Why do Modern Web Applications Fail and What Can We Do About it?

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My Research

- **Building error resilient and secure software systems**

- **Three areas**
  - Software resilience [DSN'17][DSN'18A[DSN'18B][SC'18][DSN'16][SC'16][DSN'15]
  - Web applications' reliability [ICSE'18][ICSE'16][ICSE'15][ASE15][ICSE'14A][ICSE'14B]
  - IoT Devices security [FSE'17][ACSAC'16][EDCC'16][HASE'14]

- **This talk: Web Applications' Reliability**

Modern Web Applications: Examples

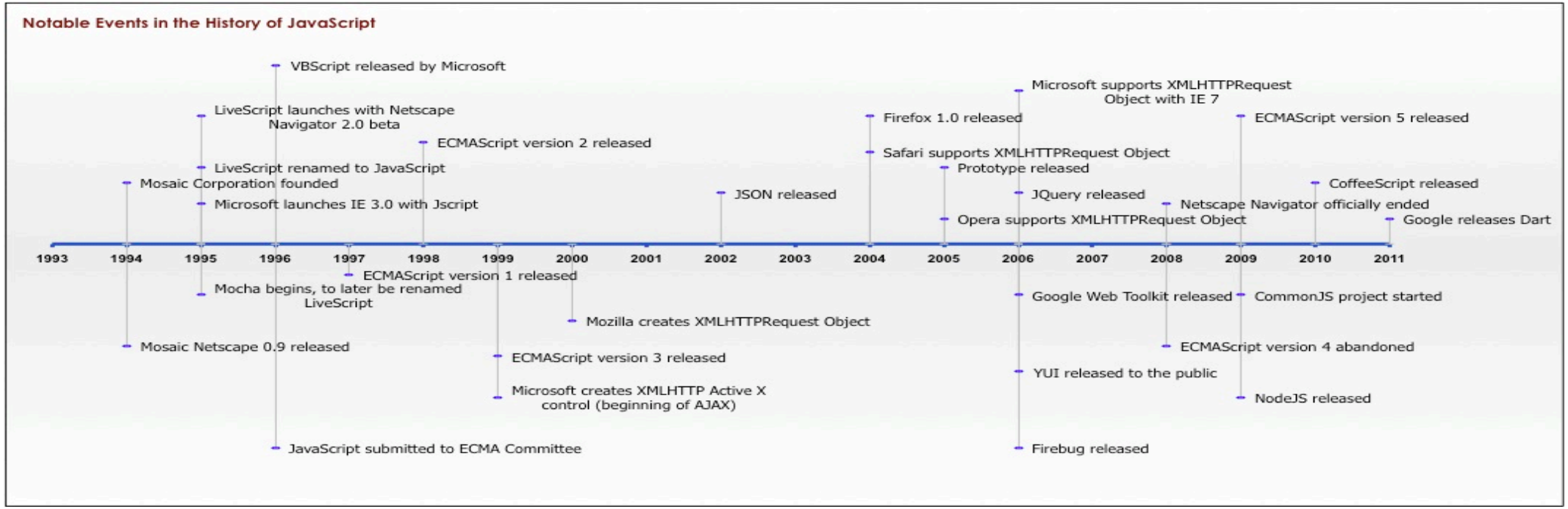
Modern Web Applications: JavaScript

- JavaScript: Implementation of ECMAScript standard
  - Client-Side JavaScript: used to develop web apps
- Executes in client's browser – send AJAX messages
- Responsible for web application's core functionality
- Not easy to write code in – has many "evil" features

4

JavaScript: History

Brief History of JavaScript (Source: TomBarker.com)

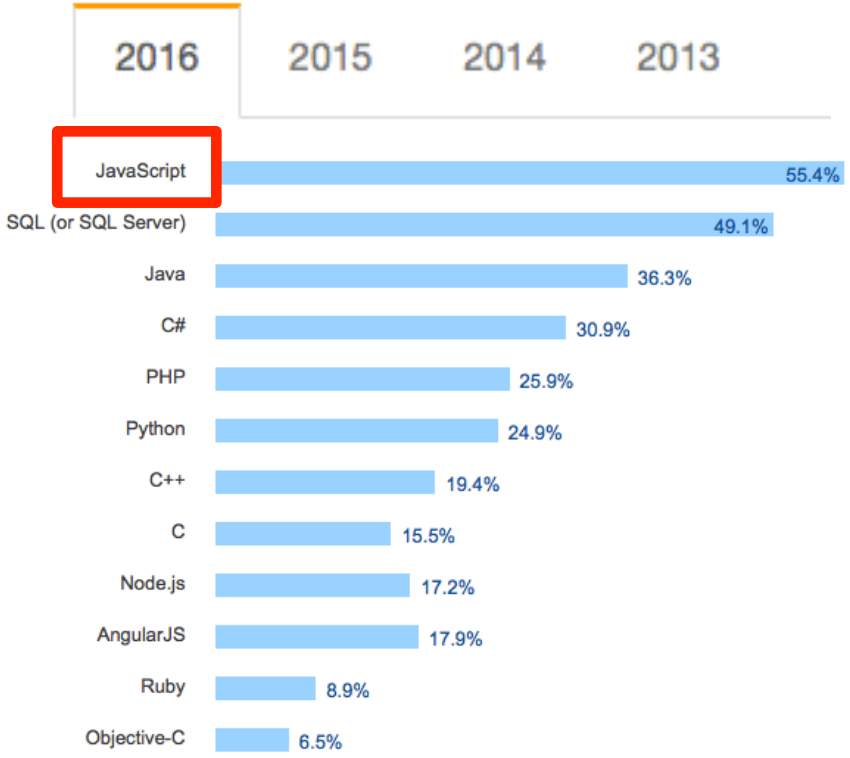


JavaScript (JS) had to "look like Java" only less so, be Java's dumb kid brother or boy-hostage sidekick. Plus, I had to be done **in ten days** or something worse than JS would have happened

– Brendan Eich (Inventor of JavaScript)

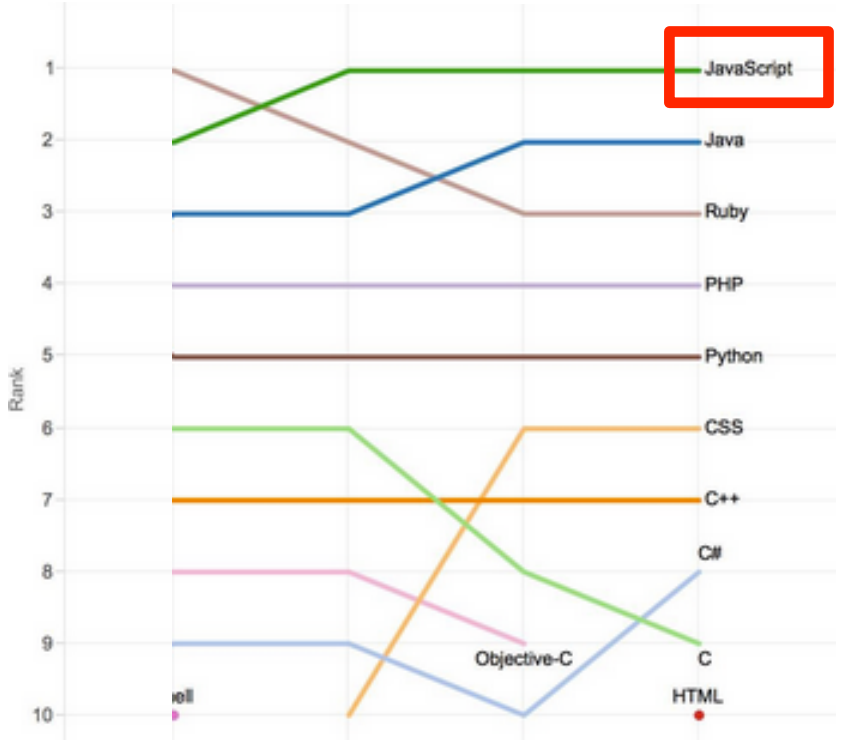
stackoverflow

JavaScript:
Most popular language

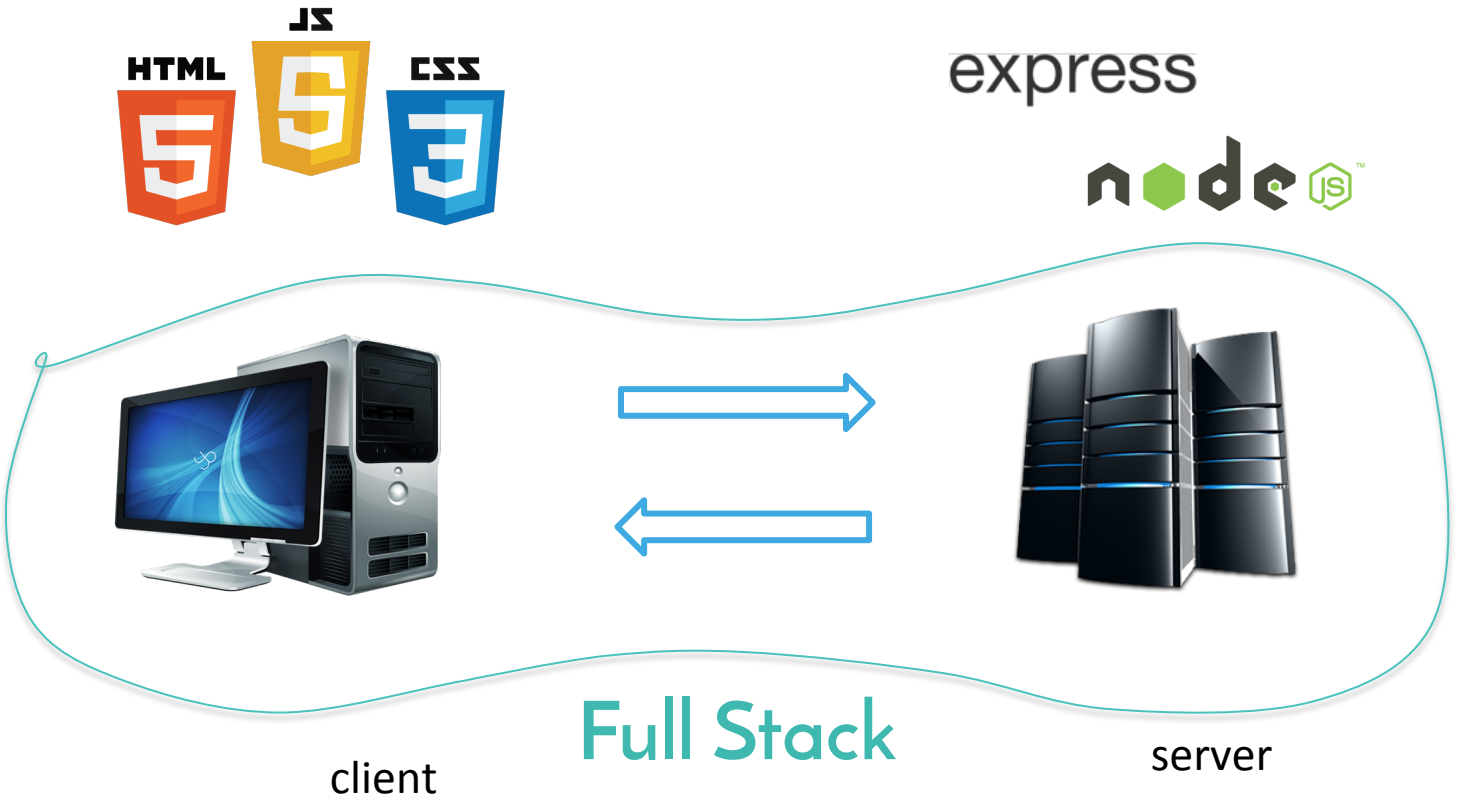


GitHub

JavaScript:
Top languages on GitHub



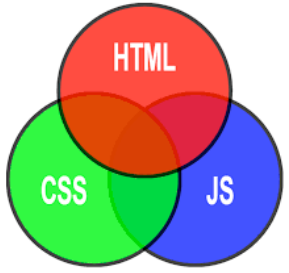
JavaScript and the Web



Analyzing JS Code: Challenges

JS has loose semantics

Lack of standard programming style & JS frameworks



Frequent cross-language interactions

Studies of JavaScript Web Applications

Performance and parallelism:
JSMeter [Ratanaworabhan-2010], [Richards-2009], [Fortuna-2011]

Reliability

?

Security and Privacy:
[Yue-2009], Gatekeeper[Guarnieri-2009], [Jang-2010]

Does Reliability Matter ?

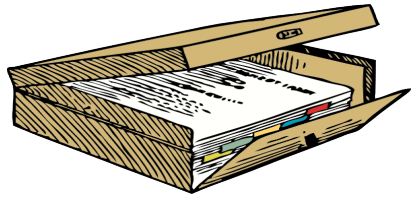
- Snapshot of iFeng.com: Leading media website in China

an error occurred when processing this directive

Talk Outline

- Motivation and Goals
- Empirical Study of reliability
- Reliability Improvements
- Conclusions and Future Directions

Bug Report Study: Methodology



Collected 502 **fixed** bug reports from 19 web applications over 10 years (2004-2014)

Qualitatively analyzed and classified bug reports manually and reading the commits

Aggregated data for further analysis

Bug Report Study: 19 Objects (15 applns, 4 libraries)

Bug Report Study: Research Questions

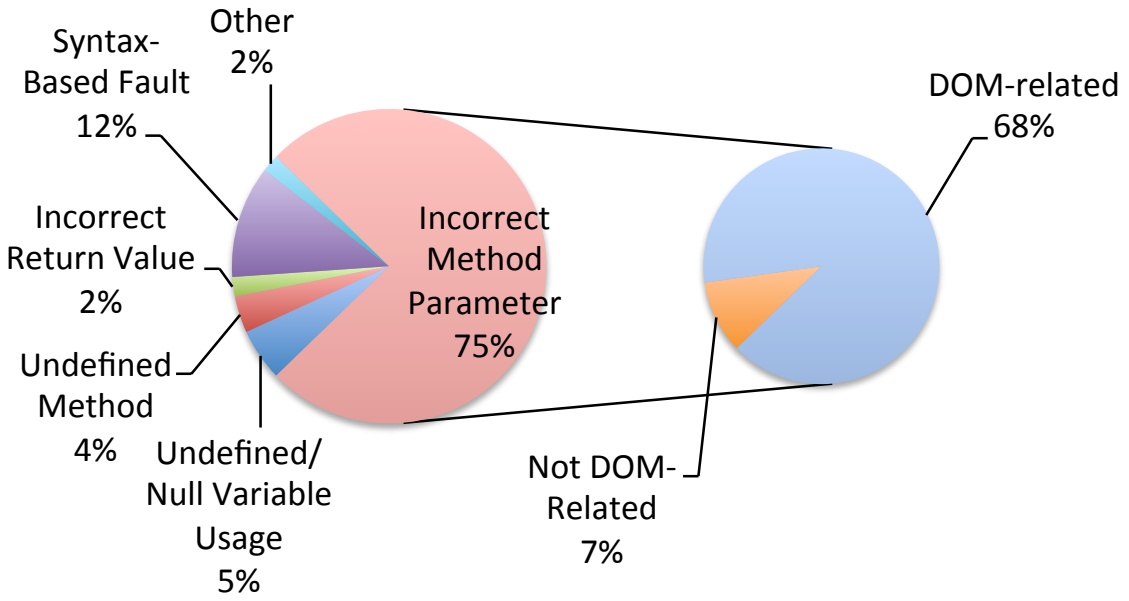
- What mistakes ***cause*** JavaScript faults?

- What ***impact*** do JavaScript faults have?

- How long does it take to fix these errors?

- How many of these faults are browser-specific ?
- How many faults can be caught by strong typing ?

Bug Report Study: Categories

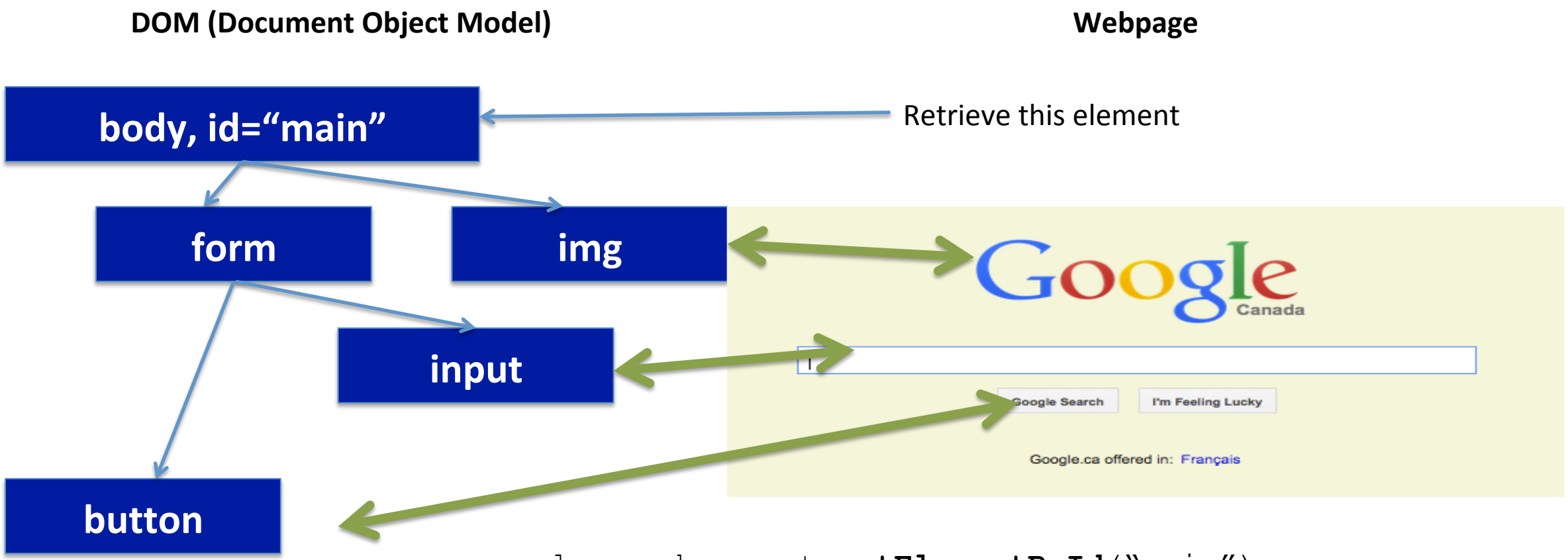


Incorrect Method Parameter Fault: Unexpected or invalid value passed to JS method or assigned to JS property

DOM-Related Fault: The method is a DOM API method

- Account for more than two-thirds of JavaScript Faults

Bug Report Study: DOM-Related Faults




```
elem = document.getElementById("main");
```

Programming Error that propagates to a DOM method parameter

DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
      var prefix = "id_";
      elem = $("#" + prefix + retrievedStr);
}
else {
      elem = $(retrievedStr);
}
elem[0].focus()
```

DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
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elem[0].focus()
```
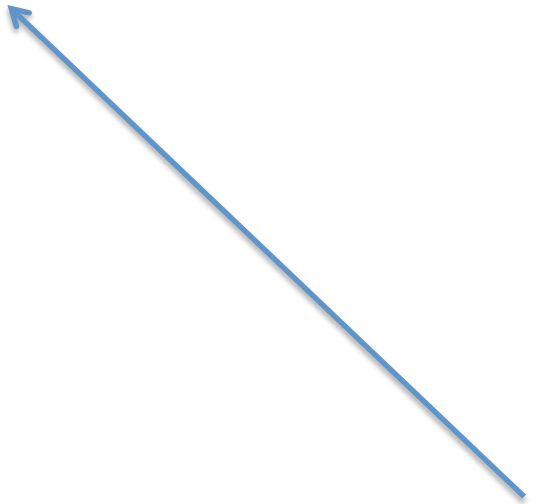



Retrieved string via XHR

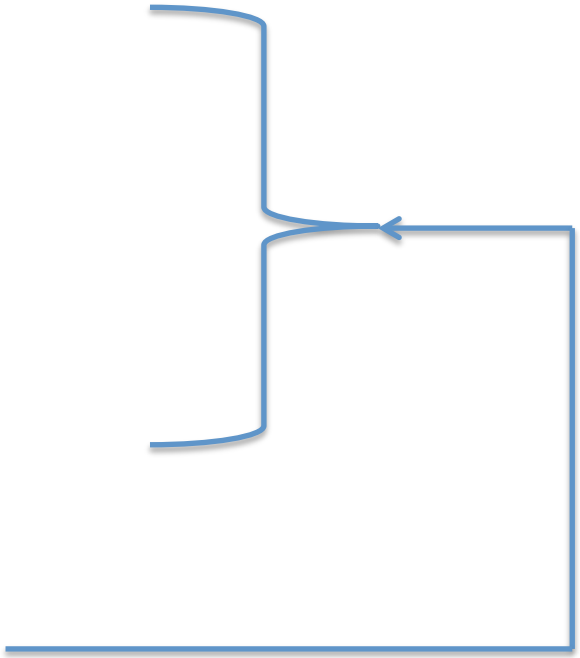
DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
      var prefix = "id_";
      elem = $("#" + prefix + retrievedStr);
}
else {
      elem = $(retrievedStr);
}
elem[0].focus()
```

Find the number of dots in the string

DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
      var prefix = "id_";
      elem = $("#" + prefix + retrievedStr);
}
else {
      elem = $(retrievedStr);
}
elem[0].focus()
```

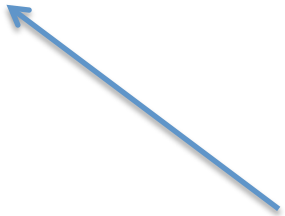


If there are no dots, prepend “id_” to the string and access it via $(). Otherwise, leave it as is, and access it via $().

DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
      var prefix = "id_";
      elem = $("#" + prefix + retrievedStr);
}
else {
      elem = $(retrievedStr);
}
elem[0].focus()
```

UNDEFINED EXCEPTION!



Retrieved string of “editor” would go here even though it has no dots, which would erroneously cause $() to use selector “editor”, which doesn’t match any elements.

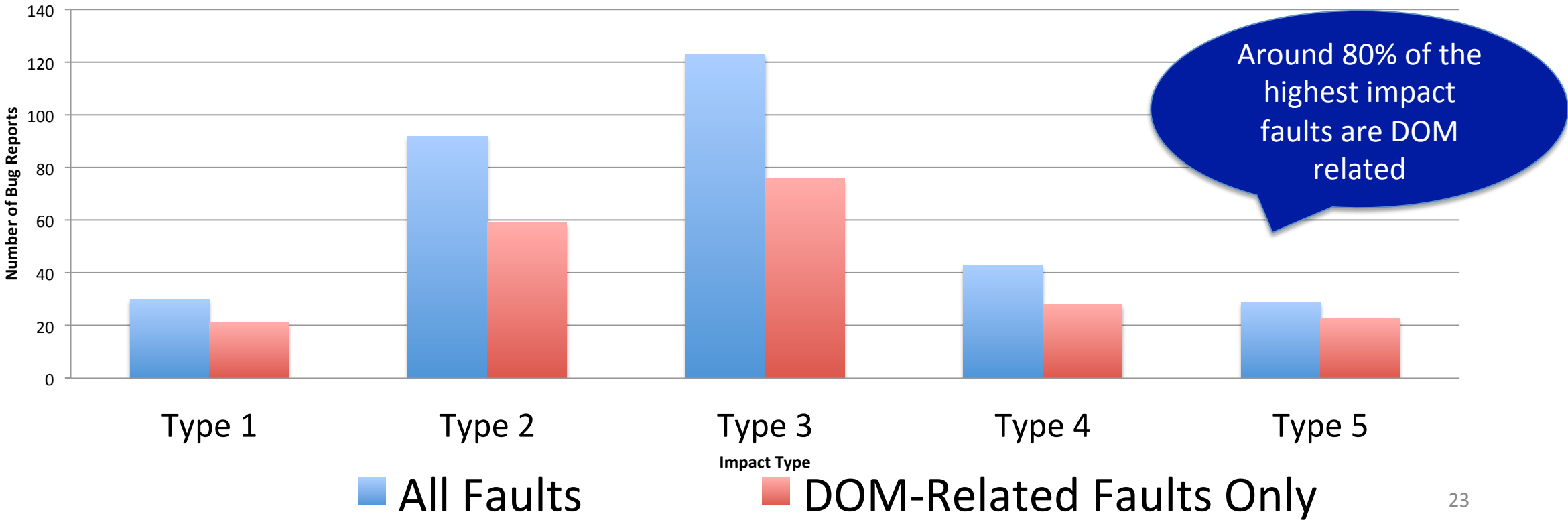
DOM-Related Fault: Example

```
var elem, retrievedStr = [Retrieved via XHR];
var dotsInStr = retrievedStr.split(".").length;
if (dotsInStr == 0) {
      var prefix = "id_";
      elem = $("#" + prefix + retrievedStr);
}
else {
      elem = $(retrievedStr);
}
elem[0].focus()
```

BUG: The assigned value should be retrievedStr.split(“.”).length – 1, as length() always returns at least 1.

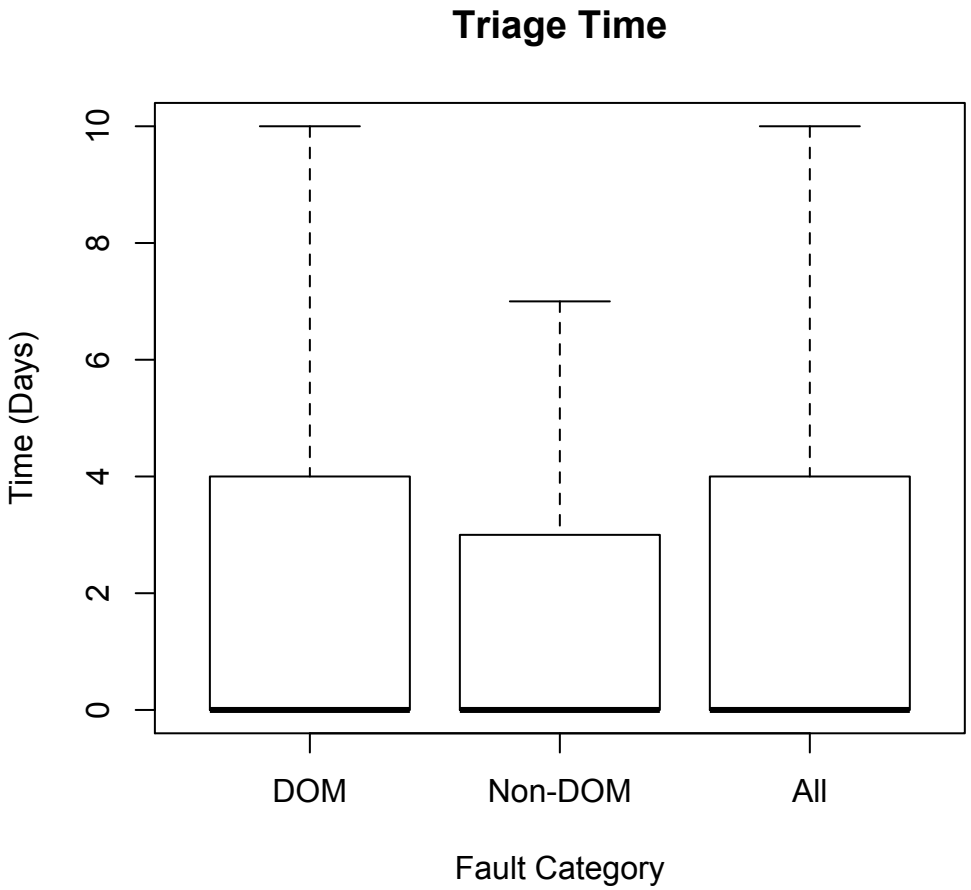
Bug Report Study: Fault Impact

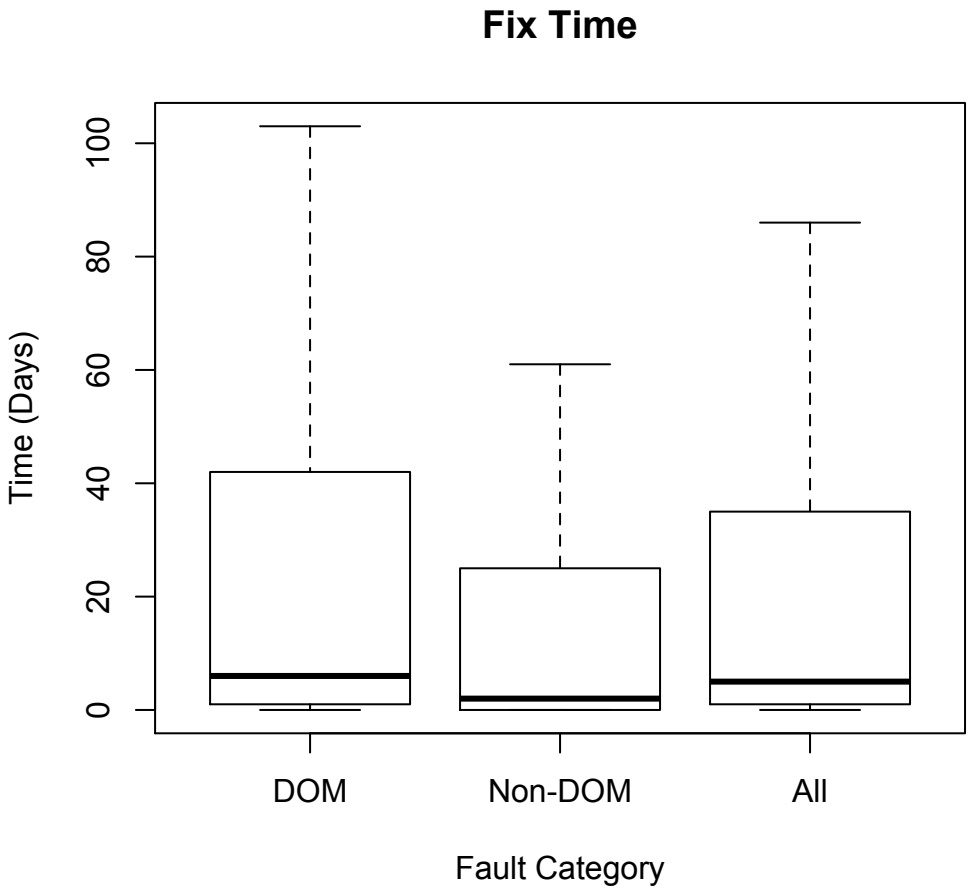
- Impact Types – Based on Bugzilla [ICSE'11]
  - Type 1 (lowest impact − e.g., cosmetic changes)
  - Type 5 (highest impact − e.g., data loss bugs)



Bug Report Study: Fix Times

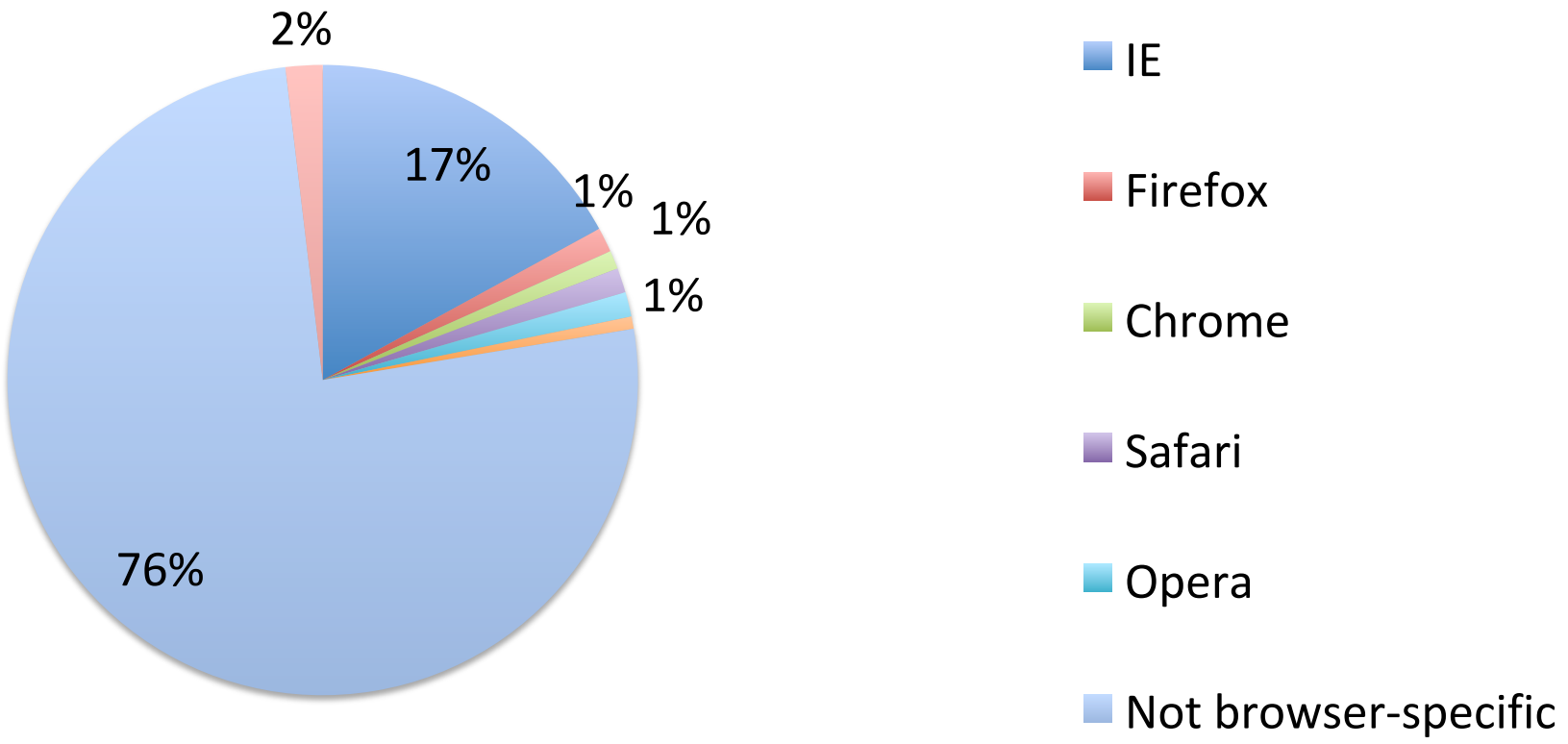
- **Triage Time**: Time it took to assign or comment on the bug
- **Fix Time**: Time it took to fix the bug since it was triaged





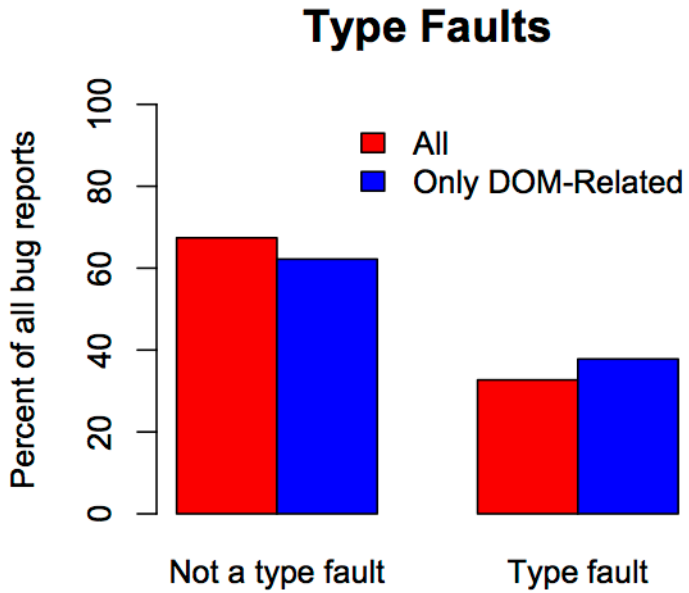
Bug Report Study: Browser Specificity

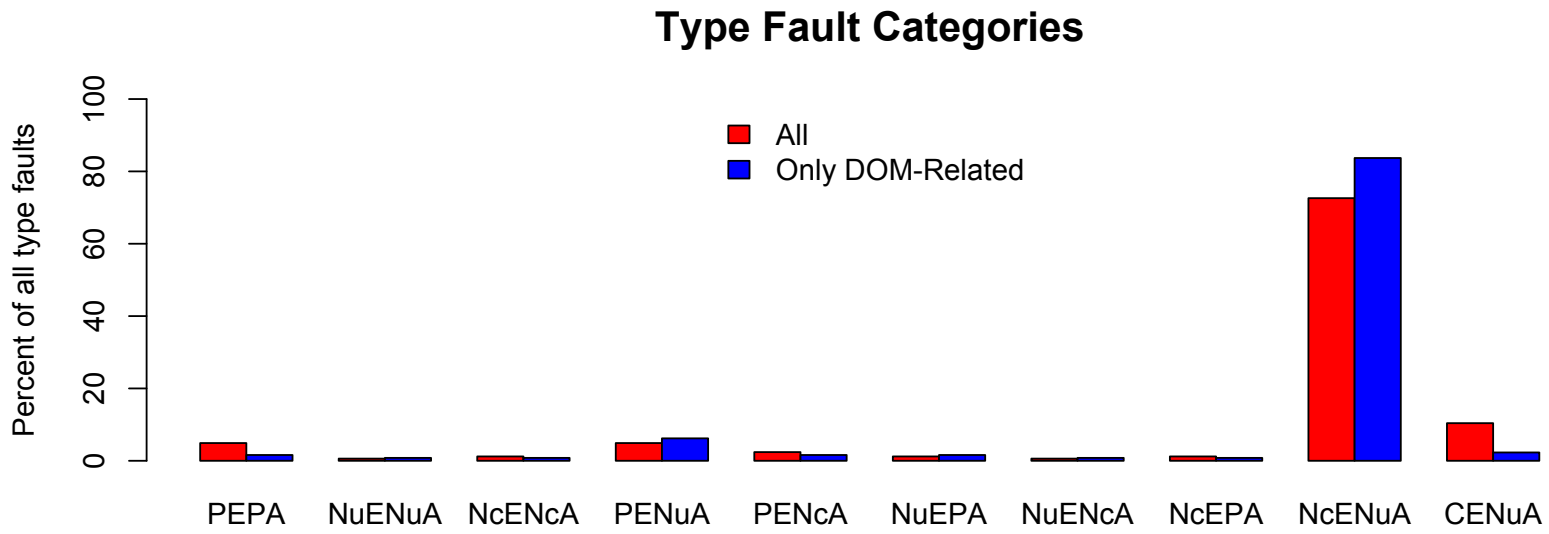
Most JavaScript faults are not browser-specific



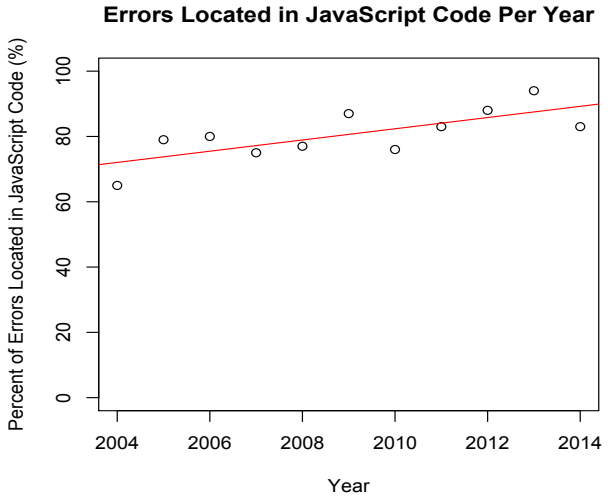
Bug Report Study: Type Faults

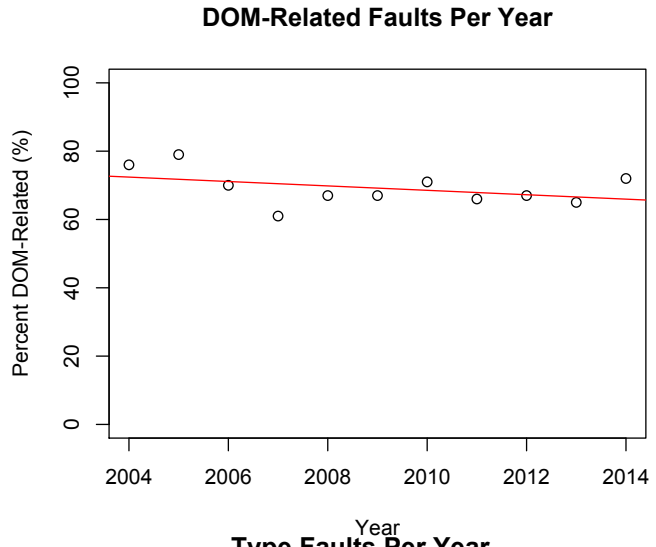
- Most DOM-related faults are NOT type faults
  - Among the type faults, a single category dominates

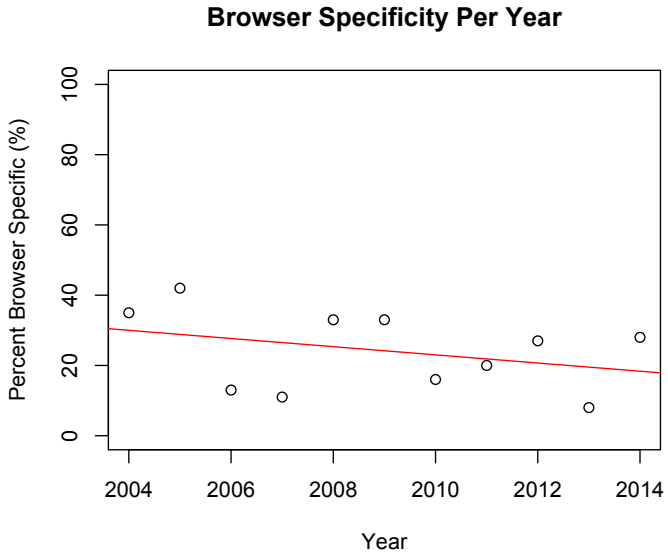


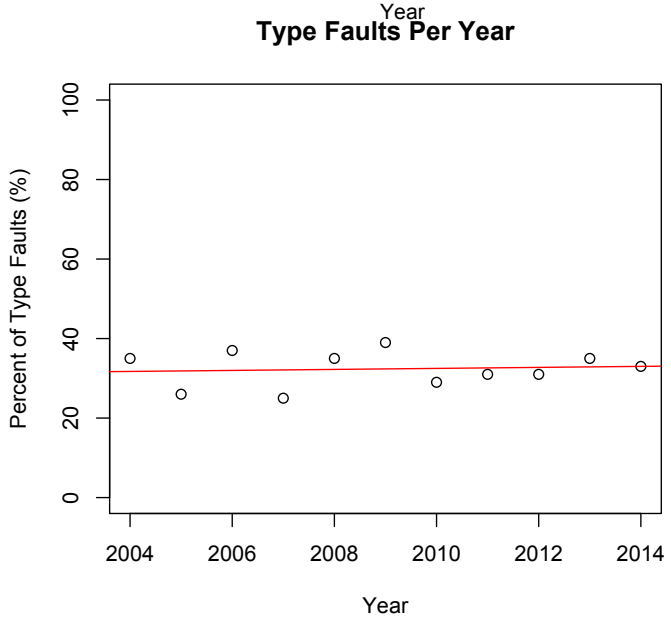


Bug Report Study: Temporal Trends









Bug Report Study: Summary

- **Bug report study of 19 applications: JS faults**
  - Over 500 bug reports analyzed; only fixed bugs considered

- **DOM-related faults dominate JavaScript faults**
  - Responsible for nearly two-thirds of all JavaScript faults
  - Responsible for 80% of highest impact faults
  - Take 50% longer time to fix for developers
  - Majority are not specific to web browser platform
  - Most DOM-related faults are NOT type errors
  - DOM-related faults have been steady over 10 years

Talk Outline

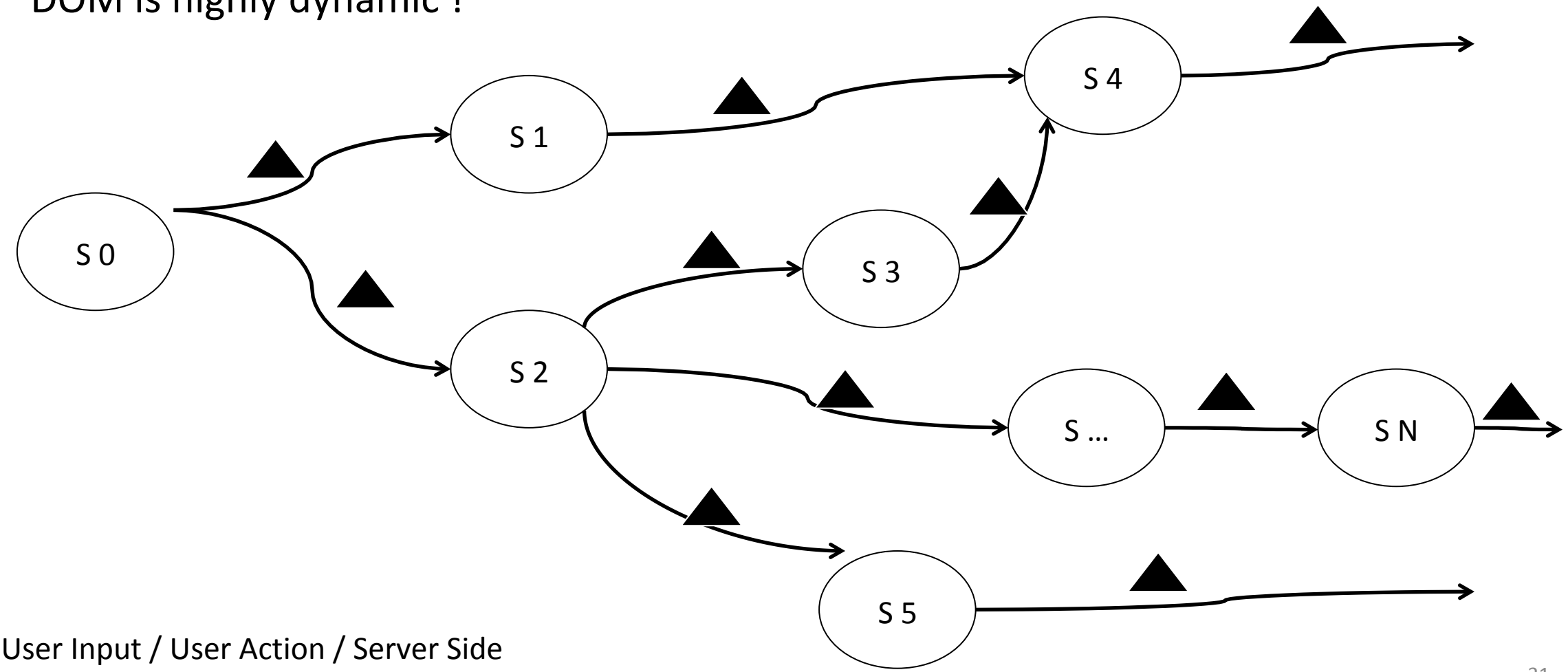
- Motivation and Goals
- Empirical Study of reliability
- Reliability Improvements
- Conclusions and Future Directions

Web Applications: Existing Techniques

- **Add gradual typing to JavaScript (e.g., TypeScript from MS, DART from Google, Flow from Facebook)**
  - Typically ignore the DOM or provide only limited support
- **Use higher-level programming idioms in JavaScript**
  - MVC Frameworks (e.g., AngularJS)
  - Functional Reactive Programming (e.g., RxJS)
- **Detecting errors in web applications: Ignore DOM**
  - Race conditions [Vechev-OOPSLA'13][Livshits-FSE'15]
  - Type Coercion Errors [Pradel – ICSE'15][Moeller − OOPSLA'14]

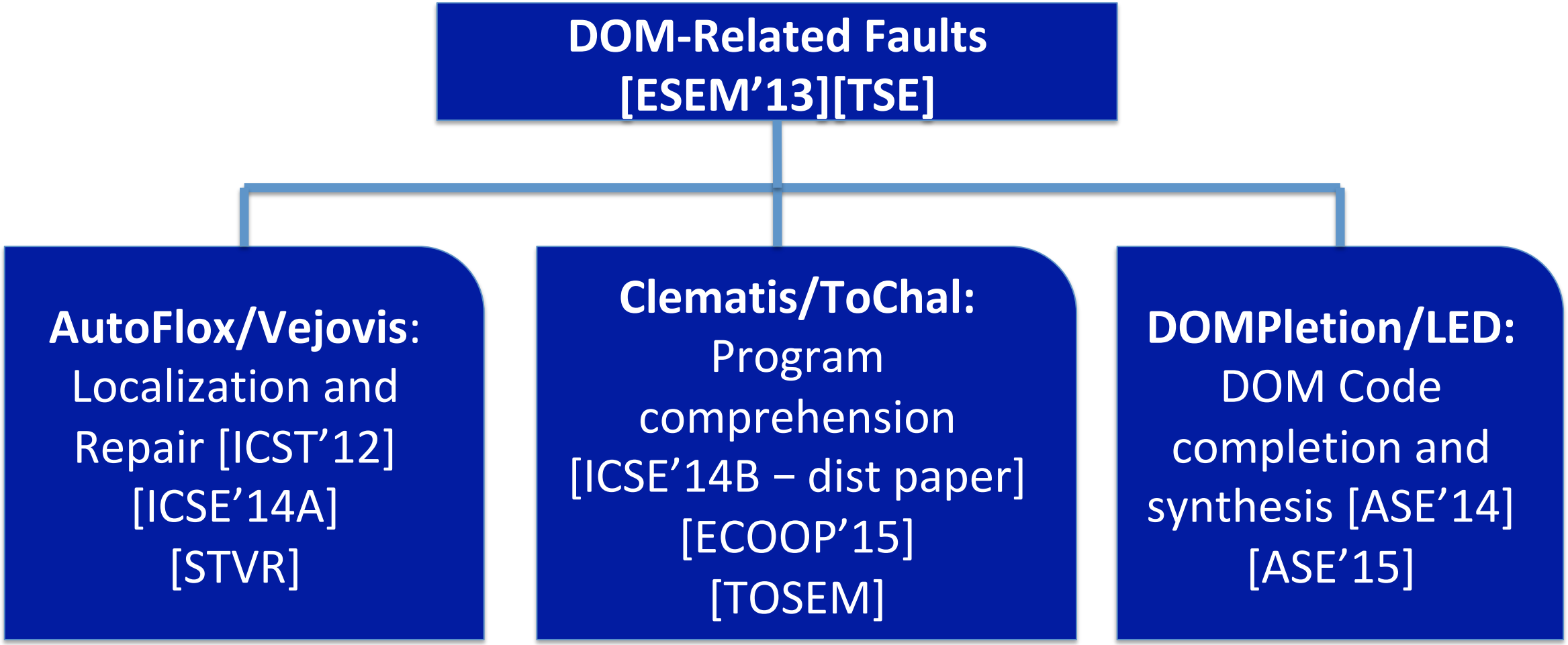
Web Applications: Challenge

DOM is highly dynamic !

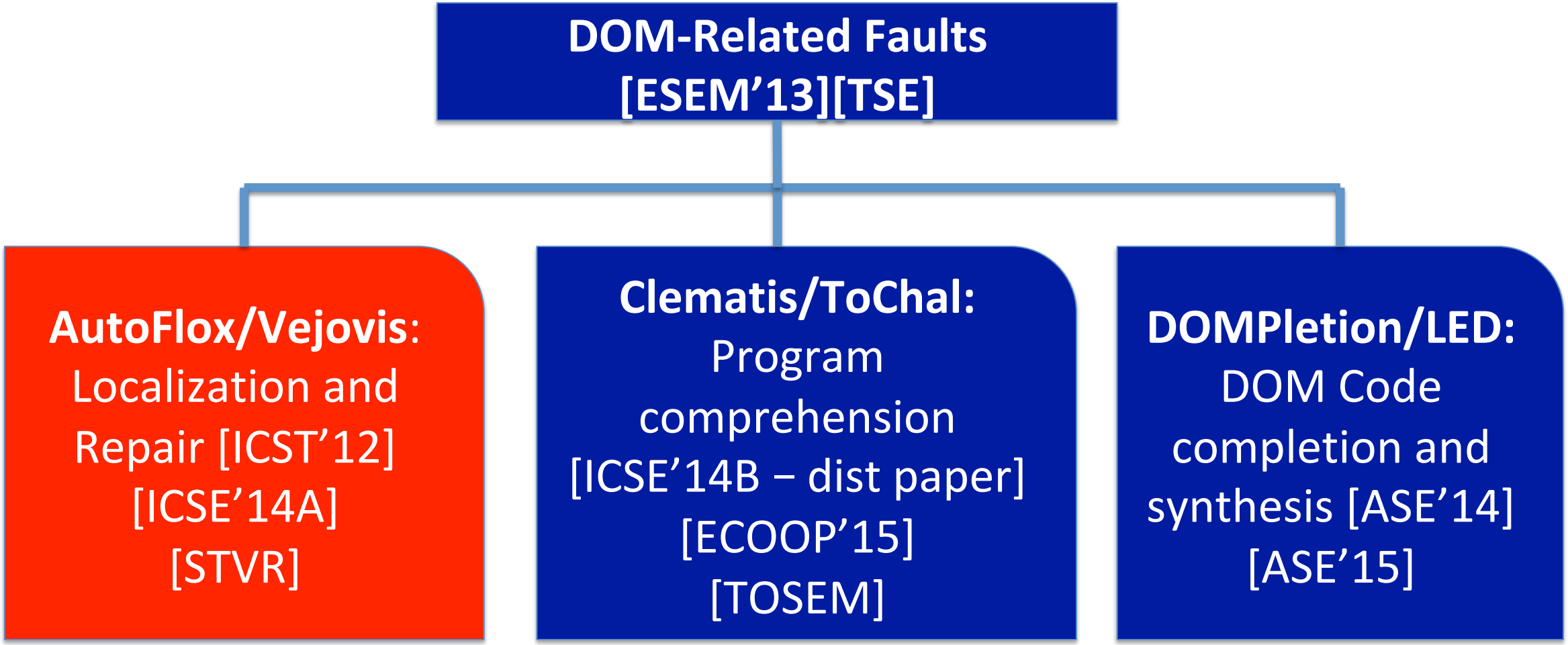


▲ User Input / User Action / Server Side

Web Applications: Our Approach



Web Applications: Our Approach



Web Applications: Program Repair (Vejovis)

WRONG

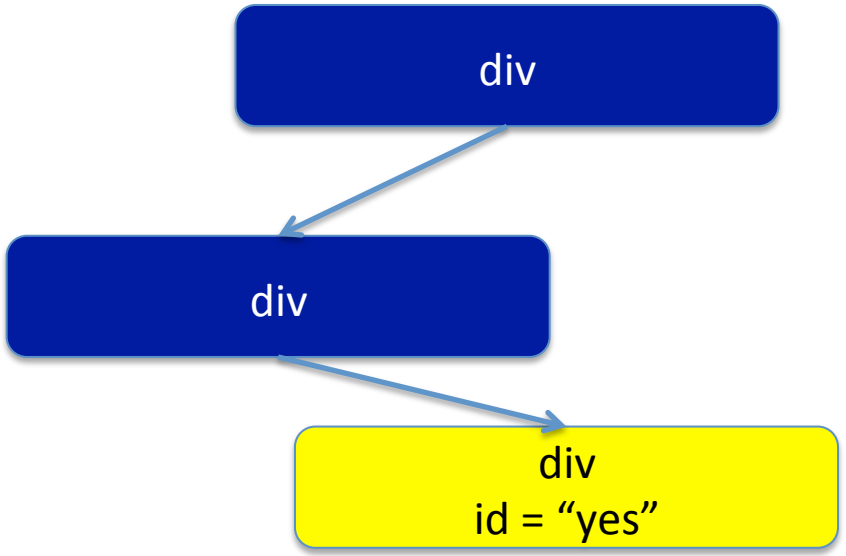
```
getElementById(“no”)
```

RIGHT

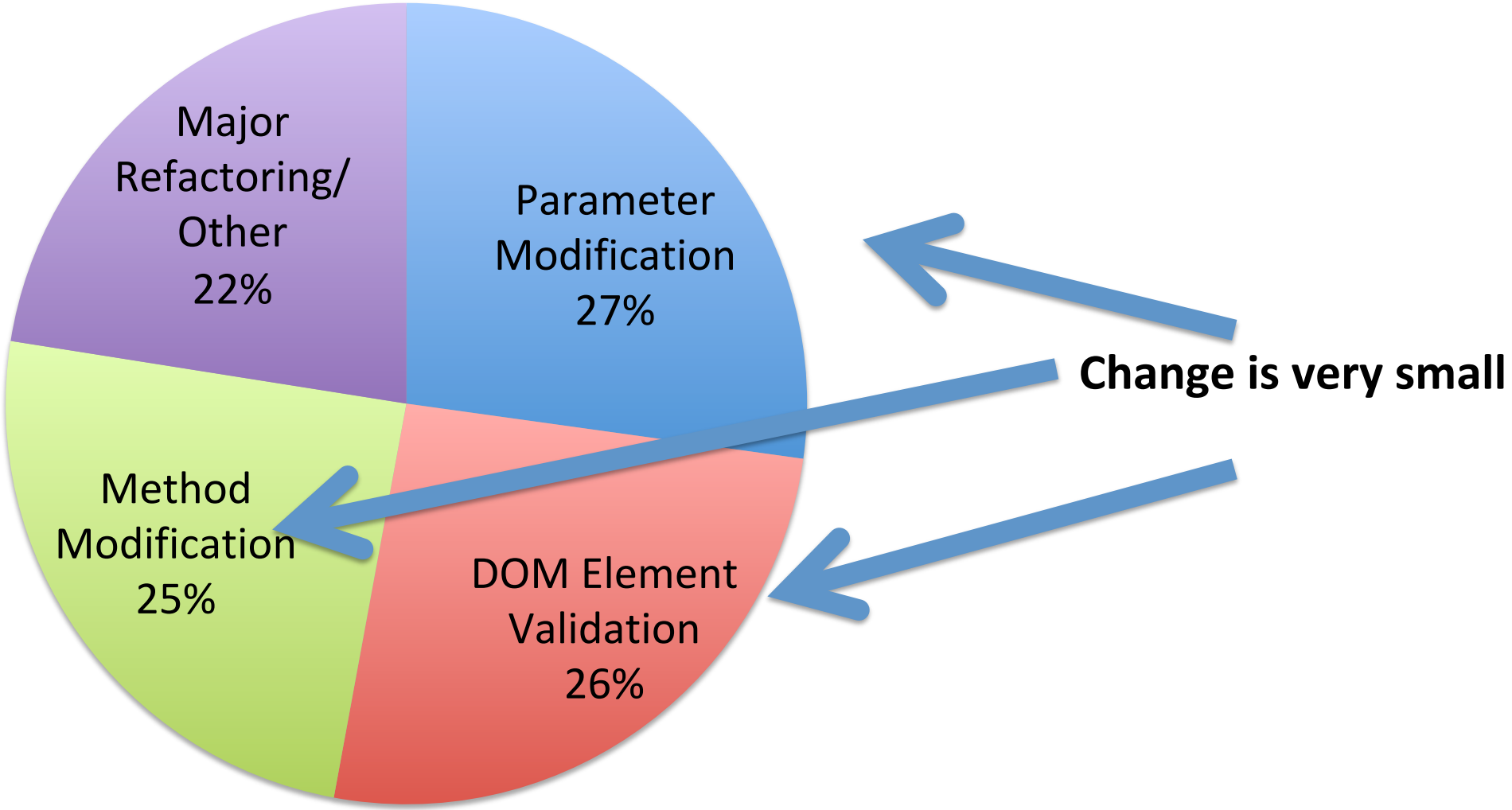
```
getElementById(“yes”)
```

Question: How do we know that we should replace “no” with “yes”

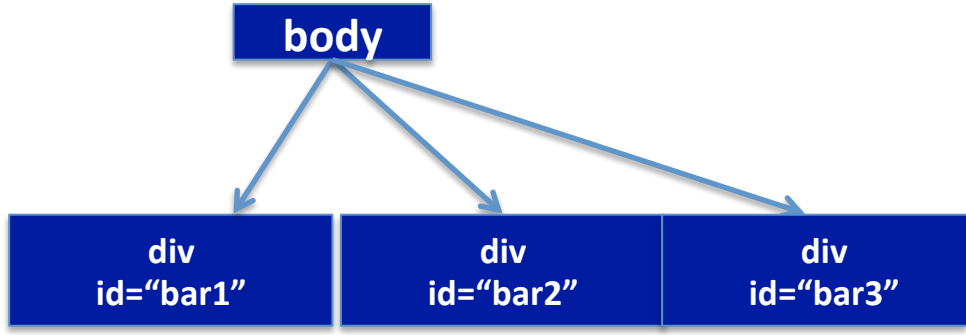
Answer: We use the DOM structure, and the JavaScript code structure



Web Applications: Bug Fix Patterns



Web Applications: Running Example




```
1   function generateId(index) {
2             var prefix = "bar";
3             var id = prefix + index;
4             return id;
5   }
6
7   function retrieveElement(index) {
8             var id = generateId(index);
9             var e = document.getElementById(id);
10            return e;
11  }
12
13  for (var i = 1; i <= 4; i++) {
14            var elem = retrieveElement(i);
15            elem.innerHTML = "Item #" + i;
16  }
```

Add the "bar" prefix to the ID

Retrieve the element with index i

Update retrieved element

Web Applications: DOM-Related Faults

```
1   function generateId(index) {
2               var prefix = "bar";
3               var id = prefix + index;
4               return id;
5   }
6
7   function retrieveElement(index) {
8               var id = generateId(index);
9               var e = document.getElementById(id);
10              return e;
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13  for (var i = 1; i <= 4; i++) {
14              var elem = retrieveElement(i);
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16  }
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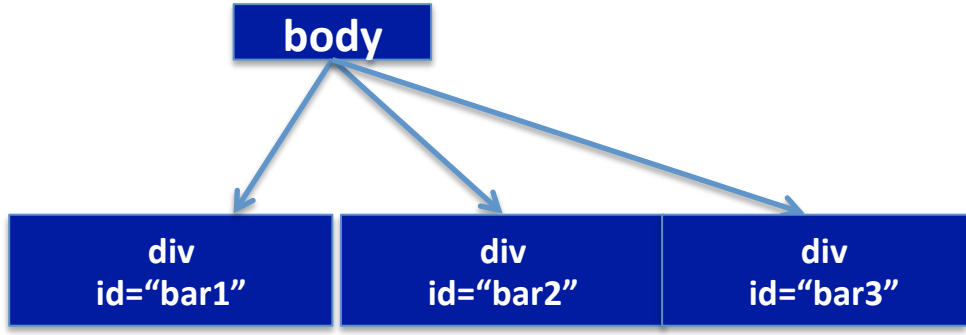

This should be "<", not "<="

Evaluates to "bar4" in 4th iteration

NULL EXCEPTION!

AutoFlox: Fault Localization [ICST'12][STVR]

```
1  function generateId(index) {
2            var prefix = "bar";
3            var id = prefix + index;
4            return id;
5  }
6
7  function retrieveElement(index) {
8            var id = generateId(index);
9            var e = document.getElementById(id)
10           return e;
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13 for (var i = 1; i <= 4; i++) {
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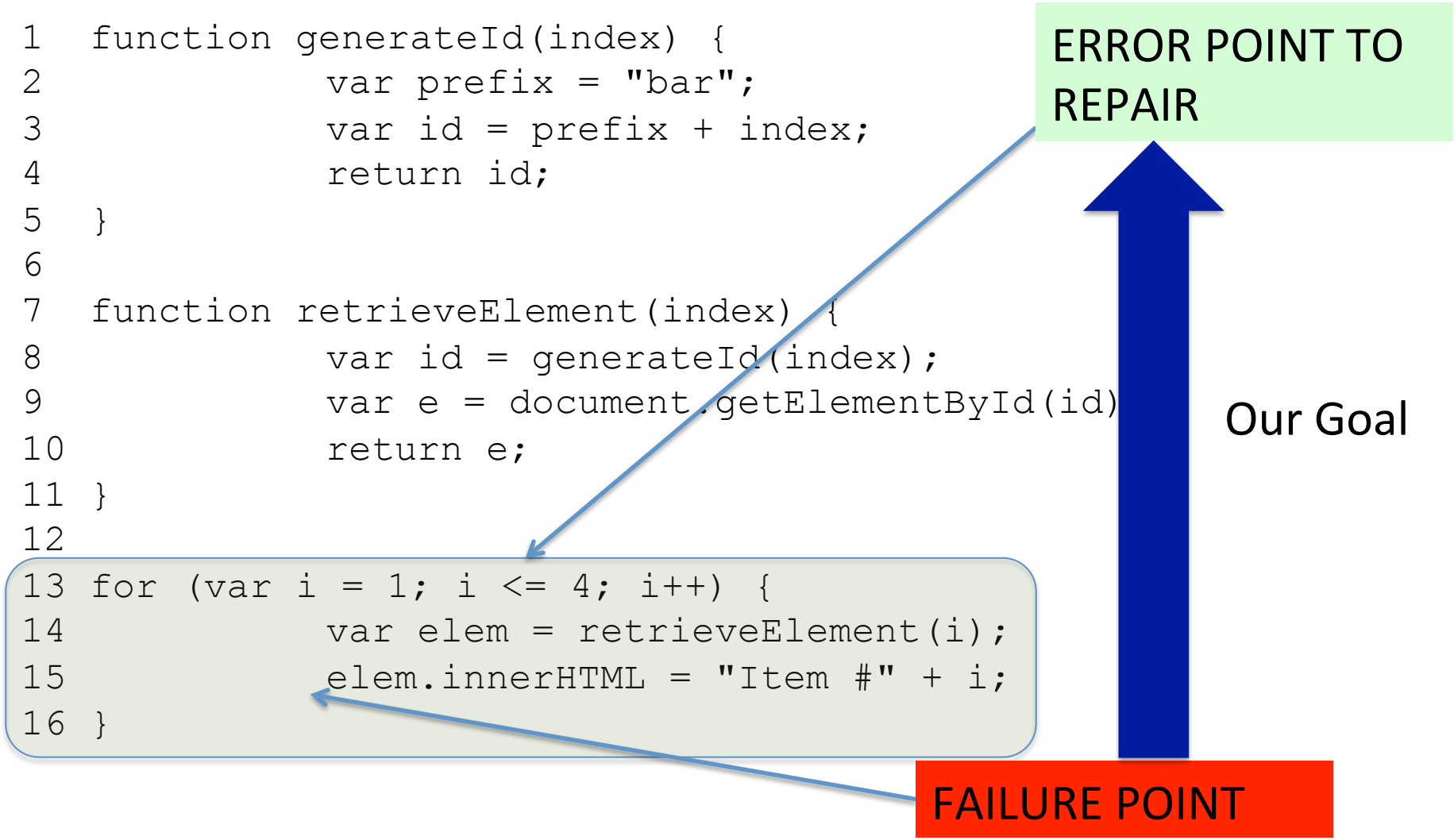

AutoFlox: Fault Localization [ICST'12][STVR]

```
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```
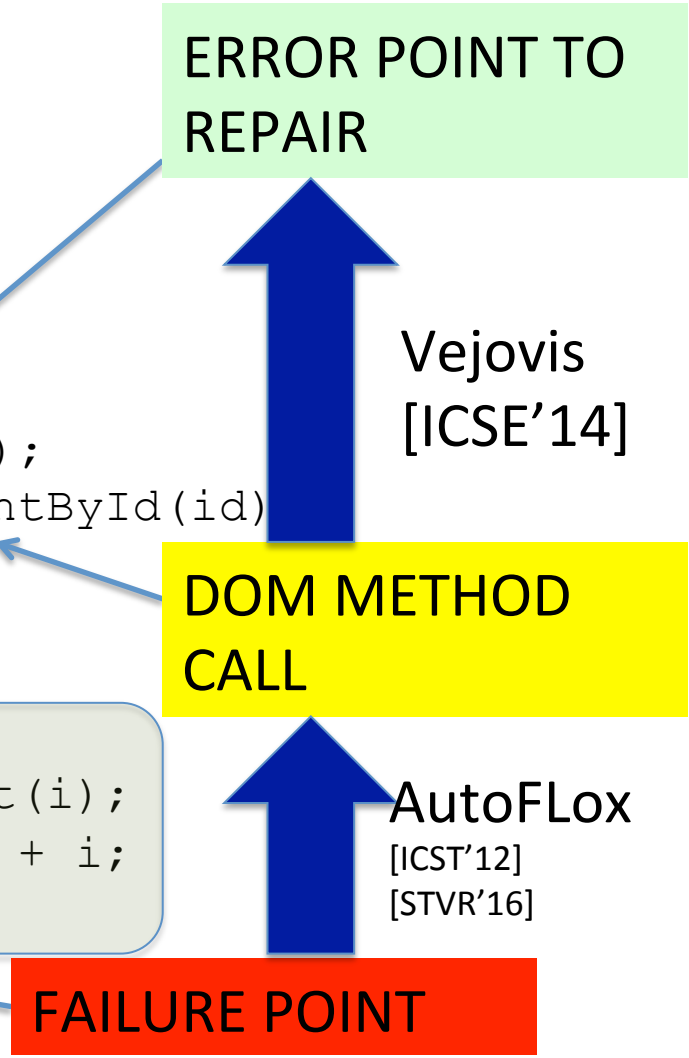



Vejovis: Fault Repair [ICSE'14]

```
1  function generateId(index) {
2              var prefix = "bar";
3
4
5  }
6
7  f
8
9
10
11 }
12
13 for (var i = 1; i <= 4; i++) {
14             var elem = retrieveElement(i);
15             elem.innerHTML = "Item #" + i;
16 }
```

"OFF-BY-ONE, SO REMOVE LAST ITERATION OF FOR LOOP"

"bar"

, and
eady
in
ions

Evaluates to "bar4"

"4"

"4" comes from iterator i

Web Applications: Vejovis Actions

- Determine **action** for programmer to match valid DOM element selectors (based on fix patterns)
  - Use String Solver (HAMPI) [Kiezun09] to find the action
  - Rank fixes based on their edit distances from original

MESSAGE TYPES
REPLACE STRING
REPLACE STRING AT ITERATION
OFF BY ONE AT BEGINNING
OFF BY ONE AT END
MODIFY UPPER BOUND
EXCLUDE ITERATION
ENSURE THAT

Web Applications: Vejovis Recall

Subject	Bug Report #1	Bug Report #2
Drupal	✔	✔
Ember.js	✔	✔
Joomla	✔	✔
jQuery	✔	✗
Moodle	✔	✔
MooTools	✔	✔
Prototype	✔	✔
Roundcube	✔	✗
TYPO3	✔	✔
WikiMedia	✔	✔
WordPress	✔	✔

We consider a fix to be correct if and only if it matches the programmers' fix for the bug.

Overall Recall: (20/22) = 91%

Web Applications: Vejovis Precision

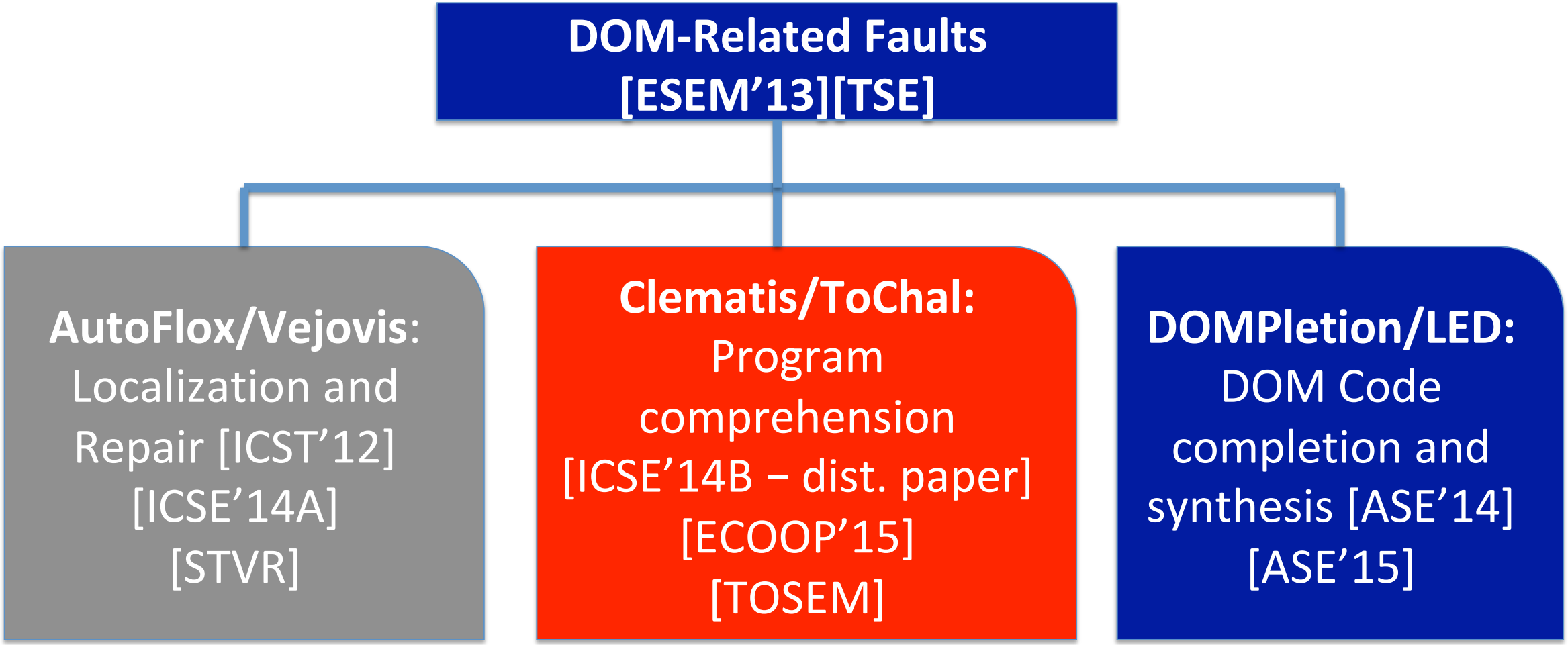
Subject	Bug Report #1	Bug Report #2
Drupal	31 / 40	1 / 4
Ember.js	1 / 2	1 / 3
Joomla	1 / 88	1 / 88
jQuery	2 / 108	-
Moodle	2 / 37	1 / 37
MooTools	2 / 2	1 / 2
Prototype	1 / 6	1 / 2
Roundcube	4 / 79	-
TYPO3	1 / 187	1 / 1
WikiMedia	6 / 24	1 / 71
WordPress	13 / 30	1 / 170

Many suggestions provided for some cases

Ranking function for fix

#1 Ranking in 13 out of 20 bugs (#2 in 3)

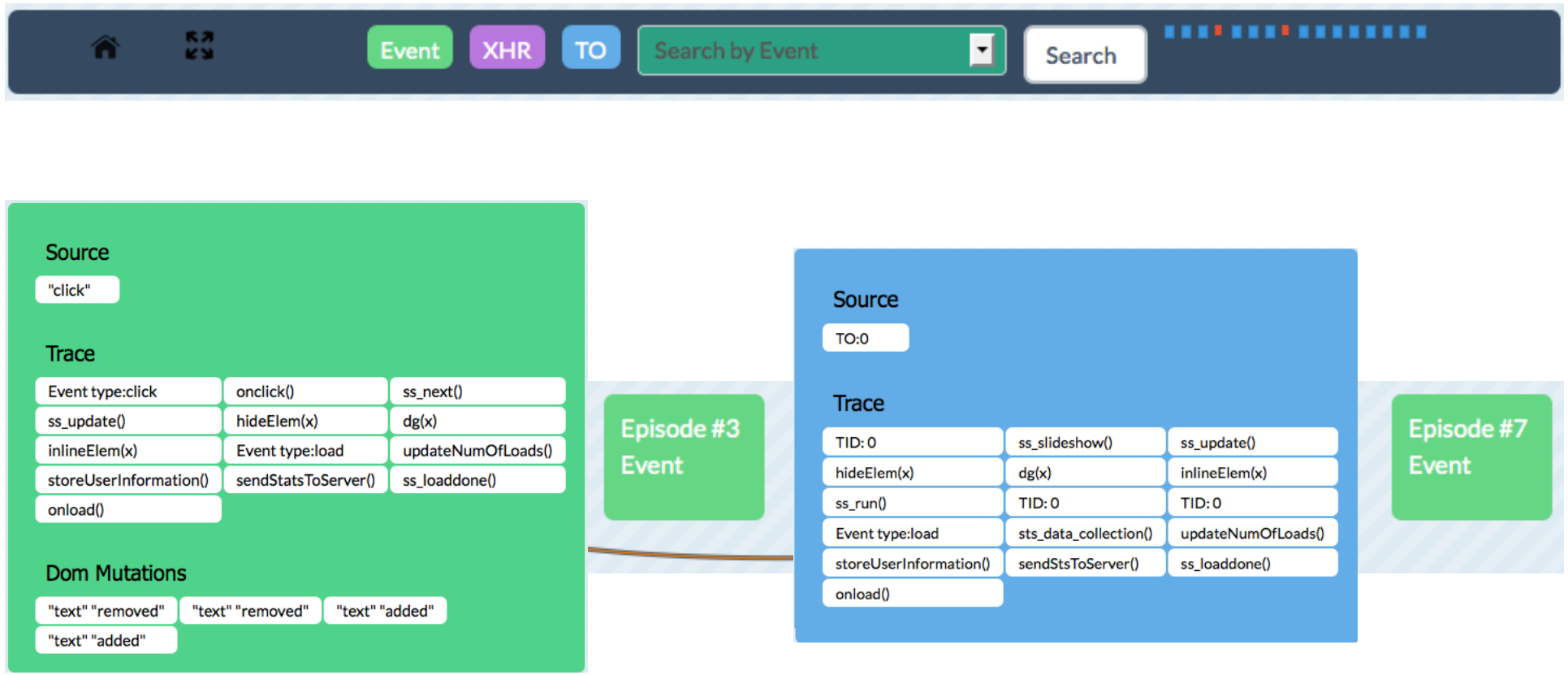
Web Applications: Our Approach



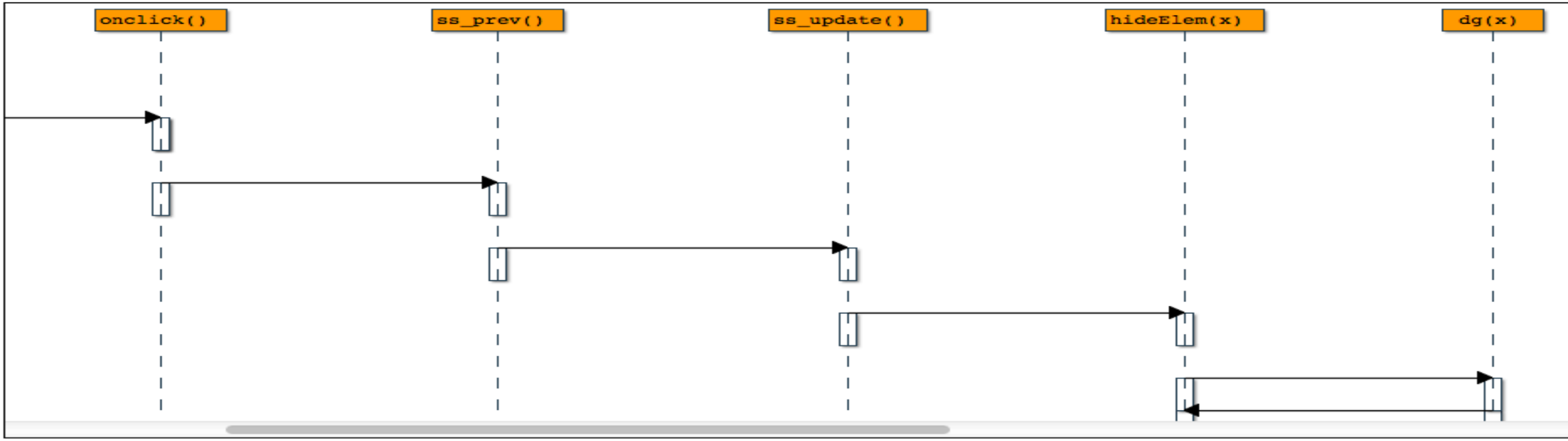
Clematis: Motivation

- **Goal**: Understand and visualize dependencies between JavaScript events and the DOM
- **Challenge**: Difficult to understand the dynamic behavior and the control flow of events
  - Event propagation due to the DOM
  - Asynchronous events (e.g., timeouts)
  - DOM state changes due to events
- **Approach**: Dynamically capture execution of JavaScript applications through instrumentation and convert it to a model

Clematis: Visualization



Episode 5 | Event Type | DOM mutations | Trace of Episode 5



phorm.js

```
function ss_update() {
        ss_cur = Math.max(ss_cur, 0);

        if (ss_cur >= ss_date.length) {
                hideElem('ss_link2');
                showElem('ss_theend');
                ss_cur = ss_date.length;
                var a = dg('ss_n');
                a.innerHTML = "Final";
                if (ss_play)
                        ss_playpause();
        }
```

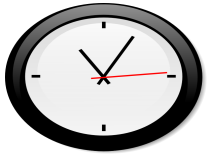
Clematis: User Experiment

- Participants
  - 20 software developers from a large software company in Vancouver (they were all well versed in web development)
  - Experimental group: Clematis
  - Control group: Chrome, Firefox, Firebug (any tool of choice)

- Procedure
  - Tasks: control flow, feature location, DOM mutations, …

- Data collection: Task completion duration & accuracy

Clematis: Results [ICSE'14 – Dist. Paper Award]



Duration

Accuracy

Task	Improvement	Task	Improvement
T1	(39%↑)	T1	(67%↑)
T2	(48%↑)	T2	(41%↑)
T3	(68%↑)	T3	(20%↑)
T4	(32%↑)	T4	(68%↑)

Task	Description
T1	Following control flow in presence of asynchronous events
T2	Finding DOM mutations caused by a DOM event
T3	Locating the implementation of a malfunctioning feature
T4	Detecting control flow in presence of event propagation

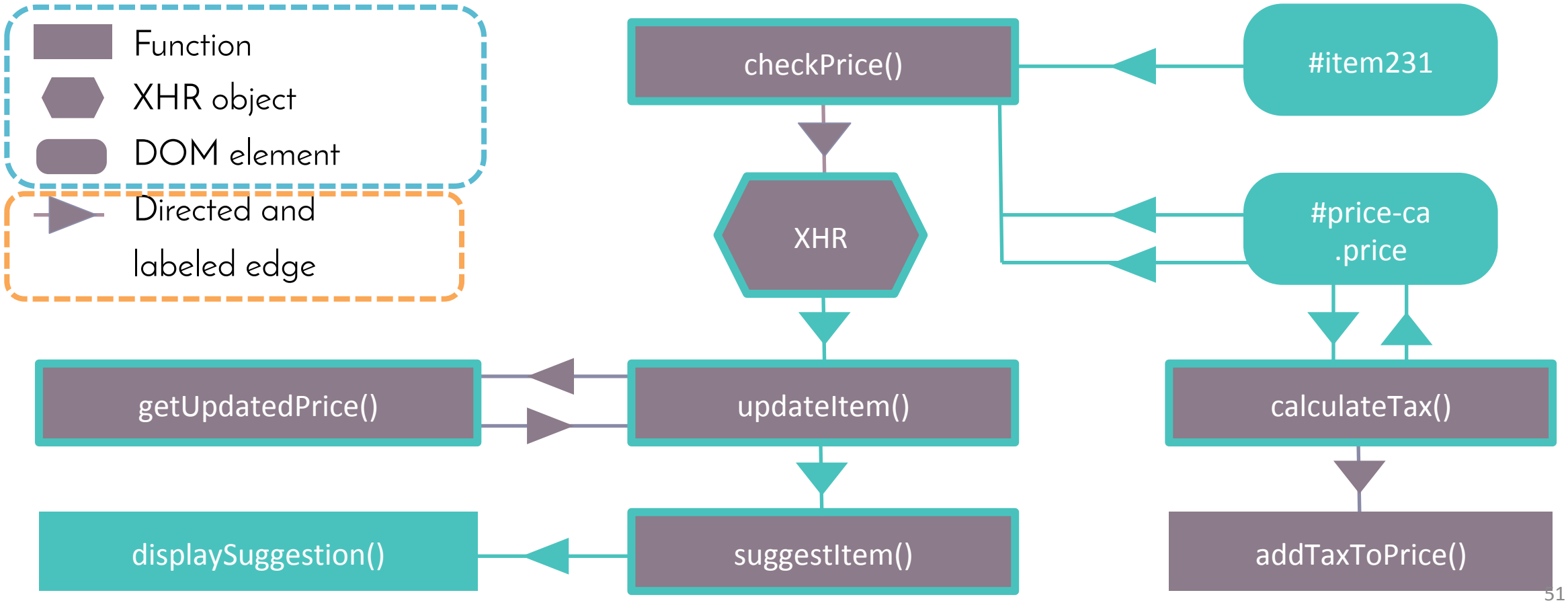
ToChal: Motivation

- Software must continually change to adapt to the changing environment.
- **Goal**: identifying parts of the program that are potentially affected by a change.

- Hybrid of static and dynamic analyses

ToChal: Approach

- Hybrid Flow Graph including the DOM



ToChal: User Experiment

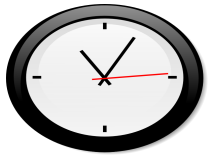
- Question: Does Tochal help developers in practice to perform change impact analysis?

- Design:
  - 12 participants from industry
  - 4 tasks: detecting and analyzing change impact
  - Measured: task completion duration and accuracy

ToChal: User Experiment Results [ECOOP'15]

Accuracy

Task	Improvement
Total	223%↑↑

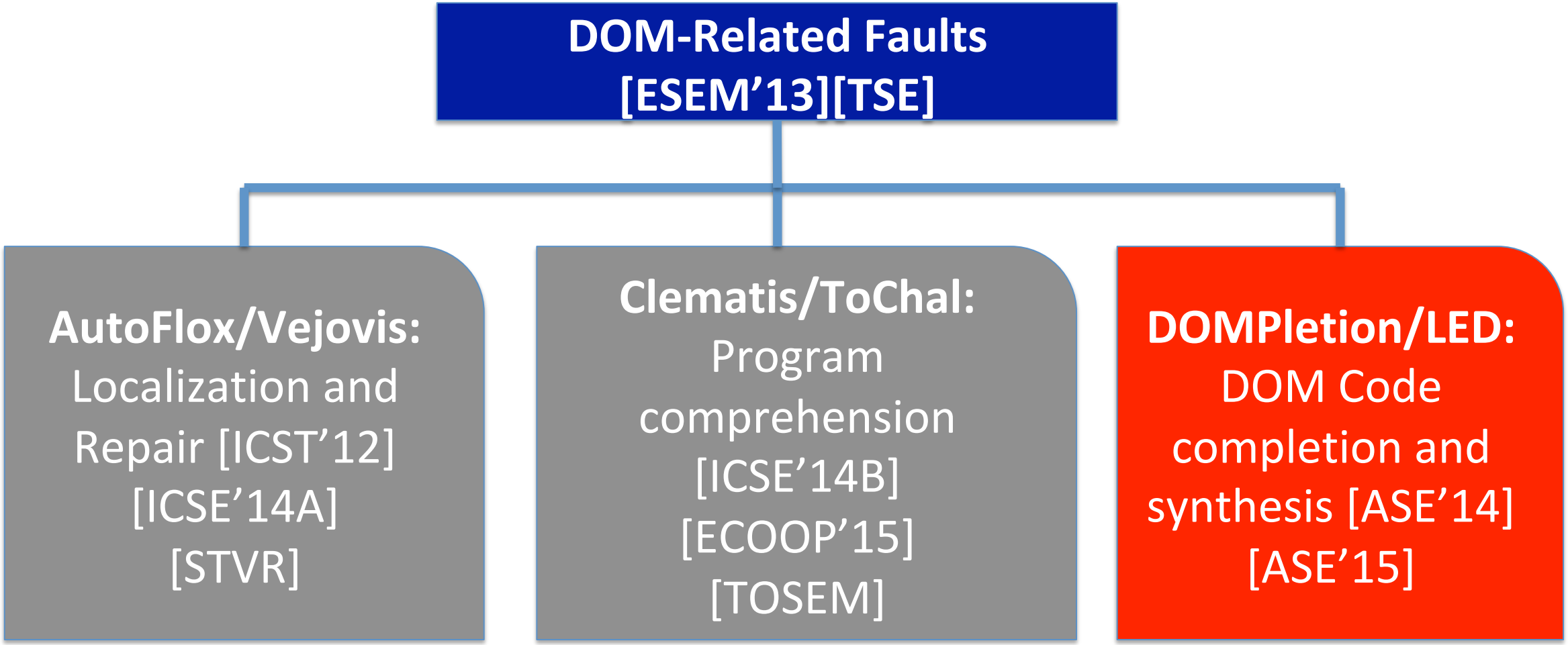


Duration

Task	Improvement
T1	78%↑↑

Task	Description
T1	Finding the potential impact of a DOM element
T2	Finding the potential impact of a JavaScript function
T3	Finding a conflict after making a new change (no ranking)
T4	Finding a bug in JavaScript code

Web Applications: Our Approach

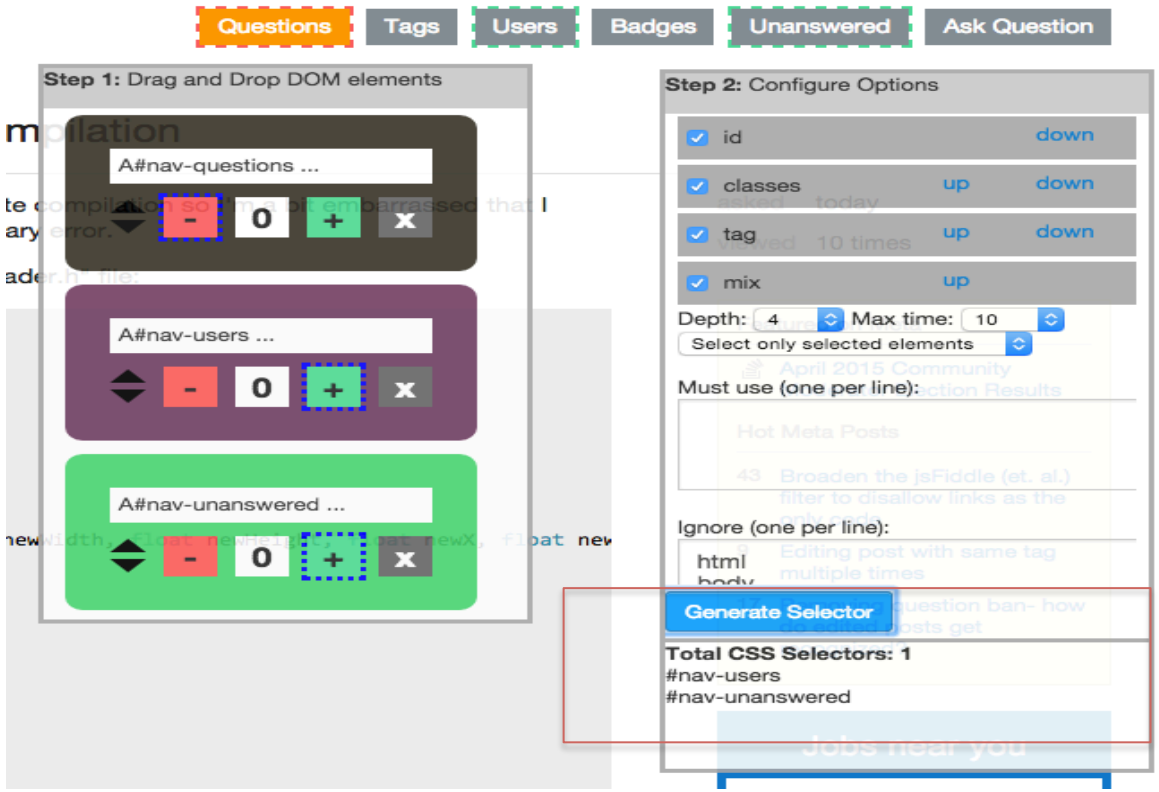


Dompletion [ASE'14]

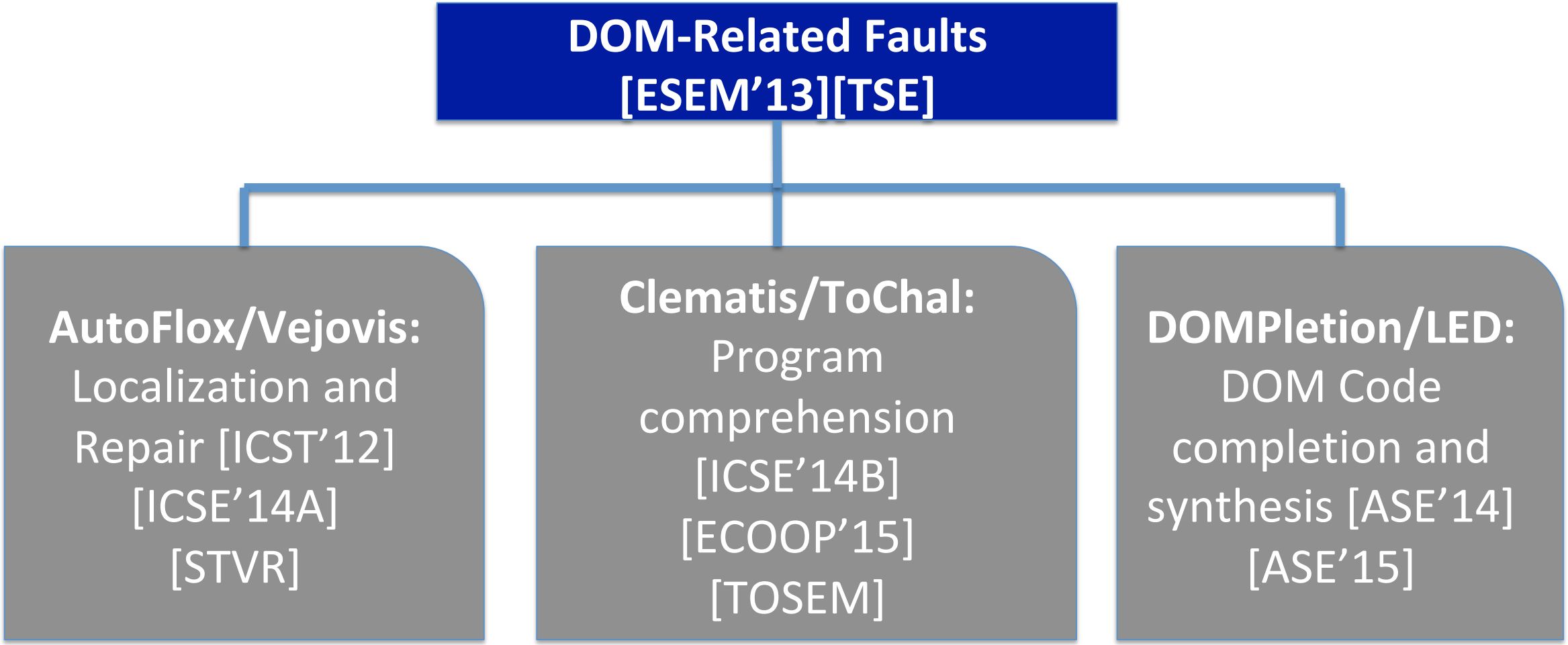
- Perform code completion for DOM-JS interactions within the IDE
- Symbolic execution for finding DOM nodes along different paths
- Learn DOM patterns through machine learning techniques

LED [ASE'15]

- Synthesize DOM element selectors (i.e., CSS selectors) automatically through programmer-supplied examples using an SMT solver



Web Applications: Our Approach



Our Recent Work

MVC Frameworks for JS

- Static analysis tools for JavaScript MVC Frameworks such as AngularJS [ICSE'15][ASE'17]

Server-side JavaScript

- Program Comprehension for server side JavaScript such as Node.js [ICSE'16][ICSE'18]

Talk Outline

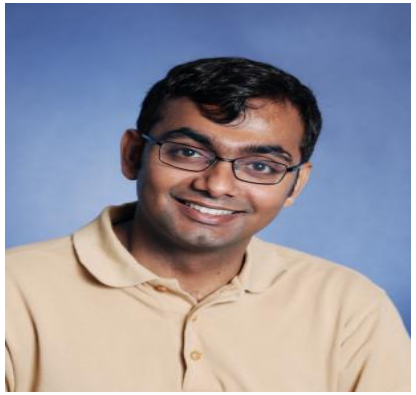
- Motivation and Goals
- Empirical Study of reliability
- Reliability Improvements
- Conclusions and Future Directions

Conclusions and Future Work

- **DOM-related faults prevalent in JavaScript**
  - Responsible for 2/3rds of all real-world bugs, and 80% of the most critical ones
  - Techniques to fix the bugs, understand root causes, and write error-free code
  - Achieved considerable improvement in reliability and understandability

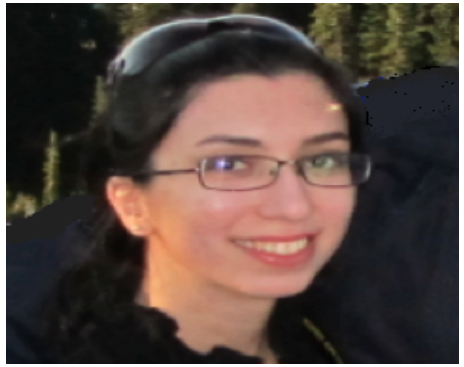
- **Future Work**
  - Extensions for JavaScript in the IoT context (ThingsJS project)
  - Understanding the Security Implications of JavaScript Faults

http://blogs.ubc.ca/karthik/software



Karthik Pattabiraman

Ali Mesbah



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