TypeDevil: Dynamic Type Inconsistency Analysis for JavaScript

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Motivation

- JavaScript: Dynamic and permissive
- Problems remain unnoticed
- Purely static analysis is limited

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- JavaScript: Dynamic and permissive
- Problems remain unnoticed
- Purely static analysis is limited

This talk: Mostly dynamic analysis to find otherwise missed errors

Example

```
function addWrapped(x, y) {
  if (y) return x.v + y.v;
  else return x.v;
}
function Wrapper(v) {
  this.v = v;
}
addWrapped({v:23});
addWrapped({v:20}, new Wrapper(3));
addWrapped({v:"18"}, new Wrapper(5));
```

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function addWrapped(x, y) {
  if (y) return x.v + y.v;
  else return x.v;
}
function Wrapper(v) {
  this.v = v;
}
addWrapped({v:23});                        // 23
addWrapped({v:20}, new Wrapper(3));        // 23
addWrapped({v:"18"}, new Wrapper(5));      // "185"
```

Incorrect behavior,

but no obvious sign of misbehavior

Observations

1) Most code follows **implicit type rules**

- A single type per variable
- A single type per object property
- Functions have fixed signatures

2) Many **bugs** are **violations of these rules**

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Example

`x.v` has types `number` and `string`

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```

Returns both `number` and `string`

Example

```
function addWrapped(x, y) {
  if (y) return x.v + y.v;
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```

```
addWrapped({v: "18"}, new Wrapper(5));
```

Goal: Program analysis to find inconsistent types of variables, properties, and functions

TypeDevil: Overview

JavaScript program

↓

Gather type observations

↓

Summarize observations into type graph

↓

Find, merge, and filter inconsistencies

↓

Warnings about inconsistent types

Types

Type = Primitive type or record type

Property names $\rightarrow$ Sets of types

Record types represent:

- Object types
- Array types
- Function types

  ”this” and ”return” as properties
- Frame types

  Local variables as properties

Type Observations

Type observation = (base, property, type)

Gather observations through **dynamic analysis** *

- Store type names of objects as shadow values
- Add type observations to global set

* Based on Jalangi (Sen et al., 2013)

Gathering Type Observations

Object literal

- Store type name as shadow
- One observation per property

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```

Shadow: ”object1”

(object1, v, number)

Gathering Type Observations

Function call

- Observations for ”this” and ”return”

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```

(function addWrapped, this, window)

(function addWrapped, return, number)

Gathering Type Observations

Variable read/write

- Observation for type of local variable (property of frame type)

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(frame addWrapped, y, undefined)

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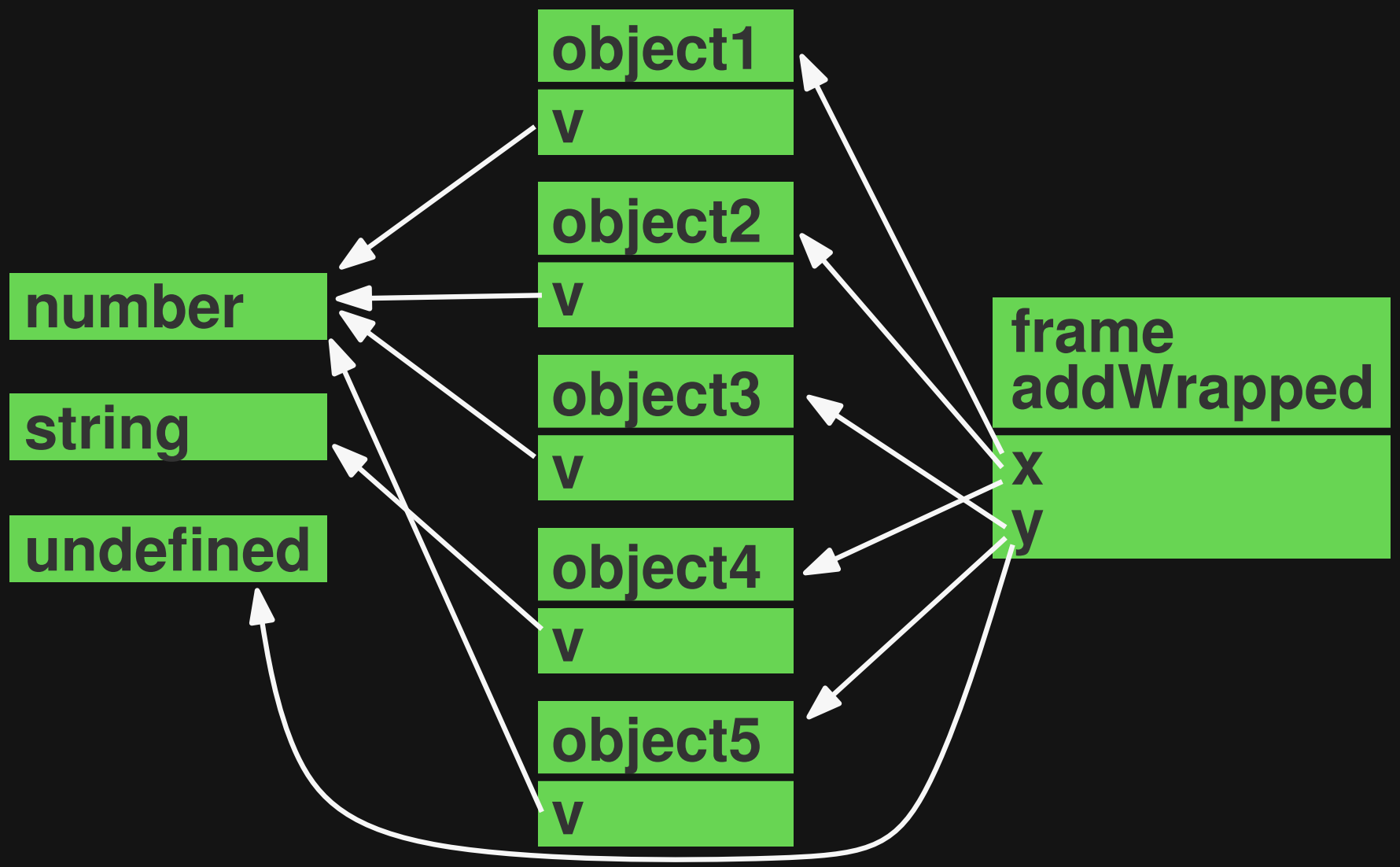
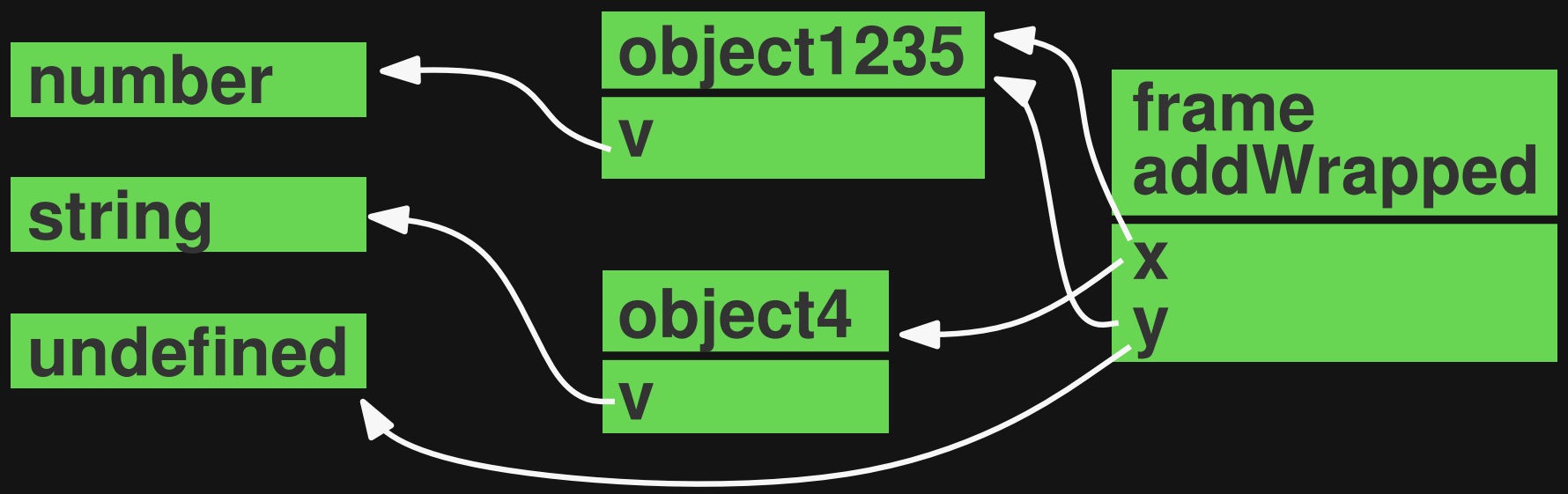
Type Graph

Nodes = type, edges = properties



Condensed Type Graph

Summarize graph by merging equivalent types



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Reporting Inconsistencies

Report nodes with multiple outgoing edges for the same property

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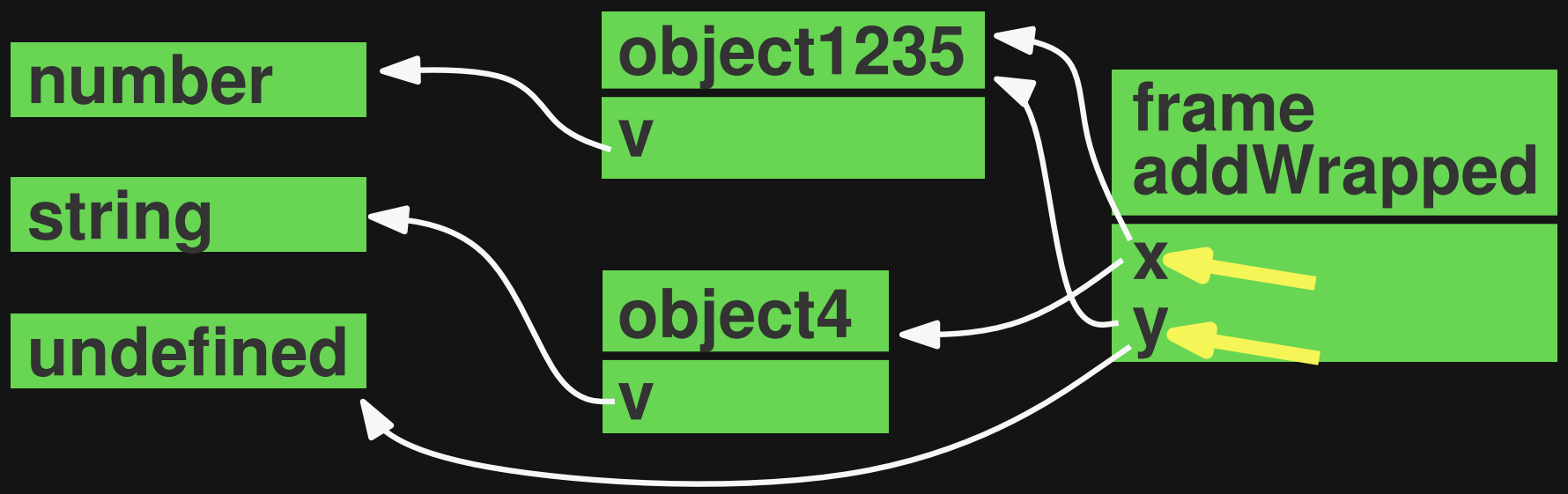
Report nodes with **multiple outgoing edges** for the same property



Inconsistencies: Example

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Inconsistencies: Example

`x.v` has types `number` and `string`

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Inconsistencies: Example

`y` has types `object` and `undefined`

```
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function Wrapper(v) {
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Prune and Merge Warnings

Prune likely false positives:

- Via belief analysis
- By degree of inconsistency
- By size of type diff
- Structural subtypes
- `null`-related

Merge warnings with same root cause:

- By dataflow relations
- By type diff
- By array type

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- By array type

Prune via Belief Analysis

Problem:

Intended polymorphism

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Intended polymorphism

```
function BigInteger(a, b, c) {
  if (a != null)
    if ('number' == typeof a)
      this.fromNumber(a, b, c);
    else if (b == null && 'string' != typeof a)
      this.fromString(a, 256);
    else
      this.fromString(a, b);
}
```

Code from Octane's crypto benchmark

Prune via Belief Analysis

Problem:

Intended polymorphism

Naive approach: Warnings about inconsistent argument types

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Approach:

- **Infer programmer beliefs from code**
- **Omit warnings about expected types**

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}
```

a may be undefined or null

Code from Octane's crypto benchmark

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    else
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}
```

a may be `number`

Code from Octane's crypto benchmark

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      this.fromString(a, 256);
    else
      this.fromString(a, b);
}
```

`b` may be `undefined` or `null`

Code from Octane's crypto benchmark

Prune via Belief Analysis

Approach:

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- Omit warnings about **expected types**

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  if (a != null)
    if ('number' == typeof a)
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      this.fromString(a, 256);
    else
      this.fromString(a, b);
}
```

a may be string

Code from Octane's crypto benchmark

Prune via Belief Analysis

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function BigInteger(a, b, c) {
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    else if (b == null && 'string' != typeof a)
      this.fromString(a, 256);
    else
      this.fromString(a, b);
}
```

Refined approach:
No warning

Code from Octane's crypto benchmark

Merge by Dataflow Relations

Problem: Multiple references may refer to a single value

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```
function f(x) {
  return g(x);
}
function g(a) {
  return a;
}
f(23);
f({p:"abc"});
```

Merge by Dataflow Relations

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Variable `x`

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Variable `a`

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g's return value

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f's return value

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```

- Variable `x`
- `f`'s return value
- Variable `a`
- `g`'s return value

Naive approach: 4 warnings

Merge by Dataflow Relations

Approach:

- **Approximate dataflow via call graph**
- **Merge warnings that may refer to the same value**

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Approach:

- Approximate **dataflow** via call graph
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Variable `x`

`f`'s return value

Variable `a`

`g`'s return value

Merge by Dataflow Relations

Approach:

- Approximate **dataflow** via call graph
- **Merge** warnings that may refer to the **same value**

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function f(x) {
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```

Refined approach: 1 warning

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Evaluation

Setup:

- Sunspider, Octane, and 7 web apps

Main results:

- Finds relevant problems:
  33 warnings, 15 are relevant
- Merging and pruning is crucial:
  578 warnings $\rightarrow$ 33 warnings

Examples

SunSpider's regexp-dna:

```
var dnaOutputStr;
for (i in seqs) {
  dnaOutputStr += seqs[i].source;
}
```

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```
var dnaOutputStr;
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}
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`string` and `undefined`

Problem: Incorrect string value "undefinedGTAGG..."

Examples (2)

SunSpider's date-format-xparb:

```
String.leftPad = function (val, size, ch) {
  var result = new String(val);
  if (ch == null)
    ch = " ";
  while (result.length < size) {
    result = ch + result;
  }
  return result;
}
```

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  var result = new String(val);
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    result = ch + result;
  }
  return result;
}
```

Returns `string` and `object`

Problem: `string` and `String` behave differently

Examples (3)

Octane's GB emulator:

```
function GameBoyCanvas() {
  this.width = 160;
  this.height = 144;
}
function initNewCanvas() {
  gb.canvas.width = gb.canvas.clientWidth;
  gb.canvas.height = gb.canvas.clientHeight;
}
```

Examples (3)

Octane's GB emulator:

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function GameBoyCanvas() {
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}
```

`gb.canvas.width` has types `number` and `undefined`

Problem: Crash when changing the emulator settings

Conclusion

Find inconsistent types in JavaScript:

- Observe types and summarize them into type graph
- Deal with intended polymorphism

Dynamic analysis:

Powerful approach to find bugs early

https://github.com/Berkeley-Correctness-Group/Jalangi-Berkeley

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Thank you!

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