SOFTWARE ANALYSIS AND TESTING

Don't Call Us, We'll Call You:

Characterizing Callbacks in JavaScript

Keheliya Gallaba, Ali Mesbah, Ivan Beschastnikh
University of British Columbia

Why JavaScript?

On the client

@WalmartLabs

ebay

IBM

node

JS

Microsoft

LinkedIn

PayPal

Joyent

redhat

CYLON.JS

Espruino

TESSEL

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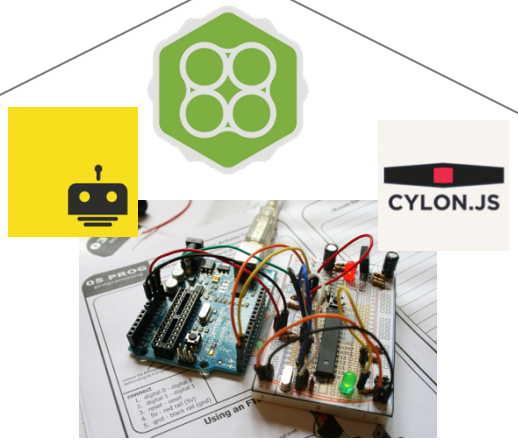


Espruino
TESSEL

Even in hardware!

Why JavaScript?

JavaScript has become the modern lingua franca!

On the client

On the server

Even in hardware!

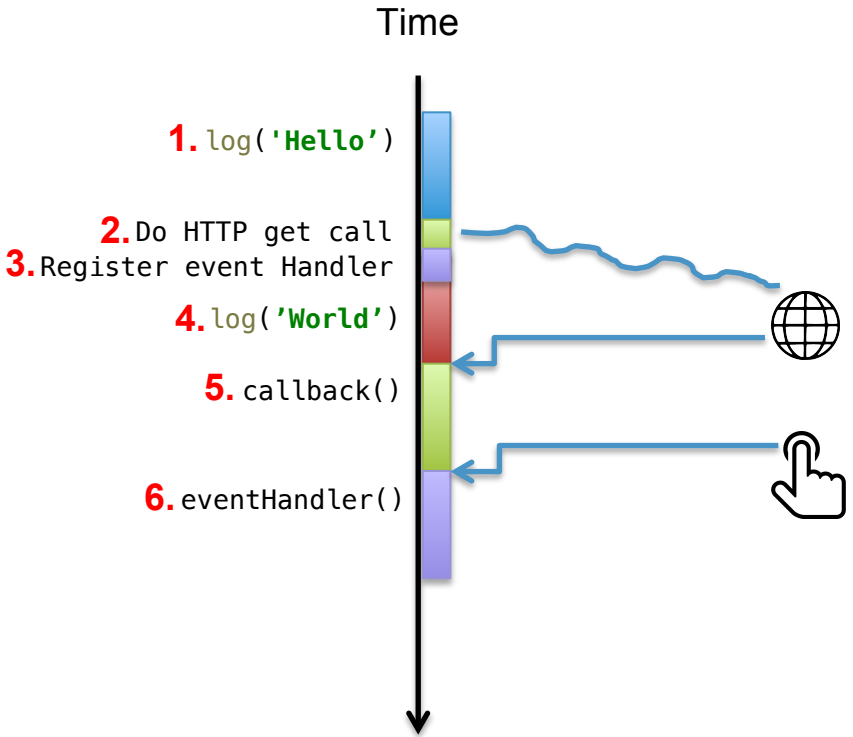
JavaScript Event-driven Model

```
console.log('Hello');

$.get('data.json', callback);

$("button").click(eventHandler);

console.log('World');
```



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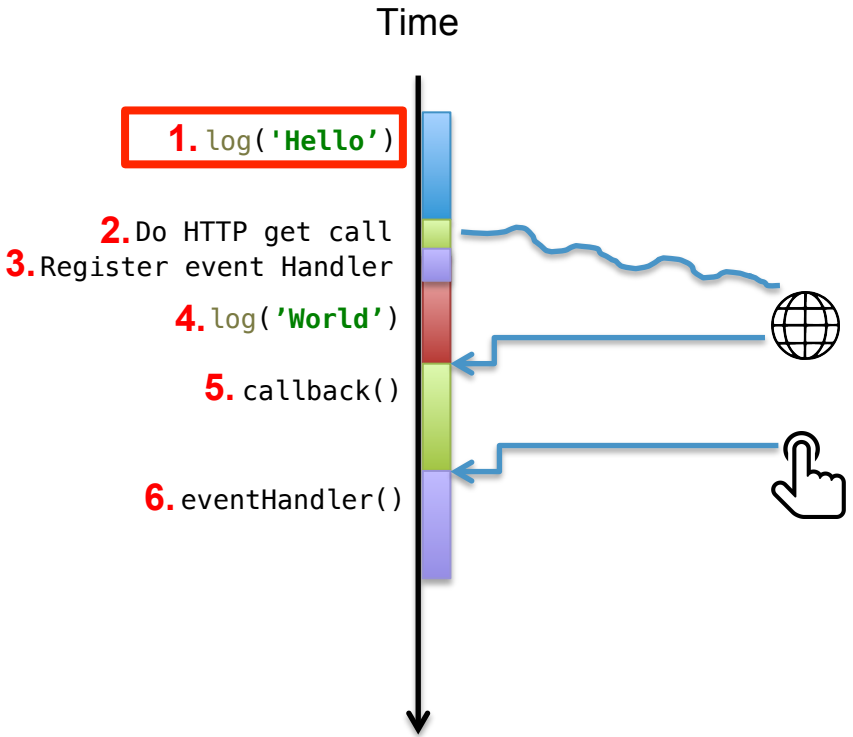

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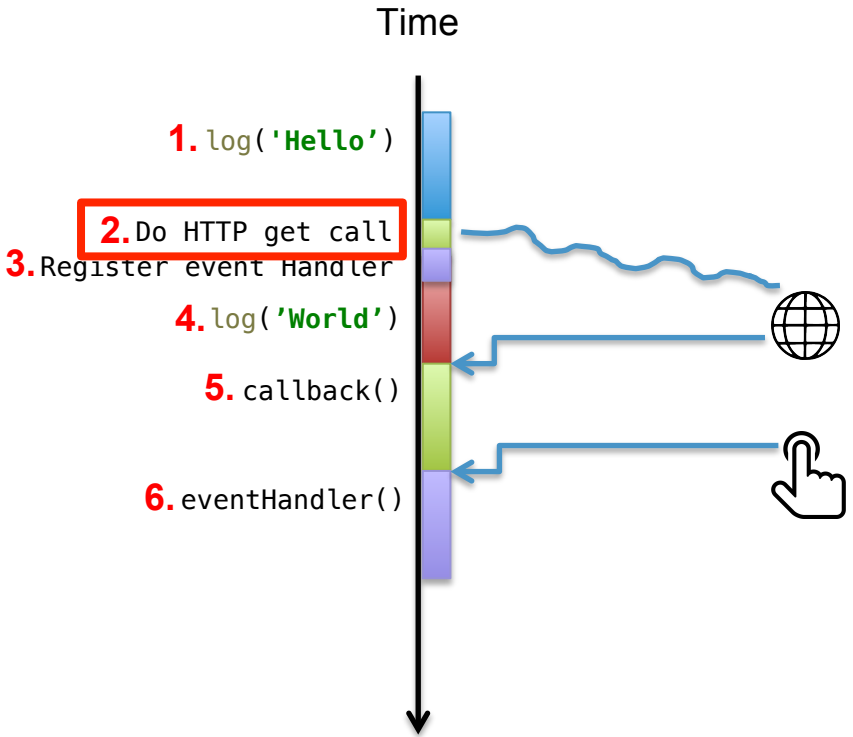

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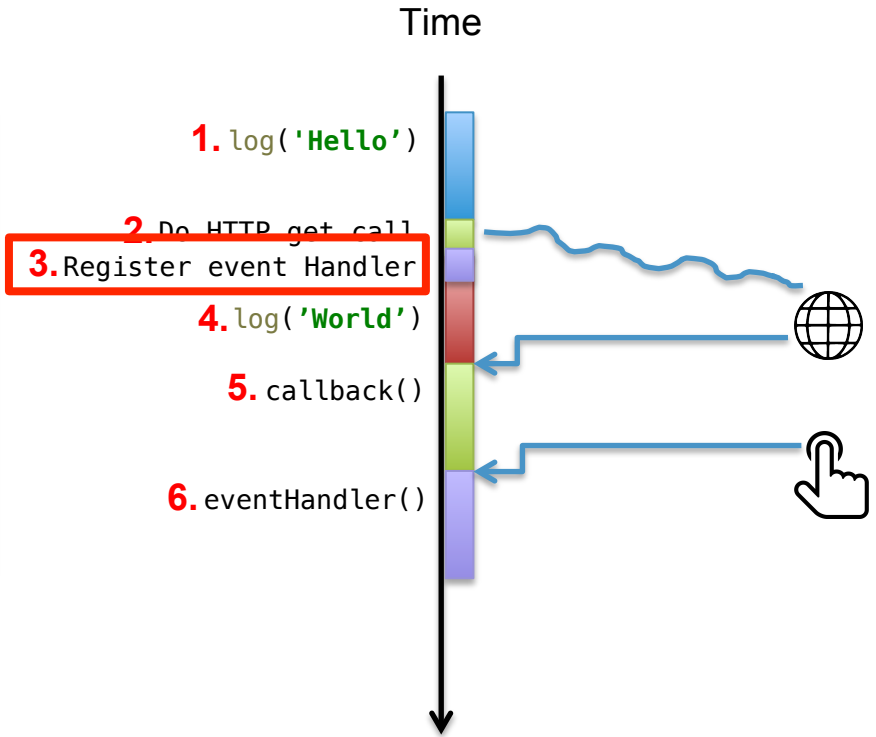

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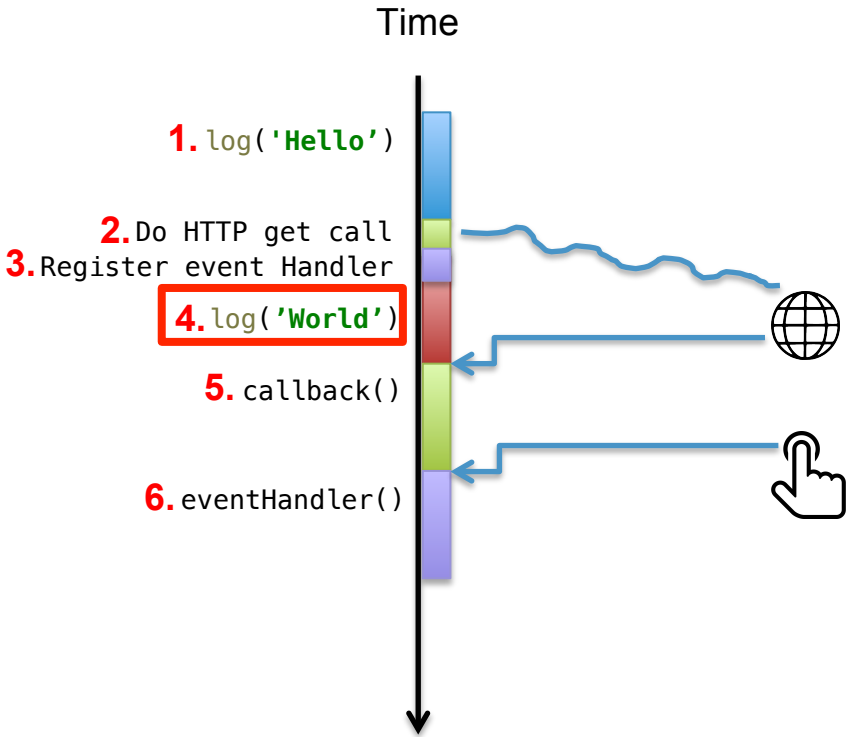

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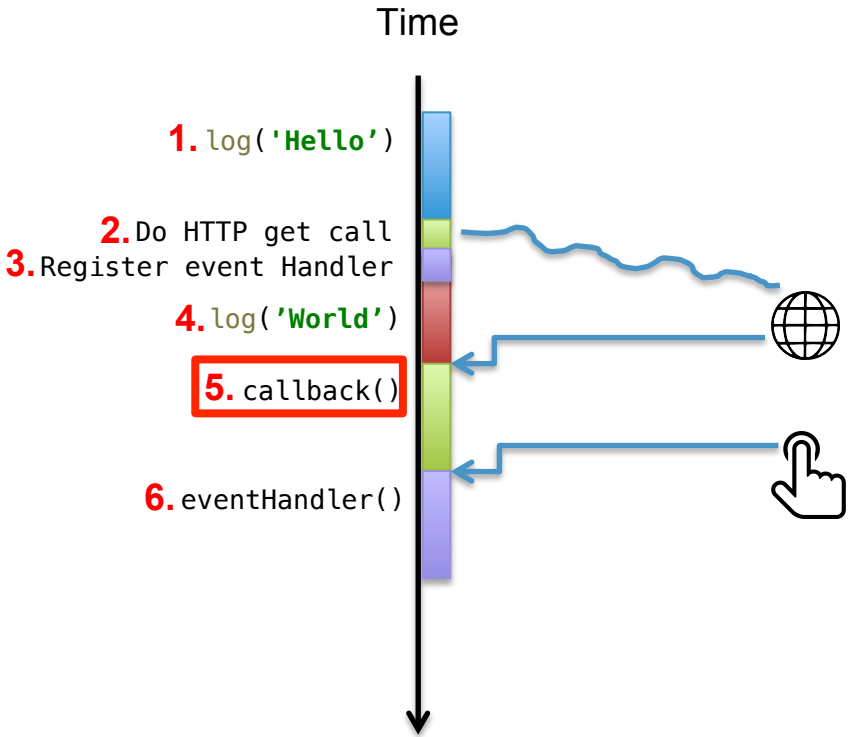

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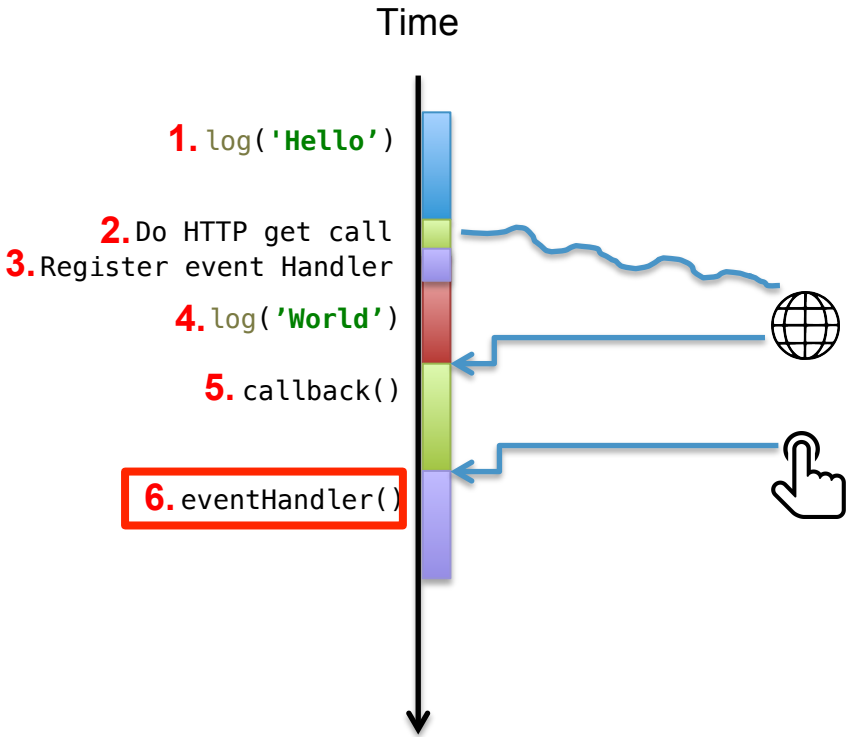

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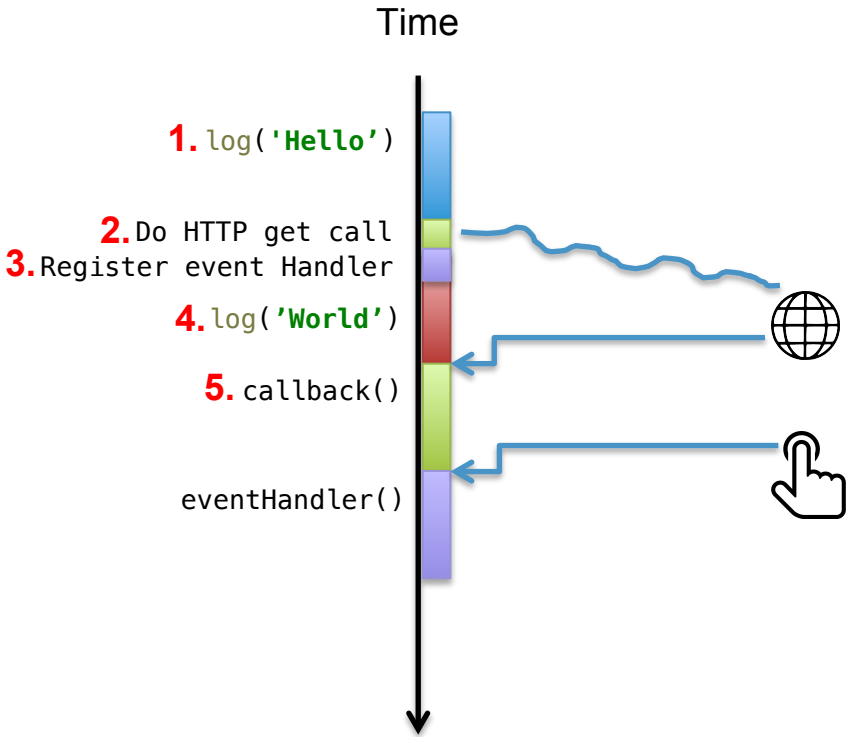

Why Callbacks?

```
$("button").click(buttonHandler);

function buttonHandler(event){
    alert("Button Clicked.");
}
```

Used For:

- HTTP Request/Response
- File I/O in Node.js
- Mouse click/drag events in the browser

Why Callbacks?

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Used For:

- HTTP Request/Response
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You cannot write an interesting program in JavaScript without using **callbacks!**

Motivation

- Callbacks are important in all non-trivial JS programs.
- But, how do developers use callbacks?
- No prior research on this topic.

Goal of this work

Outline

Motivation ✔
Methodology & Overview
Characterizing Problems
- Anonymous Callbacks
- Asynchronous Callbacks
- Nested Callbacks

Characterizing Solutions
- Error-first Protocol
- Async.js
- Promises

Conclusion

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Subject Systems

138 popular **open source** JavaScript subject systems,

from **6** distinct categories,

with both **Client-side** & **Server-side** code.

Category	Subject systems	Client side	Server side	Total files	Total LOC
NPM Modules	86		✓	4,983	1,228,271
Web Apps.	16	✓	✓	1,779	494,621
Game Engines	16	✓	✓	1,740	1,726,122
Frameworks	8	✓		2,374	711,172
DataViz Libs.	6	✓		3,731	958,983
Games	6	✓		347	119,279
Total	**138**	✓	✓	**14,954**	**5,238,448**

What is a callback?

A **callback** is a function that is passed as an argument to another function, which is expected to invoke it either *immediately* or at some point *in the future*.

```
function getInput (options, callback)
   allUserData.push (options);
   callback (options);
}

var logStuff = function () { ... }
getInput ({name:"Rich", speciality:"JavaScript"}, logStuff);
```

What is a callback?

Accepts a callback

```
function getInput (options, callback) {
   allUserData.push (options);
   callback (options);
}

var logStuff = function () { ... }
getInput ({name:"Rich", speciality:"JavaScript"}, logStuff);
```

Invokes the callback

Passing a callback as an argument to a function

A **callback** is a function that is passed as an argument to another function, which is expected to invoke it either *immediately* or at some point *in the future*.

Detecting callbacks: An example

```
1 function getRecord(id, callback) {
2   http.get('http://foo/' + id, function (err, doc) {
3     if (err) {
4       return callback(err);
5     }
6       return callback(null, doc);
7   });
8 }

10 var logStuff = function () { ... }
11 getRecord('007', logStuff);
```

`getRecord()` accepts `logStuff()` as a callback because there exist a path...

`getRecord(cb)` ➡ `http.get()` ➡ `Anonymous()` ➡ `logStuff()`

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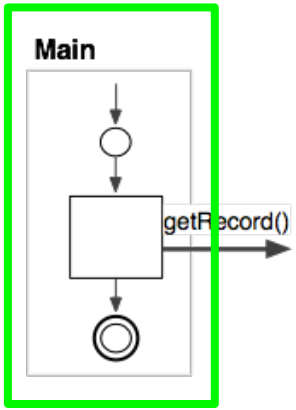

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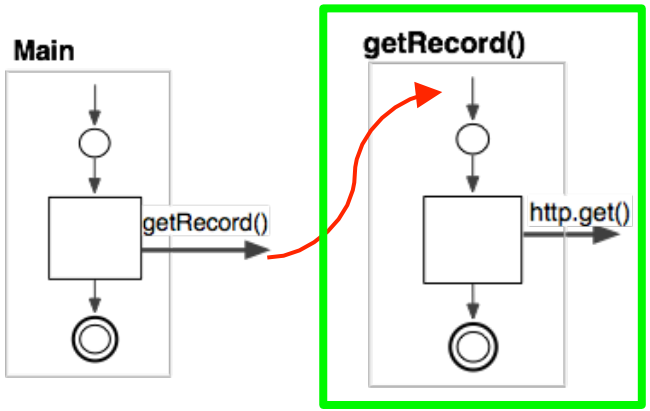

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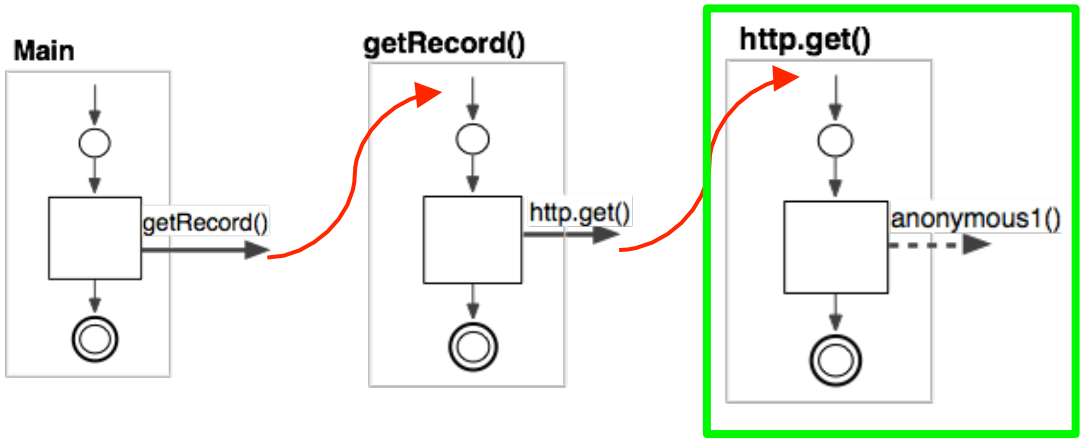

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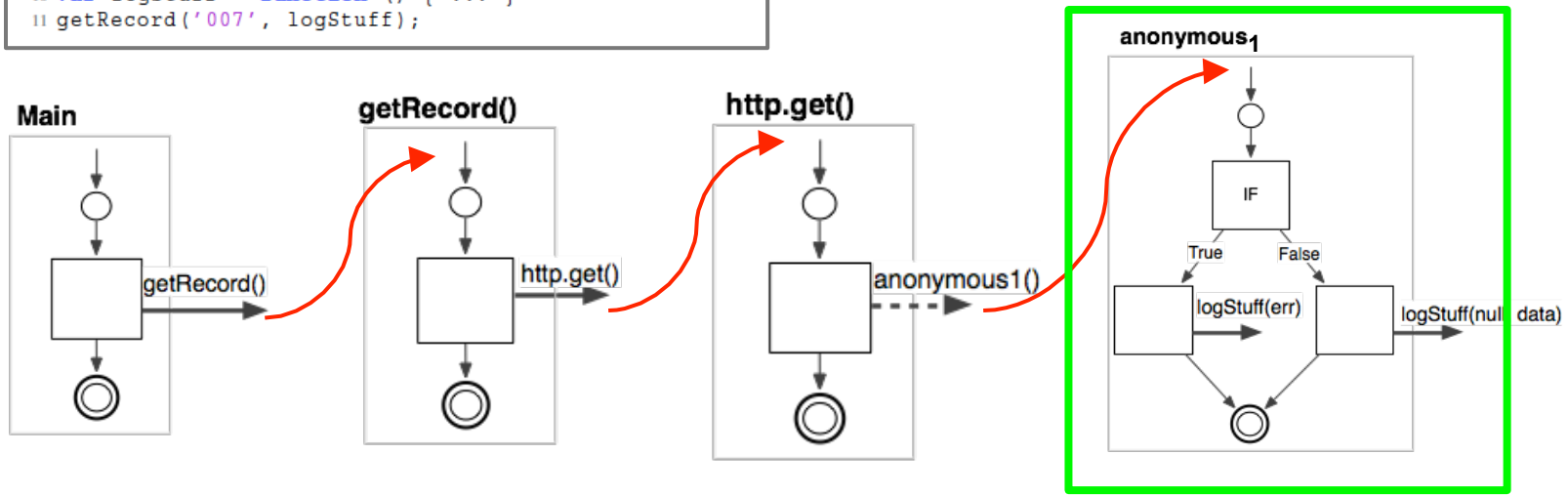

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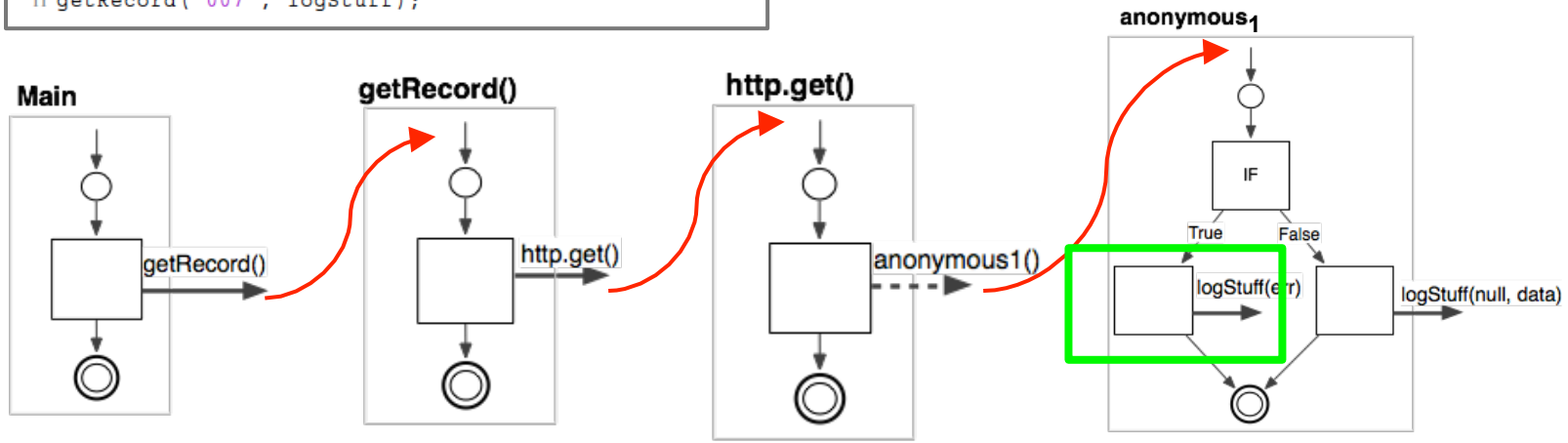

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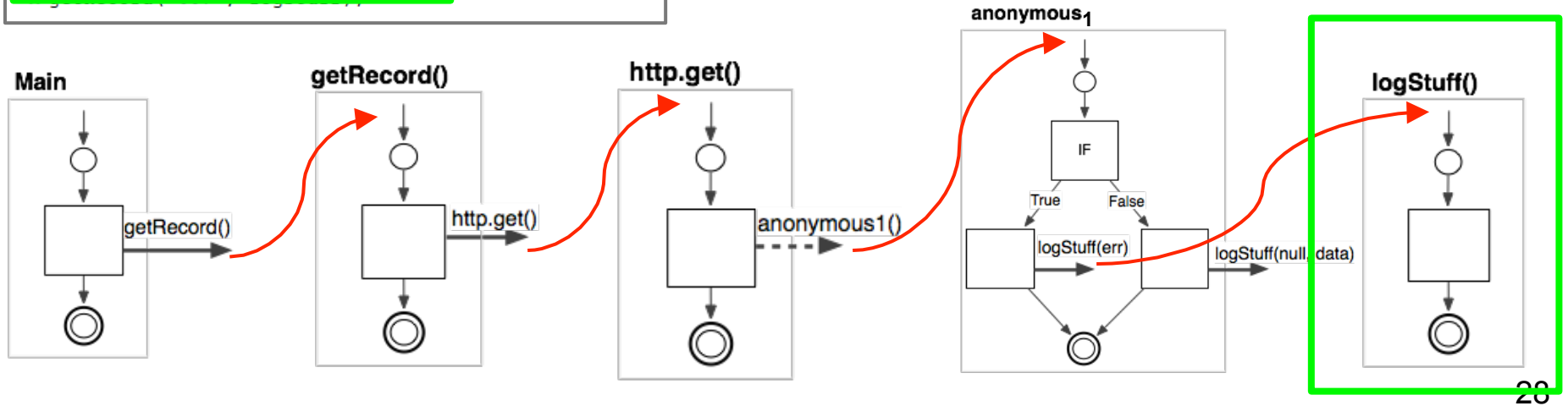

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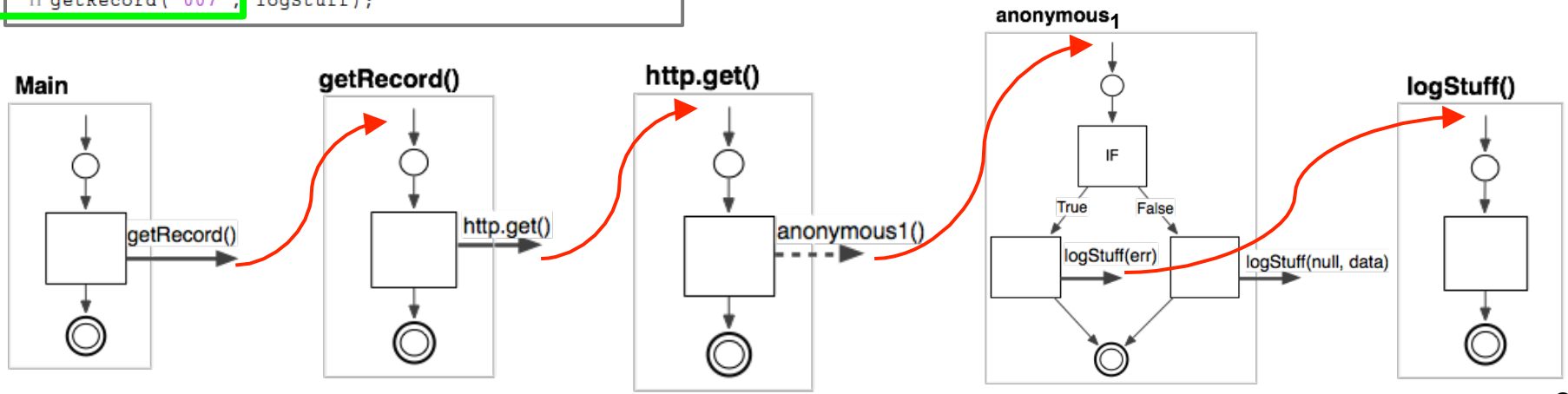

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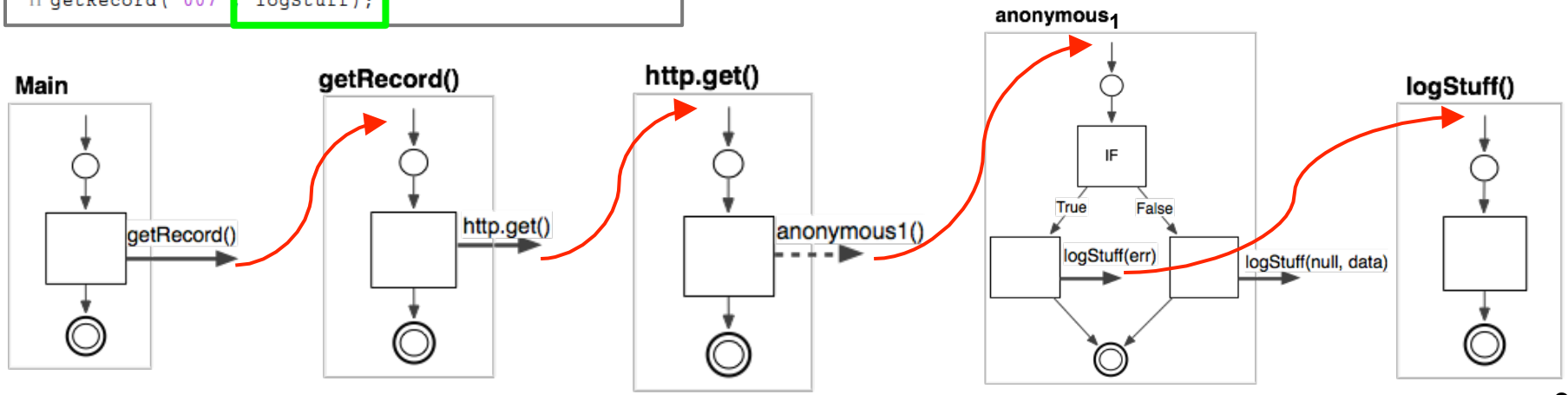


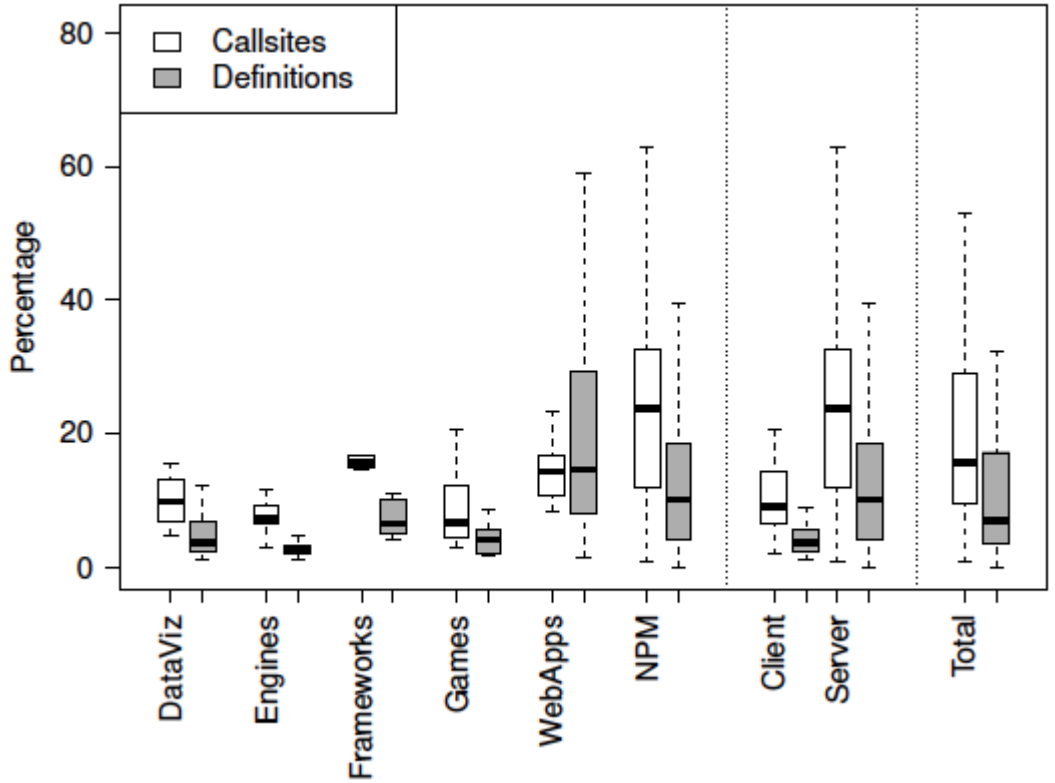
How prevalent are callbacks?

Callback-accepting function definitions

- On average, **10%** of all function definitions take callback arguments.
- They are more prevalent in server-side code **(10%)** than in client- side code **(4.5%)**.

Callback-accepting function call-sites

- **19%** of all function callsites take callback arguments.
- Callback-accepting function call-sites are more prevalent in server-side code **(24%)** than in client-side code **(9%)**.



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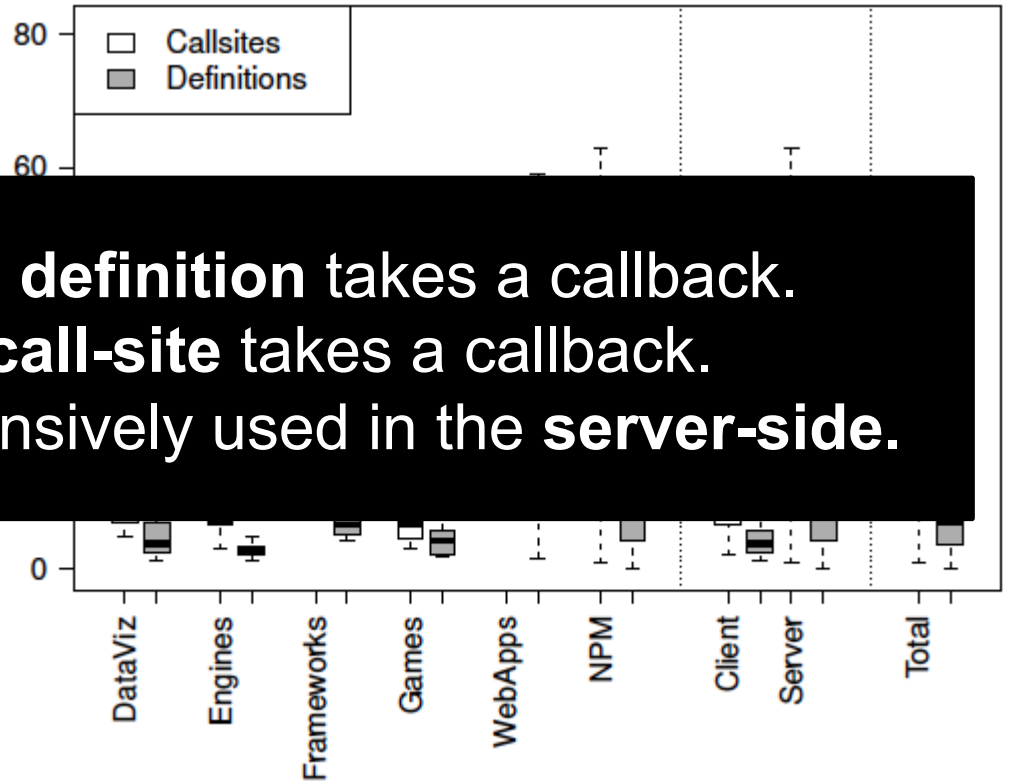

- Every 10th function **definition** takes a callback.
- Every 5th function **call-site** takes a callback.
- Callbacks are extensively used in the **server-side.**

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Methodology & Overview ✔
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JavaScript in the wild...

```
define('admin/general/dashboard', 'semver', function(semver
    ) {
  var Admin = {};

  $('#logout-link').on('click', function() {
    $.post(RELATIVE_PATH + '/logout', function() {
      window.location.href = RELATIVE_PATH + '/';
    });
  });

  ...

  $('.restart').on('click', function() {
    bootbox.confirm('Are you sure you wish to restart
        NodeBB?', function(confirm) {
      if (confirm) {
        $(window).one('action:reconnected', function() {
          app.alert({ alert_id: 'instance_restart', });
        });

        socket.emit('admin.restart');
      }
    });
  });
  return Admin;
});
```

Anonymous callbacks

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17         });

19         socket.emit('admin.restart');
20       }
21     });
22   });
23   return Admin;
24 });
```

Notorious for:
Difficulty to debug, maintain, test, or reuse

Anonymous Vs. Named Callbacks

If a function callsite is ..

- callback-accepting and
- has an anonymous function expression as an argument

..it is an instance of an anonymous callback.

```
1 function getRecord(id, callback) {
2   http.get('http://foo/' + id, function (err, doc) {
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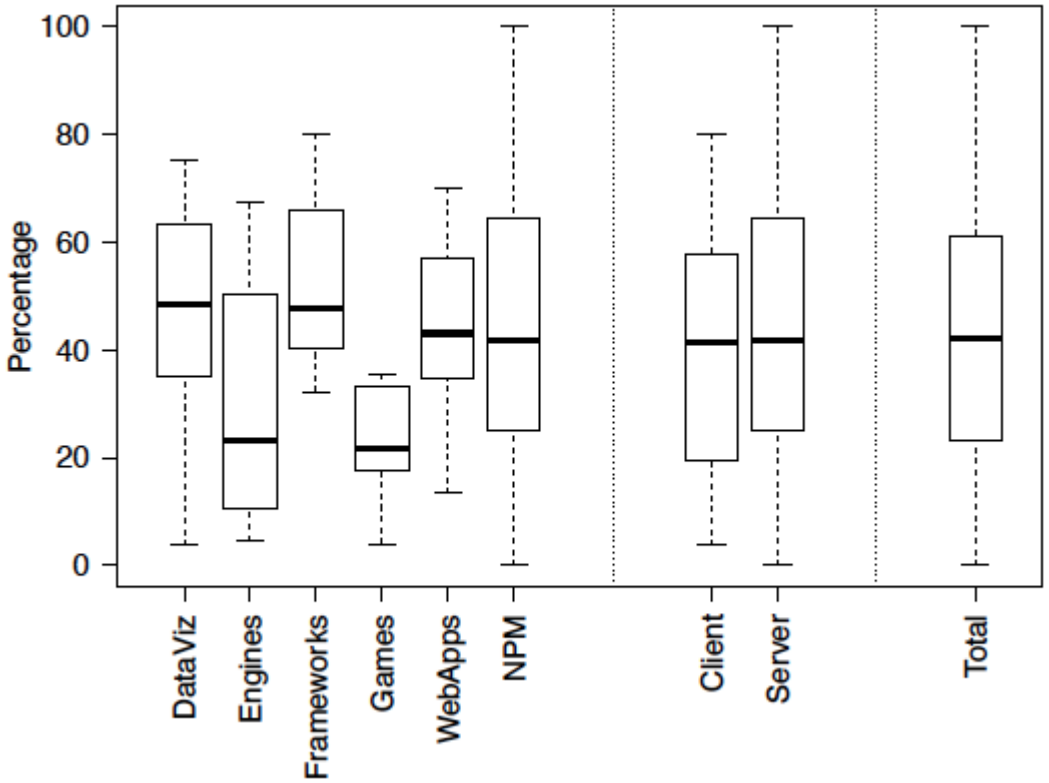
```

Anonymous Vs. Named Callbacks - Results

- **43%** of all callback-accepting function callsites are invoked with at least one anonymous callback.
- There is little difference between client-side and server-side code in how they use anonymous callbacks.



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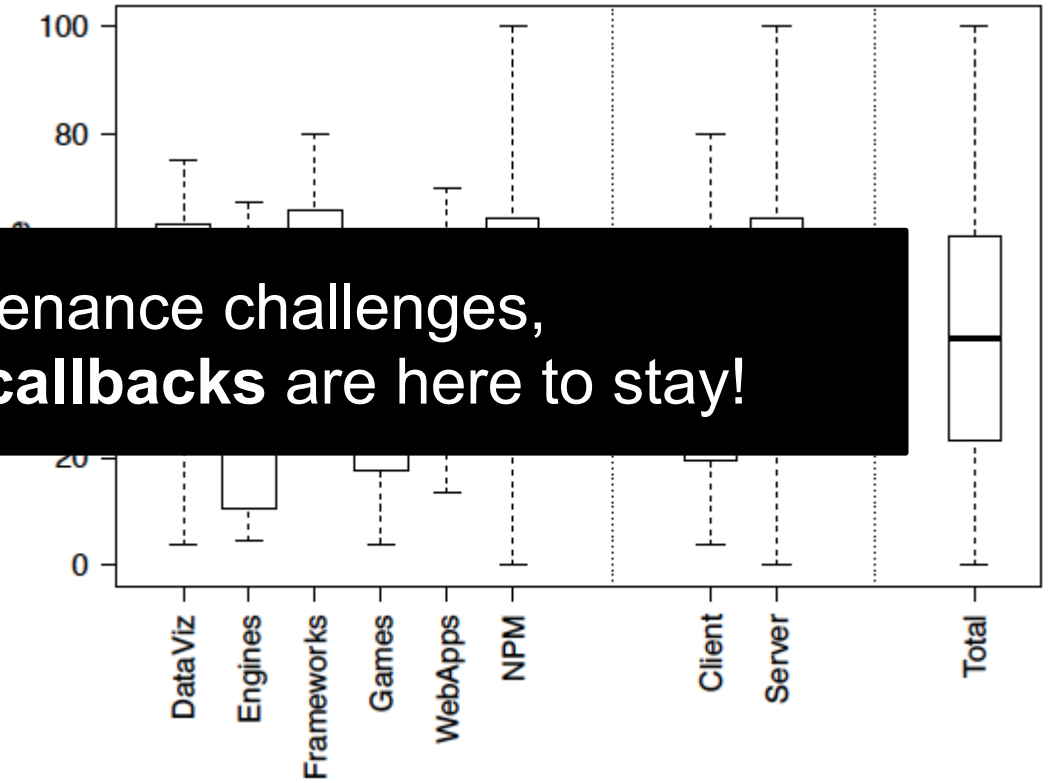

In spite of maintenance challenges,
Anonymous callbacks are here to stay!

Asynchronous callbacks

```
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2    var Admin = {};

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8    });

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16           app.alert({ alert_id: 'instance_restart', });
17         });

19         socket.emit('admin.restart');
20       }
21     });
22   });
23   return Admin;
24 });
```

Notorious for:
Making it hard to reason about the execution.

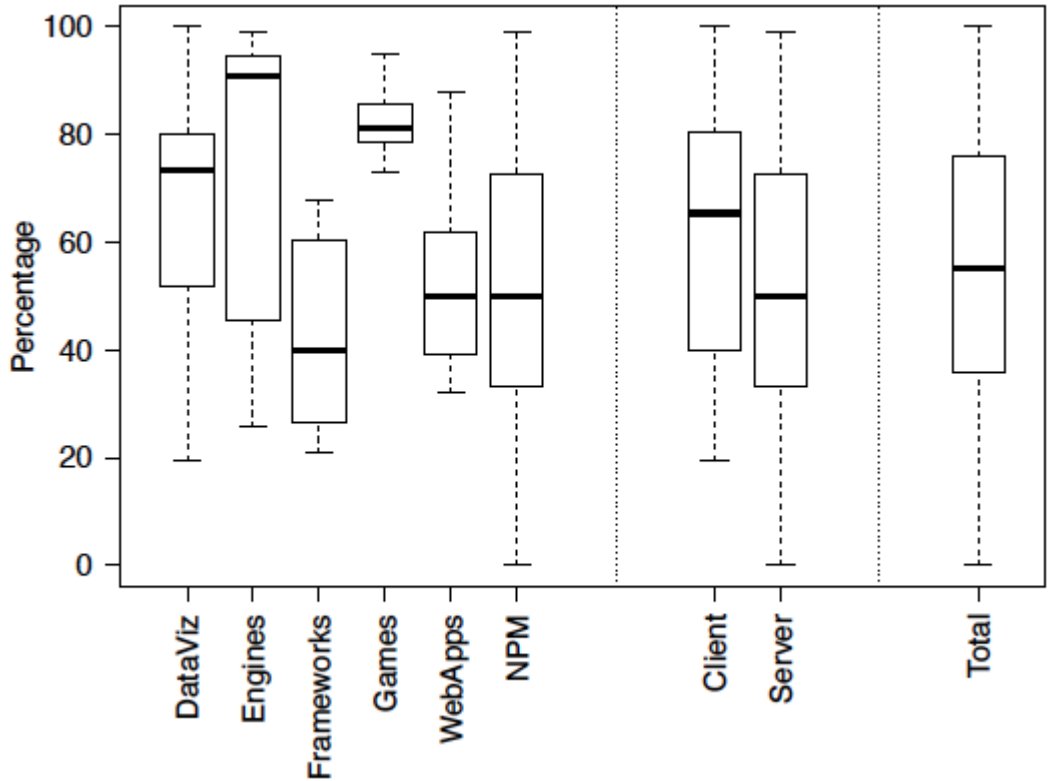
Asynchronous Callbacks

Category	Examples	Availability
DOM events	`addEventListener`, `onclick`	Browser
Network calls	`XMLHTTPRequest.open`	Browser
Timers (macro-Task)	`setImmediate()`, `setTimeout()`, `setInterval()`	Browser, Node.js
Timers (micro-task)	`process.nextTick()`	Node.js
I/O	APIs of `fs`, `net`	Node.js

Some Asynchronous APIs in JavaScript

Asynchronous Callbacks – Results

- More than half **(56%)** of all callbacks are Asynchronous.
- Asynchronous callbacks, on average, appear more frequently in client-side code **(72%)** than in server-side code **(55%)**.



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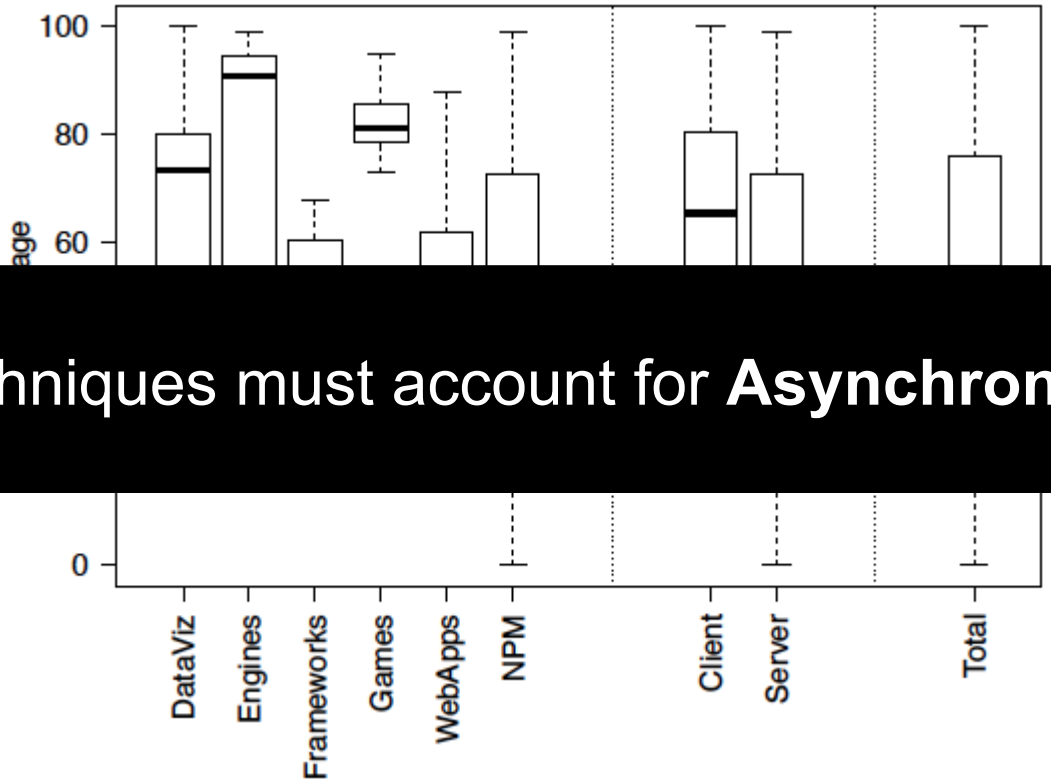

Program analyses techniques must account for **Asynchrony.**

Nested Callbacks

Nesting Level

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23   return Admin;
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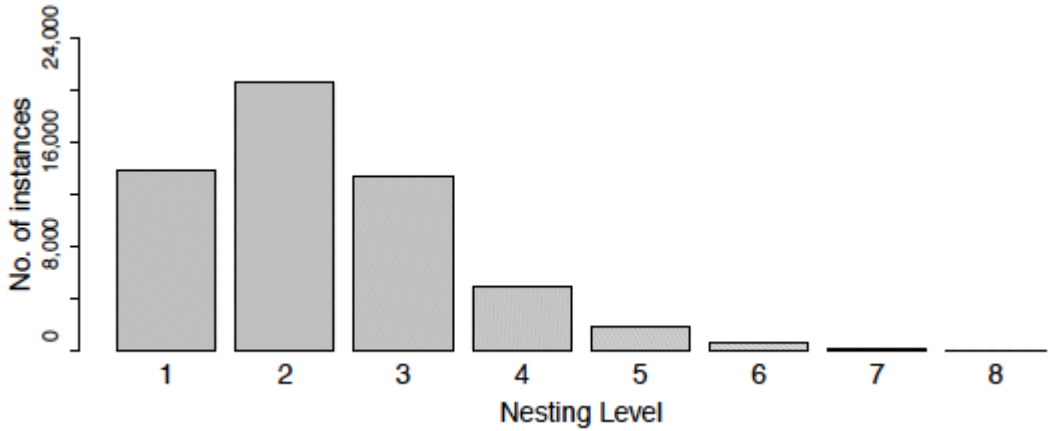
```

Notorious for:
Callback hell aka Pyramid of Doom

Nested Callbacks - Results

- Callbacks are nested up to a depth of 8.
- There is a peak at nesting level of 2.



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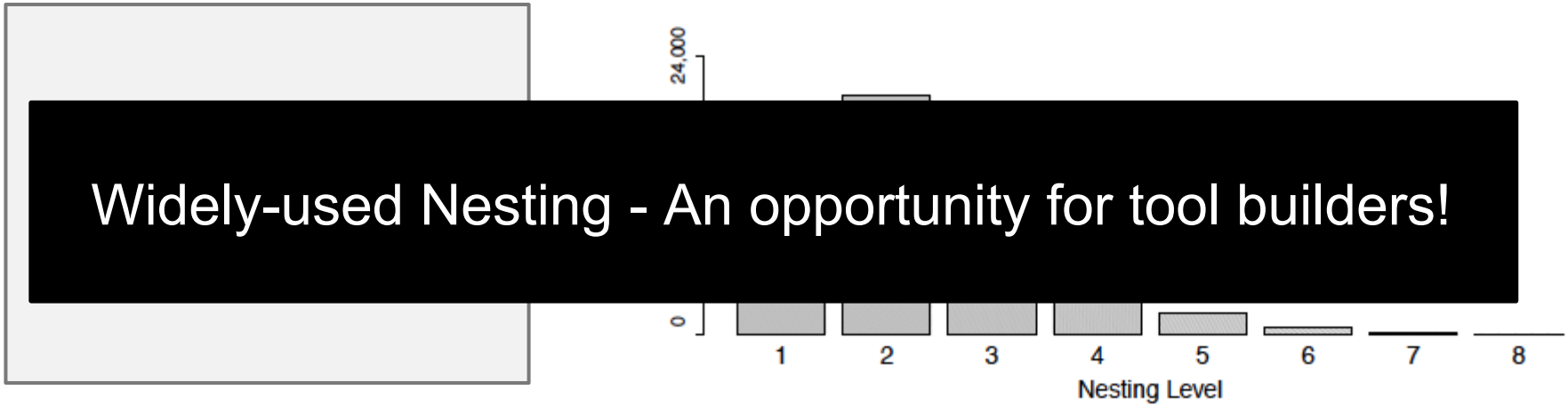

Widely-used Nesting - An opportunity for tool builders!

Outline

Motivation ✔
Methodology & Overview ✔
Characterizing Problems ✔
- Anonymous Callbacks ✔
- Asynchronous Callbacks ✔
- Nested Callbacks ✔

Characterizing Solutions
- Error-first Protocol
- Async.js
- Promises

Conclusion

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- Characterizing Solutions
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Conclusion

Error-first Protocol

- JS has no explicit language support for asynchronous error-signaling
- Developer community has the convention:

Dedicate the 1st argument in the callback to be a permanent place-holder for error-signalling

```
1  var fs = require('fs');
2  // read a file
3  function read_the_file(filename, callback) {
4      fs.readFile(filename, function (err, contents) {
5          if (err) return callback(err);
6
7          // if no error, continue
8          read_data_from_db(null, contents, callback);
9      });
10 }
11
12 function read_data_from_db(err, contents, callback) {
13     //some long running task
14 }
15
16 read_the_file('/some/file', function (err, result) {
17     if (err) {
18         //handle the error
19         console.log(err);
20         return;
21     }
22     // do something with the result
23 });
```

Error-first Protocol

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```

Error-first Protocol - Results

To detect error-first protocol we checked

- if the first parameter **p** of a function definition **f** has the name ‘error’ or ‘err’
- if **f**’s callsites also contain ‘error’ or ‘err’ as their first argument.

We found

- **20%** of function definitions follow the error-first protocol
- The error-first protocol is used twice as often in server-side code than in client-side code (**30%** Vs **16%**)
- **73%** (63 out of 86) NPM modules and **93%** (15 out of 16) web applications had instances of it.

Error-first Protocol - Results

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Cannot depend on APIs/libraries to enforce **error-first protocol**.

Usage of Async.js

Async.js: popular library to manage asynchronous control flow, and to help with functional programming. For example:

Without Async.js

```
var users = [];
fetchUsers(function() {
  renderUsersOnPage(function() {
    fadeInUsers(function) {
      loadUserPhotos(function() {
         // do something
      });
    });
  });
});
```

With Async.js

```
var users = [];
async.series([
  function(callback) {
    fetchUsers(callback);
  },
  function(callback) {
    renderUsersOnPage(callback);
  },
  function(callback) {
    fadeInusers(callback);
  }
  function(callback) {
    loadUserPhotos(callback);
  }
]);
```

Usage of Async.js - Results

- More than half of the web applications (**56%**) use Async.js.
- Usage is much lower (**11%**) in the NPM modules.
- Async.js library is used differently in these 2 categories of subject systems.

Top 10 Async.js invoked methods in JavaScript Web Applications (Left) and NPM modules (Right).

Rank	Method	Count	Rank	Method	Count
1	nextTick	18	1	parallel	189
2	queue*	16	2	apply	81
3	each	14	3	waterfall	72
3	setImmediate*	14	4	series	61
3	series	14	5	each	48
6	auto*	11	6	map	37
6	waterfall	11	7	eachSeries*	20
6	parallel	11	8	eachLimit*	12
9	map	10	9	whilst*	10
9	apply	10	9	nextTick	10

The * symbol denotes calls that do not appear in both tables.

Usage of Async.js - Results

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9	apply	10	9	nextTick	10

Difference in API usage across categories indicate different underlying concerns in callback management!

The * symbol denotes calls that do not appear in both tables.

Conclusions

- Callbacks are extensively used in the **server-side**
- Program analyses techniques must account for **Asynchrony**
- In spite of maintenance challenges, **Anonymous callbacks** are here to stay
- Widely-used Nesting - An opportunity for tool builders.
- Cannot depend on APIs/libraries to enforce **error-first protocol**.

```
http://salt.ece.ubc.ca/callback-study
```

Extra Slides

Usage of Promises

Promises: a native language feature for solving the Asynchronous composition problem. For example:

Without Promises

```
getUser('mjackson', function (error, user) {
  if (error) {
    handleError(error);
  } else {
    getNewTweets(user, function (error, tweets) {
      if (error) {
        handleError(error);
      } else {
        updateTimeline(tweets, function (error) {
          if (error) handleError(error);
        });
      }
    });
  }
});
```

With Promises

```
getUser('mjackson')
        .then(getNewTweets,null)
        .then(updateTimeline)
        .catch(handleError);
```

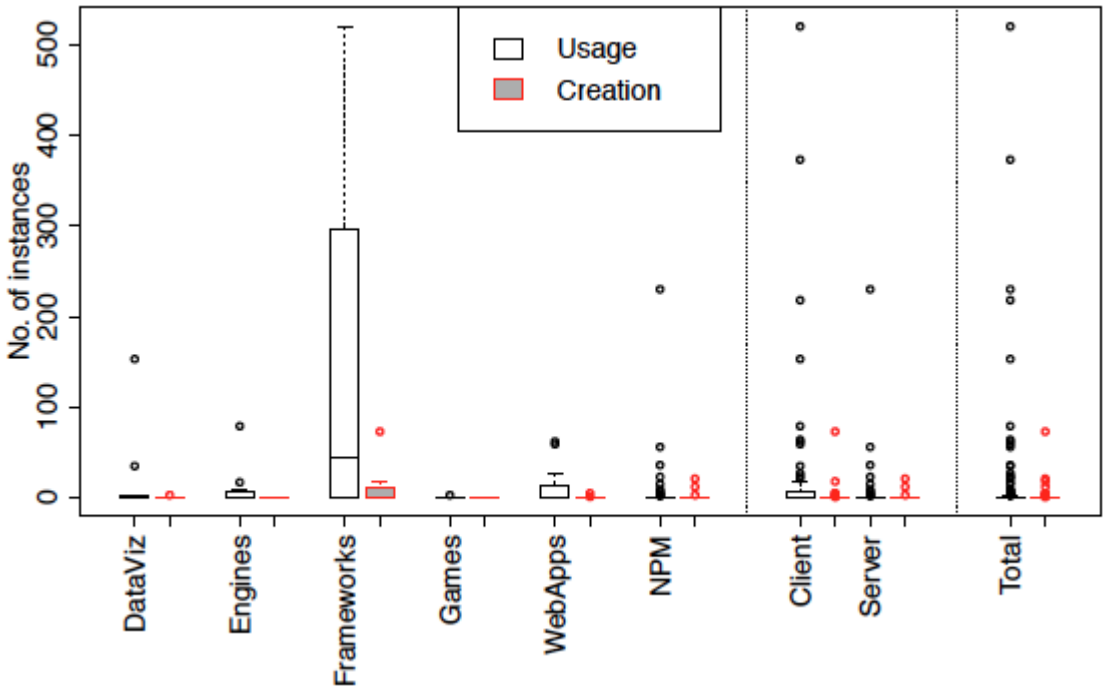
Usage of Promises - Results

27%

37 of 138
subject systems
use Promises.

Category	Subjects creating Promises (%)	Subjects using Promises (%)
DataViz libraries	6	31
Game Engines	0	25
Frameworks	50	75
Games	0	17
Web Applications	13	50
NPM Modules	3	12
Total	8	26

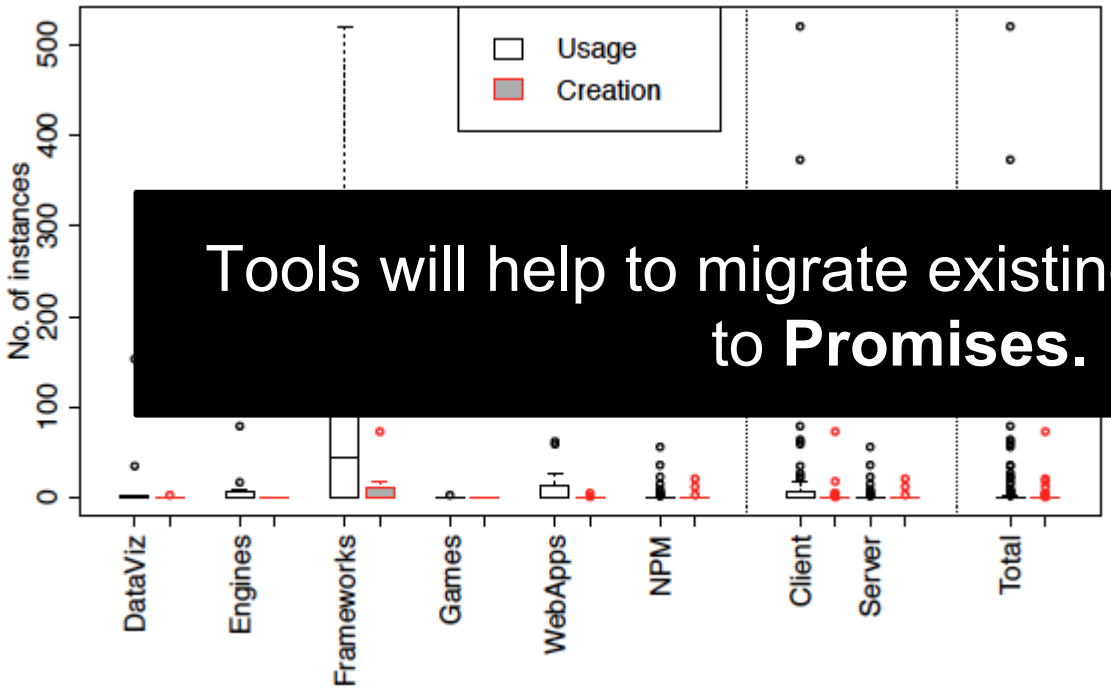
Usage of Promises - Results



Promises are prominently used on the Client-Side

Max: 513 usage instances

Usage of Promises - Results



Tools will help to migrate existing large projects to **Promises.**

Promises are
on the
de

Max: 513 usage instances

Callback Accepting Functions

- **f** is a *callback-accepting function definition* if at least one argument to **f** is used as a callback.

- A parameter **p** of a function **f** definition is a callback..
  - if **p** is invoked as a function in the body of **f**
  - if **p** is passed to a known callback-accepting function (e.g., `setTimeout()`)
  - if **p** is used as an argument to an unknown function **f ′**
    - and then we can recursively determine if **p** is a callback parameter in **f′**

- a *callsite* is callback-accepting if it is of
  - a function that was detected to be callback-accepting, as above
  - a function known a-priori to be callback-accepting (e.g., `setTimeout()`)