and optimize JavaScript
Architecture of JavaScript engine

JavaScript

Parser

Abstract syntax tree

Bytecode generator

Bytecode

Interpreter

JIT compiler

Execution

Assembly code
JIT compiler do lots of optimization

- Bound check elimination
- Constant folding
- Dead code elimination
- Common subexpression elimination
- Redundancy elimination
- ...

```
var c = a + b;
var d = a + b;  // var d = c;
var c = a + b;
var d = c;
```
JIT compiler is error-prone

- JavaScript is a weakly and dynamically typed language.

```javascript
var a = 1234;
a = "zhunki";
a = {};
```
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- A direct optimization is not realistic due to the potential ambiguity of variable types.

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- A direct optimization is not realistic due to the potential ambiguity of variable types.
- JIT compiler profiles variable types with runtime information to make optimization decisions.

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JIT compiler is error-prone

- The number of JIT compiler bugs is around four times that of the parser/interpreter bugs during the past four years.
JIT compiler is error-prone

- Among 8 successful Pwn2Own demonstrations in 2019 to 2021, 6 of them exploit 5 JIT compiler bugs.

- CVE-2021-21220 (JIT)
- CVE-2020-9805 (JIT)
- CVE-2019-9813 (JIT)
- CVE-2019-6217 (JIT)
- CVE-2019-6216 (JIT)
How to detect JIT compiler bugs?

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  - Mainly using crash as the oracle
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  - Is it enough?
880207: Math.expm1 typing bug

- \( \text{Math.expm1}(x) = e^x - 1 \)

function foo(){
    return Object.is(Math.expm1(-0), -0);
}
880207: Math.expm1 typing bug

- Math.expm1(x) = e^x - 1
- Object.is determines whether two values are the same value.

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- Object.is determines whether two values are the same value.
- What harm can the subtle difference between -0 and 0 cause?
- **Exploiting the Math.expm1 typing bug in V8**
Remark

• There are many other JIT compiler bugs:
  • only cause subtle difference before/after optimization rather than crash
  • but could be exploitable.
Insight

- JIT compiler shall only speed up but never change the output.
How to detect JIT compiler bugs?

• Current existing JavaScript engine fuzzors:
  • Mainly using crash as the oracle
  • Is it enough?
• We need an enhanced oracle to detect both crash and non-crash JIT compiler bugs.
Our approach

1. Activating JIT compiler for each test case.
2. Precisely capturing discrepancy caused by JIT compiler.
3. Mutation strategy to reveal JIT compiler bugs.
1. Activating JIT compiler

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```javascript
function opt(){
  ...
}

for(var i=0; i<1000; i++)
  opt();
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- JIT compiler can be activated when certain JavaScript code becomes hot, i.e., being executed enough times.
- We wrap the testing content into a function (opt) and invoke it inside for loops.
- The number and times of for loops are determined by optimization conditions of each JavaScript engine.
2. Capturing discrepancy

```javascript
function opt(){
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```

- Compare if the return value of optimized function before JIT and after JIT deeply equals.
2. Capturing discrepancy

```javascript
function opt(){
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var beforeJIT = opt();
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var afterJIT = opt();
if(!deepEquals(beforeJIT, afterJIT))
    crash();
```

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- Compare if the return value of optimized function before JIT and after JIT **deeply** equals.
- To eliminate false alarms, we forbid the generation of some APIs:
  - Math.random()
  - Date.now()
  - ...
3. Mutation strategies

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- Increasing the probability of generating JIT bug related elements:
  - Arrays
  - Objects
  - Interesting numbers
  - ...
3. Mutation strategies

function opt(){
    arrays, objects, interesting numbers...
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FuzzJIT implementation

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- One template + Fuzzilli
FuzzJIT implementation

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• One template + Fuzzilli
• Fuzzilli is a coverage-guided fuzzor for JavaScript engines based on a custom intermediate language (FuzzIL).
• Fuzzilli provides:
  • Coverage guidance
  • Fuzzing queue organization
  • Test case execution
  • Fault detection
  • ...
1-month evaluation: found new bugs

- JavaScriptCore (10)
  233353: undefined/NaN
  239757: undefined/NaN
  239758: -Infinity/Infinity
  228068: True/False
  232866: -NaN/NaN
  233118: crash
  232869: 1/-1
  -: -Infinity/Infinity
  -: 255/0
  -: crash

- V8 (5)
  1224283: undefined/123
  12471: 14951/14955
  11977: True/False
  1276923: crash
  12495: opt()/11
1-month evaluation: found new bugs

• SpiderMonkey (2)
  1747013: opt()/NaN
  1747777: crash

• ChakraCore (16)
  6783: True/False
  059706: crash
  6762: crash
  6763: crash
  6764: crash
  6765: crash
  6766: crash
  ...

1-month evaluation: coverage

• FuzzJIT outperforms state-of-the-art fuzzers
  • Superion: +30.04%
  • DIE: +3.48%
  • Fuzzilli: +16.47%
Thank you!

Q & A

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