Understanding Asynchronous Code

by

Thomas Lieber

B.S.E. Computer Science, Princeton University (2009)

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Master of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2013

Author ....
Department of Electrical Engineering and Computer Science
May 22, 2013

Certified by ....[illegible]...................
Robert C. Miller
Associate Professor
Thesis Supervisor

Accepted by ....[illegible]...................
Leslie Kolodziejski
Chair, Department Committee on Graduate Students

Understanding Asynchronous Code

by

Thomas Lieber

Submitted to the Department of Electrical Engineering and Computer Science
on May 22, 2013, in partial fulfillment of the
requirements for the degree of
Master of Science

Abstract

JavaScript on the web is difficult to debug due to its asynchronous and dynamic nature. Traditional debuggers are often little help because the language's idioms rely heavily on non-linear control flow via function pointers. The aim of this work is to create a debugging interface that helps users understand complicated control flow in languages like JavaScript. This thesis presents a programming editor extension called Theseus that uses program tracing to provide real-time in-editor feedback so that programmers can answer questions quickly as they write new code and interact with their application. Theseus augments the call graph with semantic edges that allow users to make intuitive leaps through program traces, such as from the start of an asynchronous network request to its response. Participants in lab and classroom studies found Theseus to be a usable replacement for traditional breakpoint and logging tools, though no significant difference was found in their ability to complete programming tasks.

Thesis Supervisor: Robert C. Miller
Title: Associate Professor

Acknowledgments

My advisors Rob Miller and Joel Brandt. Max Goldman, Katrina Panovich, Elena Agapie, Elena Glassman, Juho Kim. All of UID, really. Henry Lieberman. Erek Speed, Stephie Wu, Ruben Perez, and Calvin Lewis for being pretty much sane. Ge Wang and Perry Cook for being pretty much insane. Nick Bryan, Jeff Mickey. Mom, Adrienne, Grandma, and the rest of my family and friends. Moxie.

This work was supported in part by Adobe, and by the National Science Foundation under award number SOCS-1111124. Any opinions, findings, conclusions, or recommendations in this thesis are the author's, and they do not necessarily reflect the views of the sponsors.

a little further down the line,
another little piece of mind

Contents

1 Introduction **9**

1.1 Motivation & Problem 9

1.2 Theseus 10

1.3 Benefits 12

1.4 Specific Contributions 13

1.5 Organization of This Document 13

2 Related Work **14**

2.1 Interrogative Debugging 15

2.2 Answering Reachability Questions 15

2.3 Omniscient Debuggers 16

2.4 Control Flow Visualization 17

2.5 Collecting Program Traces 18

3 User Interface **20**

3.1 Call Counts & Reachability Coloring 20

3.2 Structured, Retroactive Logging 22

3.2.1 Asynchronous Links 24

3.3 Usage Scenario 25

3.3.1 Discussion 26

4 System Design **27**

4.1 Trace Collection with *fondue* 27

4.1.1 Nodes: Signposts of Execution Flow 28
4.1.2 Source Code Transformations 30
4.1.3 Capturing Variable Values 33
4.1.4 Accessing the Trace 34
4.2 Debugging with Theseus 35
4.2.1 Node.js 35
4.2.2 Chrome 36

5 Evaluation **37**
5.1 Lab Study 37
5.1.1 Methods 38
5.1.2 Results 43
5.2 Node.js Mini-Course 53
5.2.1 Observations 54

6 Conclusions & Future Work **59**

A Source Code From the Lab Study **65**
A.1 Task T2: du 65
A.2 Task T3: Laggy AJAX UI 65
A.2.1 index.html 65
A.2.2 main.js (included from index.html) 67
A.3 Task T4: Real-Time Chat 68
A.3.1 app.js (Node.js server code) 68
A.3.2 index.html 69
A.3.3 main.js (included on index.html) 70
A.4 Task T5: Faulty Auto-Complete 71
A.4.1 app.js (Node.js server) 71
A.4.2 index.html 74

List of Figures

1-1 Screenshot of Theseus in action 10

3-1 Screenshot of Theseus in action 21

3-2 Screenshot of call counts and reachability coloring 21

3-3 How the structured log is constructed 24

4-1 System design overview 28

5-1 Types of values programmers inspect while debugging 48

5-2 Node.js course activity 56

List of Tables

4.1 *fondue*'s JavaScript function naming convention 29

5.1 Lab study pre-survey questionnaire 39
5.2 Summary of lab study results 43
5.3 Actions performed by users during the Canvas Painter task 49
5.4 Actions performed by users during the du task 50
5.5 Actions performed by users during the Laggy AJAX UI task 51
5.6 Actions performed by users during the Chat task 51
5.7 Actions performed by users during the Name Directory task 52
5.8 Node.js course detailed activity summary 57

Chapter 1

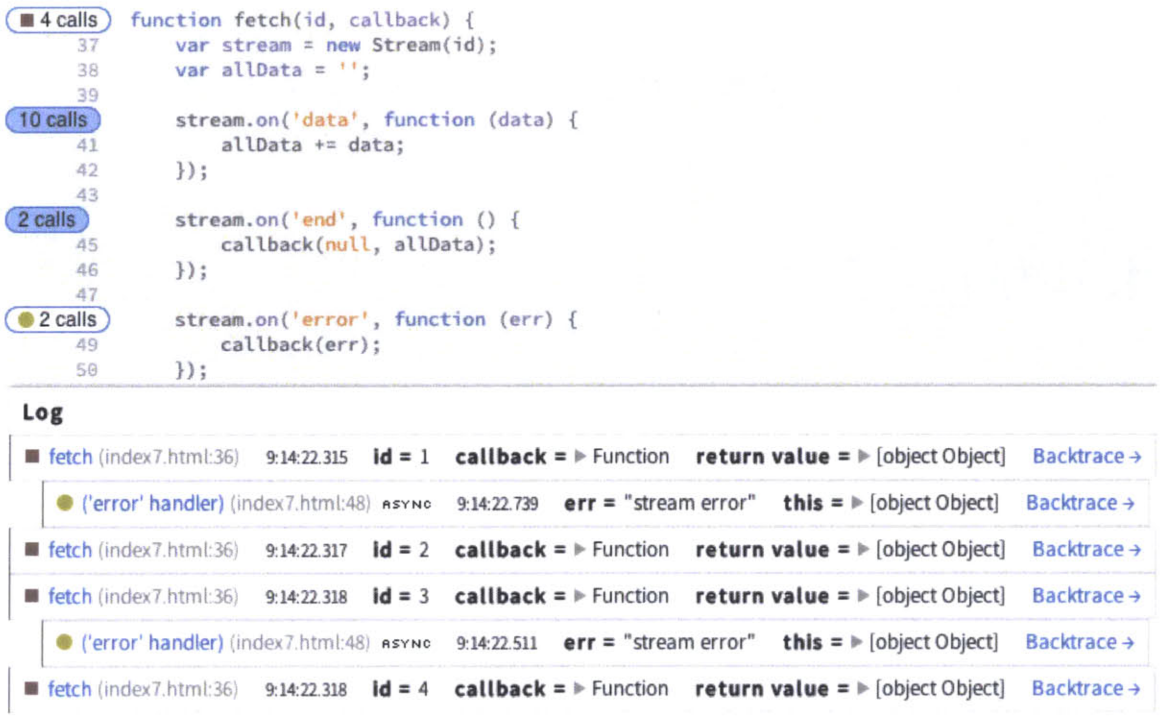
Introduction

1.1 Motivation & Problem

The process of writing and debugging code involves asking a multitude of questions about how the code works [14, 25]. Most of the work a computer does is invisible and virtually instantaneous, so many of those questions are mundane, but frequent, such as what values a certain variable has taken. Since code is often vast and complex, many of the questions concern reachability, such as whether any network operations happen downstream of a particular function call. A 2008 survey found that many of the questions programmers ask were difficult to answer with the debugging tools of the time, and there is reason to believe that we still have a long way to go [25].

Two of the most commonly used debugging tools are print statements and breakpoints. Those interfaces are simple, general, and make it possible to answer many day-to-day programming questions. However, they have many problems. Both require users to modify the program before the interesting part of the code runs in order to use them. They also don't scale well with the complexity of the code under consideration. Viewing program state from a breakpoint is like examining a film frame by frame, and crafting useful log statements can be like crafting a second user interface to an application.

Thankfully, researchers have created tools that are better designed to address the questions programmers ask of their code. Several will be described in the next



```
function fetch(id, callback) {
    var stream = new Stream(id);
    var allData = '';

    stream.on('data', function (data) {
        allData += data;
    });

    stream.on('end', function () {
        callback(null, allData);
    });

    stream.on('error', function (err) {
        callback(err);
    });
```

```
■ fetch (index7.html:36)  9:14:22.315  id = 1  callback = ▶ Function  return value = ▶ [object Object]  Backtrace →
    ● ('error' handler) (index7.html:48) ASYNC  9:14:22.739  err = "stream error"  this = ▶ [object Object]  Backtrace →
■ fetch (index7.html:36)  9:14:22.317  id = 2  callback = ▶ Function  return value = ▶ [object Object]  Backtrace →
■ fetch (index7.html:36)  9:14:22.318  id = 3  callback = ▶ Function  return value = ▶ [object Object]  Backtrace →
    ● ('error' handler) (index7.html:48) ASYNC  9:14:22.511  err = "stream error"  this = ▶ [object Object]  Backtrace →
■ fetch (index7.html:36)  9:14:22.318  id = 4  callback = ▶ Function  return value = ▶ [object Object]  Backtrace →
```

Figure 1-1: Screenshot of Theseus in action. The call counts next to the `fetch()` *function and 'error' callback function have been selected, populating the log with all their invocations.*

chapter. Although they usually make it easier to answer questions that are otherwise difficult to answer, they often *complement* breakpoints and log statements rather than replace them. They add to the complexity of an IDE without simplifying it. The aim of my research is to create a single interface that can answer the difficult questions without being too cumbersome to answer the easy ones as well.

1.2 Theseus

Theseus is the implementation of those ideas that will be discussed in this thesis. It is designed for debugging JavaScript, a dynamic language that is popular but not well supported by debugging tools. JavaScript's idioms encourage the use of *callbacks* for everything from asynchronous event handlers to synchronous array iteration. Callbacks cause control flow to branch often and become difficult to follow. Theseus is an extension for the Brackets code editing environment[1] and can be used to debug

[1] `http://brackets.io/`

JavaScript running in the Node.js stand-alone virtual machine[2] or the Chrome web browser[3].

Theseus consists of two interfaces for understanding program behavior. The first is a layer on top of the code editor to show which paths of the code have been executed. The other is a call tree for showing how those paths interact. See Figure 1-1 for what Theseus looks like during a typical debugging session.

When the user examines the source code for an application that is currently running with the Theseus debugger, the code is redrawn to reflect the execution history of the program so far. Code that has never been executed is given a darker background so that it can be readily identified. A small widget is placed in the gutter of the text editor adjacent to every function definition, showing the number of times that function has been called. When clicked, adds that function to the *active query* . When functions in the query have been called, a log panel appears showing information about all invocations of those functions, including the data they accepted as parameters and the data they returned. The log is structured like a call tree. Invocations which are nested beneath other invocations of functions in the query will be nested that way in the log. The caller/callee relationship is extended to include asynchronous connections, such as functions that return callback functions and invocations of those callback functions.

The information in the interface is based on a program trace that is collected in real time, so the log is populated retroactively when the user modifies the query, and updates as new information comes in. Formerly unexecuted code lights up immediately upon being executed. Call counts update as they are invoked. Callbacks for delayed network events appear under the corresponding requests as the responses arrive.

Theseus also allows the inspection of multiple programs at once. This is most useful when the programs are related, such as a client and server. Call counts are shown in the source code for both, and when the active query contains functions from

[2]`http://nodejs.org/`

[3]`https://www.google.com/chrome/`

client and server, timestamps are used to order them chronologically in the same log. Less naive strategies are described in Chapter 6, Conclusions & Future Work.

1.3 Benefits

Theseus allows programmers to watch their code execute. They can determine whether a function has been called simply by pulling up its source code. Since the information updates in real time, they can verify that the timing and frequency with which functions are called matches what they expect. Furthermore, reachability coloring enables users skimming a source file to easily find the relevant portions of the code, since they will be grayed out.

Theseus makes it simple to inspect the values of parameters and return values. Formatting print statements and hitting a breakpoint at the right time are unnecessary because Theseus automatically displays all of the data flowing in and out of the function when it is added to the query. The information comes from the program trace, so the program does not need to be restarted, nor the function re-run, in order to inspect any of those values.

Theseus unties callback knots into structured call trees. Theseus' logs allow programmers to inspect data upstream and downstream of any function call, even up and down chains of events. When those chains of events interleave, such as in a server that performs long-running operations to satisfy requests, the log's entries are grouped by request if the request handler is part of the query (for an example with streams, see Figure 1-1).

In short, Theseus reduces the preparation and orchestration required to inspect the run-time behavior of code. In our user studies, we found that users appreciated the ability to get a summary of how the code has run with a glance at the editor, and the ability to inspect the data flow through one or more functions just by clicking them. My hope is that with a streamlined interface, programmers will inspect more often, guess less, and understand code more quickly.

1.4 Specific Contributions

This thesis demonstrates the feasibility, benefits, and usability of real-time code coverage information in the form of call counts and the coloring of dead code. I have released Theseus, a Brackets editor extension for debugging JavaScript, under an open source license.

Furthermore, lab and classroom studies were used to validate the interface ideas. Lab study participants found the interface to be easy to use and worthy of recommendation to friends, commenting that this is the way debuggers should work. The study provided information on the types of information programmers seek to gather with existing debuggers, which can be used in the future to inform the creation of debuggers that choose values for inspection automatically, as does Theseus.

Lastly, I also present a method for augmenting a JavaScript call tree automatically with edges for asynchronous (event registration/activation) links by detecting common forms of event registration, and describe how it might be improved with modification to the virtual machine. The current method can be implemented with simple abstract syntax tree (AST) rewriting rules as the code is instrumented for trace collection. An algorithm for walking the call tree (which is now a directed acyclic graph) is also presented.

1.5 Organization of This Document

Chapter 2 discusses related work, from debugging tools to program trace collection techniques. Chapter 3 presents the Theseus interface and design process. Chapter 4 describes the system's implementation and relevant algorithms. Chapter 5 covers our lab study and experiences deploying Theseus in a tutorial setting with college students. Chapter 7 concludes the thesis and describes future work.

Chapter 2

Related Work

In 1997, Henry Lieberman lamented the 30-year stagnation of debugging tools, pointing out that many programmers still named "inserting print statements" as their debugging technique of choice [18]. As we discovered in our lab study, print statements still play a significant role, though programmers felt embarrassed to admit it. However, debugging interfaces designed with human psychological limitations in mind have become more common. Field work and lab studies such as [25, 14] have identified the types of questions programmers ask while programming, measured how much time they spend answering them, and called attention to the areas where programmers need the most help. Theseus may be used to answer at least 40% of the types of questions programmers asked during Sillito's studies that they found were not supported by existing tools, including:

- How is control getting (from here to) here?
- Why is not control reaching this point in the code?
- Which execution path is being taken in this case?
- Under what circumstances is this method called or exception thrown?
- How does the system behavior vary over these types or cases?
- Where should this branch be inserted or how should this case be handled?

- What will be (or has been) the direct impact of this change?

In this section I will describe some of the relevant interfaces and techniques that have been created to answer these and other questions programmers ask. I will also describe how each project relates to the work of this thesis. The selection is broad, including projects that serve as inspiration in addition to those that have similar approaches, in order to accurately portray the context in which this research was carried out.

2.1 Interrogative Debugging

Whyline is a debugging interface that helped Alice programmers fix bugs nearly 8 times faster than than programmers without it [10] and made Java programmers more than twice as fast [11]. It is an example of an *interrogative debugger* that works by collecting a program trace and generating a list of "why did" and "why didn't" questions the user might have about their program's behavior. Questions can be about various aspects of a program, such as the user interface ("Why is this text blue?") or an object's fields ("Why didn't the value of x change?"). Answers are generated using program slicing and presented as chains of events in the code, such as an event firing, a value being changed, and the wrong branch of a conditional statement being taken.

The main difference between Whyline and Theseus is when they would be used. Whyline helps locate the code that is relevant to a particular change, while Theseus visualizes the behavior of the code at that location. For example, if Whyline led a user to the `if`-statement that they need to change to add a feature, then Theseus could visualize the code paths that would be affected by making a change there.

2.2 Answering Reachability Questions

Reacher focuses on reachability questions, those that require "reasoning about causality, ordering, type membership, repetition, and choice" [13, 14, 15]. LaToza and Myers identified those questions as among the most time-consuming for people to answer because existing tools could only answer them indirectly. Users ask Reacher about the relationship between several functions and Reacher presents a compact graph representation of those functions' connectivity, such as which functions call one another directly or indirectly, whether one function calls another in a loop or within a conditional, and the temporal ordering of two calls that happen in sequence. It relies on static analysis instead of program traces, so it can answer questions such as "In what cases *might* this function be called?" but not "In what cases *has* this function been called?" for a given run of a program, as does Theseus.

Stacksplorer [7] and Blaze [12] focus on answering simple reachability questions during program change tasks, specifically finding possible callers and callees of the function currently being edited. The primary difference between these two projects is how much of the stack they show at a time. Stacksplorer shows callers on the left of the code editor and callees on the right. Blaze shows an entire code path end-to-end so that users can quickly navigate callers and calles that are several levels removed from the focused function. Both rely on static analysis for that data. Both helped developers perform maintenance tasks faster and with higher success rates than without them, though neither helped significantly more than the other.

2.3 Omniscient Debuggers

Step debuggers allow users to understand control flow by slowing the computer down so that it takes things one step at a time. One common limitation of step debuggers is that they usually only show the current program state and cannot step backwards. By inspecting program traces instead of running processes, *omniscient debuggers* allow users to move forward and backward in time. ZStep is an example of an omniscient debugger [19]. With ZStep, a user can step forward and backward by line or expression, but also in other ways, such as to the point when any given expression was evaluated, to the next time the GUI was updated, or to when a particular screen element was drawn. Several other omniscient debuggers allow users to make similar non-linear jumps. An omniscient debugger for Java called TOD allows users to jump back to the time that a variable was changed by clicking a "why?" link next to its current value in a variables panel [22]. JIVE is a debugger that highlights the portions of a program's timeline where a variable's values fell within a particular range [3]. Users can step through the code from any of those points. Finally, IntelliTrace is a tool that allows users to index into a program trace by selecting the corresponding event, such as a UI event or an exception [21]. Navigating a program trace by jumping between key points allows users to rapidly jump to the point of the execution that corresponds with a bug, or, when the time of interest is unknown, to skim the program's history more quickly than step-by-step. They have also been used to create more helpful stack traces, such as JavaScript stack traces that cross event boundaries [24], and even client-server boundaries [20].

Most of the edges used to navigate the trace in those projects don't exist in the call graph even though they do exist in the programmer's mind. In pilot tests of Theseus, I noticed that when I did not call out the asynchronous edges in a call graph as special, users didn't perceive them as special. A person looking at the idiomatic JavaScript code for a callback function wants to be able to step into it, and Theseus makes the connection. With a step debugger that doesn't support that kind of leap, the programmer needs to recognize the situation as one which the debugger doesn't support and change strategies.

2.4 Control Flow Visualization

Software visualization has a long history [9], from Lieberman's representation of function calls as 3-dimensional objects [17] to LogoMedia, which allowed users to find bugs by sonifying program execution [2]. One of the most influential for Theseus was the essay "Learnable Programming", in which Bret Victor outlines several of the features he believes a learnable programming environment and language should have [26]. He presents a way of visualizing control flow by displaying intermediate values in a panel displayed alongside the code. Each line contains a semantically appropriate visualization of a value being computed on that line, such as a notched, rotated circle to represent an angle stored as a number. The list of past values extends to the right and a scrubber along that axis changes the output to match the currently selected moment in time. Gaps in the timeline can indicate lines that were skipped when an alternate branch was taken. This technique works well for visualizing code behavior within a single function, and Theseus' log is an attempt to scale the idea to multiple functions (albeit with relatively impoverished visualizations of the values themselves). Theseus' technique for displaying historical values in a log sacrifices code locality since the information appears in a separate panel.

VELD has a similar intent to Victor's interface, but uses a different approach [23]. VELD lets users choose their own level of abstraction by visualizing user-created events. For example, to investigate lock contention, a user instruments their code to generate events for when a lock is used and visualizes those events with VELD.

DejaVu is a similar project with a narrower domain, real-time video processing [8]. DejaVu associates the values of variables with the frame of video being processed so that users can inspect the values by scrubbing to different points in the video. Widgets displaying those values are placed on a canvas along with drawings, programmers' notes, and intermediate versions of the images being processed. Each canvas the user creates is a hand-made slice of the program's state.

2.5 Collecting Program Traces

Recording complete program traces has historically been difficult, though feasible [22]. Timelapse (Brian Burg, currently in review[1]) promises self-contained, fully-replayable traces of entire web pages within WebKit browsers [1]. The instrumentation library for Theseus is limited in that it does not record changes to the structure of the web page. Timelapse's more complete program traces would allow Theseus to keep the web page in sync with the debugging session, as when using ZStep.

Theseus uses a handful of routines specific to the Theseus interface for querying

[1]Timelapse `http://homes.cs.washington.edu/~burg/projects/timelapse/`

the program trace, but several higher-level approaches to accessing trace data have been researched. Caffeine [6] and JavaTA [4] are Prolog-based languages that can search for call paths matching a set of predicates. PTQL is a variant of SQL designed for querying traces as if they were stored in a relational database [5]. There is also a Self-like syntax for executing queries over objects in the heap [16]. Building on the ideas of those projects would make it easier to port Theseus to other languages and environments, and allow users to write their own queries over the call graph.

Chapter 3

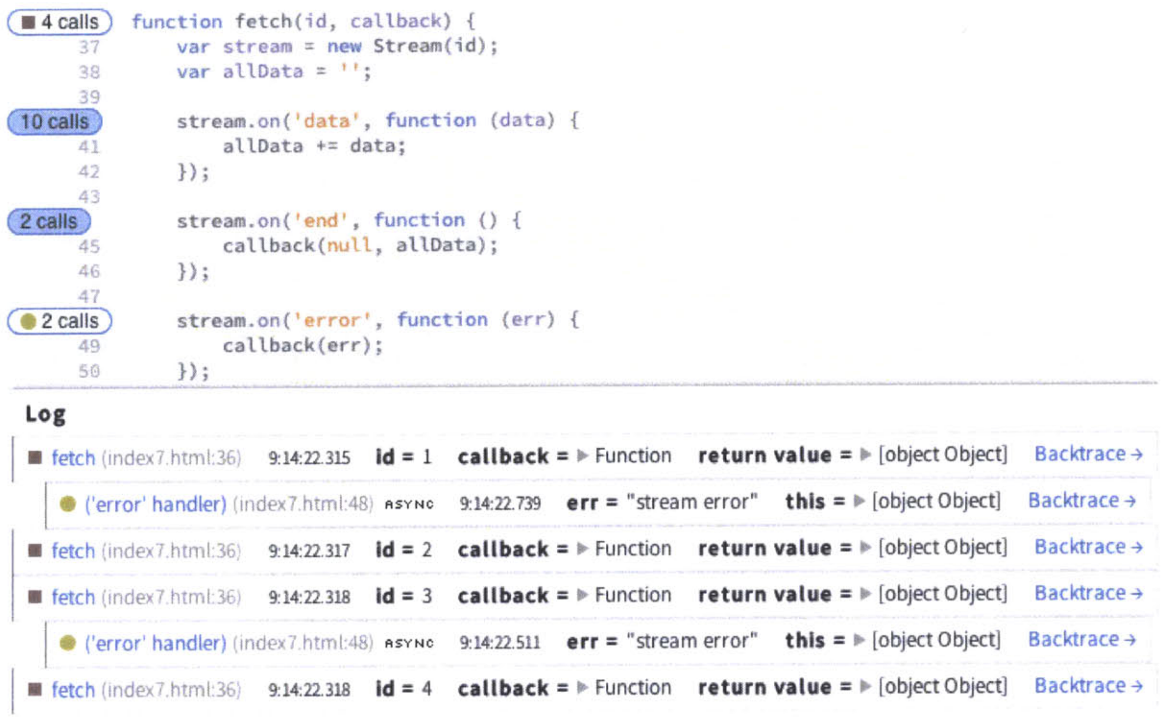
User Interface

The primary interface in Theseus is the code itself, which Theseus augments with real-time information about its execution: call counts and reachability coloring. The secondary interface is a panel that appears at the bottom of the window for displaying call trees when a query is active. Figure 3-1 shows a typical session in which the user determines which calls to `fetch()` resulted in a call to the error callback by adding both to the active query. The following sections will discuss each of the features of this interface in detail, followed by an example usage scenario.

3.1 Call Counts & Reachability Coloring

As soon as Theseus detects that the code being viewed in the editor is also being executed somewhere on the local machine (in Chrome, Node.js, or both simultaneously), Theseus adds call counts to the left of every function definition and begins coloring all the code according to whether it has been called.

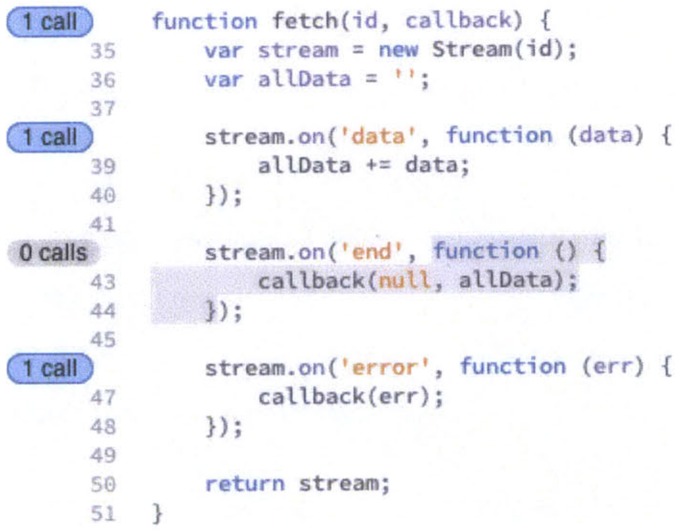
The call counts appear in the gutter next to the first line of every function definition, where the line number and breakpoint indicator would normally reside. The rounded rectangle containing the number, called a *pill*, is gray when the count is zero, but turns blue when the number is greater than zero. The pills turn dark blue when the mouse moves over them so that the user knows they can be clicked (which opens the log—see the next section). The counts update in approximately real time,



```
function fetch(id, callback) {
    var stream = new Stream(id);
    var allData = '';

    stream.on('data', function (data) {
        allData += data;
    });

    stream.on('end', function () {
        callback(null, allData);
    });

    stream.on('error', function (err) {
        callback(err);
    });
```

```
■ fetch (index7.html:36)   9:14:22.315   id = 1   callback = ▸ Function   return value = ▸ [object Object]   Backtrace →
    ● ('error' handler) (index7.html:48) ASYNC   9:14:22.739   err = "stream error"   this = ▸ [object Object]   Backtrace →
■ fetch (index7.html:36)   9:14:22.317   id = 2   callback = ▸ Function   return value = ▸ [object Object]   Backtrace →
■ fetch (index7.html:36)   9:14:22.318   id = 3   callback = ▸ Function   return value = ▸ [object Object]   Backtrace →
    ● ('error' handler) (index7.html:48) ASYNC   9:14:22.511   err = "stream error"   this = ▸ [object Object]   Backtrace →
■ fetch (index7.html:36)   9:14:22.318   id = 4   callback = ▸ Function   return value = ▸ [object Object]   Backtrace →
```

Figure 3-1: Screenshot of Theseus in action. The call counts next to the `fetch()` *function and 'error' callback function have been added to the active query, populating the log with all their invocations.*



```
function fetch(id, callback) {
    var stream = new Stream(id);
    var allData = '';

    stream.on('data', function (data) {
        allData += data;
    });

    stream.on('end', function () {
        callback(null, allData);
    });

    stream.on('error', function (err) {
        callback(err);
    });

    return stream;
}
```

Figure 3-2: Screenshot of call counts and reachability coloring. The `fetch()` *function and the 'data' and 'error' callback functions have been invoked once each, but the 'end' callback handler has not.*

updating at approximately 10 Hz.

When the call count for a function is zero, the background color of its source code is changed to a dark gray. Since inline function definitions are common in JavaScript, the coloring only extends from the first character to the last character of the function definition. The 'end' callback in Figure 3-2 demonstrates this. The coloring changes back to normal as soon as the call count is incremented.

In early prototypes, I sought to create an interface for answering the most challenging reachability questions first. Unfortunately, while it was *possible* to answer many questions with those interfaces, it was very difficult to teach others how. I scaled back the scope until I reached an interface that presented no difficulty to uninitiated users: call counts and reachability coloring. The interface lost any notion of the order functions were called in relative to one another unless the user happened to be looking at the call counts just as they changed, but gained learnability. It could still be used for answering simple reachability questions, since call counts in a callback chain would all be equal if everything worked, and decrease near the end of the chain when there was a breakdown. Call counts also turned out to be convenient click targets for activating Theseus' log.

3.2 Structured, Retroactive Logging

When a call count pill is clicked, that function is added to the *active query*. The query matches any invocations in the call graph of any of those functions. The matched invocations are displayed in a log panel that appears automatically whenever the query is non-empty. Invocations that have already occurred are added to the log immediately, as if they had been in the query from the start, and new invocations are added as they occur.

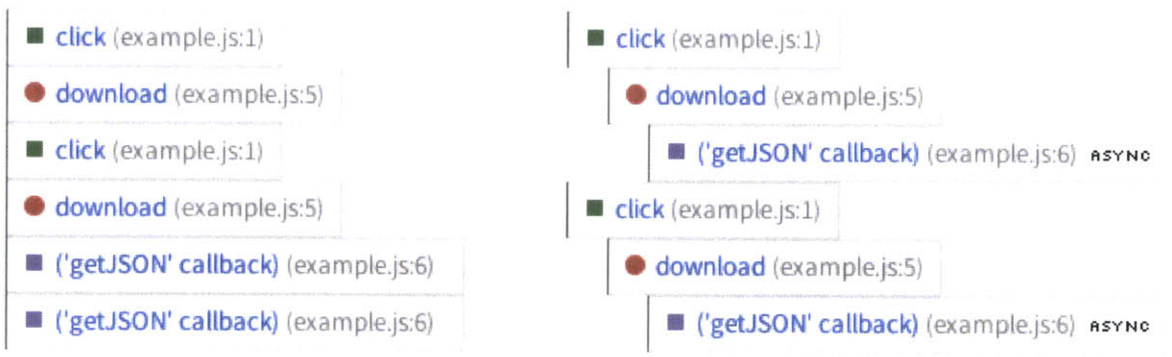
The log is laid out like a call tree, an outline of the program's execution featuring only the functions in the query. An invocation will be displayed as a direct descendant of another invocation if it was called directly, or if there is a call chain connecting them with no other invocations in the query results between them.

The entry in the log for every invocation includes all of the values passed into and out of the function on that invocation. That includes arguments that were passed in, arguments that were added beyond the list of declared arguments, the return value if an explicit return statement was reached, and the exception that was thrown if one was thrown. To minimize the amount of noise in the log, information that can be assumed, such as the default return value of `undefined` of functions that have no `return` statements, is not displayed.

Arrays and objects are summarized with strings like `[Array:2]` and `[Object]`, but the keys and values they contain can be inspected in place by clicking their name or the disclosure triangle that appears just to its left. Vertical space is made so that they can all be shown at once. Nested arrays and objects behave the same way. The depth that they can be explored is capped by technical limitations as described in Chapter 4, System Design.

Each log entry also has a button labeled 'Backtrace' that will temporarily replace the log with a list of all the invocations that were on the stack at the time the function was called. Their entries also display input and output values.

In earlier prototypes, the query was ordered. If the user clicked the pill for function A, then clicked the pill for function B, then only call chains that passed through function A *then* function B would be matched. The call counts reflected the number of log items that would be added if you clicked them (i.e. the number of times the function was called downstream of the current query). This caused more trouble than it was worth. Every time a function was added to the query, it put the interface into a new mode. If the user clicked a pill and then became interested in a different function, they had to remove the old function from the query in order to see all the information about the new function. However, relaxing the ordering constraint clears up most of those issues though it can result in additional clutter in the log, and when the *number* of call paths that go through a pair of functions is required, the user must count them instead of relying on the call counts in the pills.



```
■ click (example.js:1)
● download (example.js:5)
■ click (example.js:1)
● download (example.js:5)
■ ('getJSON' callback) (example.js:6)
■ ('getJSON' callback) (example.js:6)
```

```
■ click (example.js:1)
  ● download (example.js:5)
    ■ ('getJSON' callback) (example.js:6) ASYNC
■ click (example.js:1)
  ● download (example.js:5)
    ■ ('getJSON' callback) (example.js:6) ASYNC
```

Figure 3-3: How the structured log is constructed. Left: a flat, chronological log, as you would get by adding print statements. Right: a structured log shows the call tree. In this example, `download()` *calls* `getJSON` *(not in the log), passing a callback handler for when the download finishes. The responses come back out of order and would require the programmer to deduce which response goes with which request, but the structured log treats the asynchronous operation as a synchronous call for visualization.*

3.2.1 Asynchronous Links

In the log, asynchronous calls are treated like direct calls. For example, if one function kicks off an asynchronous operation, such as registering a callback, then each invocation of that callback will be treated as if it were a descendant of the function that created it. When an invocation is nested beneath another due to this kind of asynchronous relationship, the child is tagged with the word 'async' like the 'getJSON' handler in Figure 3-3.

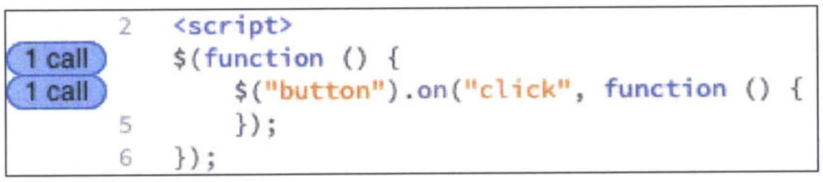
Having a call tree structure doesn't change the ordering of synchronous calls, but it can change the order of asynchronous calls relative to one another. This makes the Theseus interface presented here inappropriate for debugging race conditions, but ways to solve this problem are discussed in Chapter 6, Conclusions & Future Work. The invocations are, however, sorted chronologically relative to their siblings.

A choice must be made about where to put an invocation that is both a synchronous and asynchronous descendant of other invocations in the log. This could happen if the function that kicks off an asynchronous operation and the function that calls it are both in the active query. Currently, Theseus shows that invocation in a single location, though the alternative of showing the log entries in both locations with pointers to each other may also be a good choice.

3.3 Usage Scenario

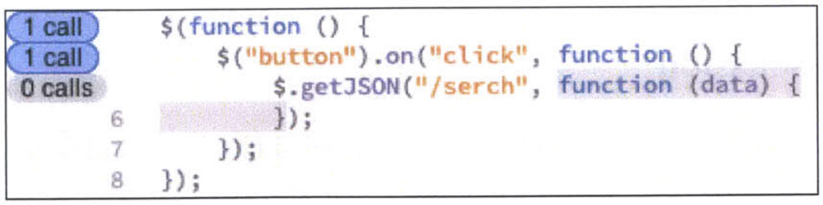
As a demonstration of how Theseus can be used to rapidly understand asynchronous code, in this section, we show an example code authoring session. Max's task is to add JavaScript to a web page so that when a search button is clicked, the page will download search results via AJAX and display them on the page.

Max begins by connecting an event handler to a search button. Once he has entered the code to the best of his ability, he wants to verify that he made no mistakes. To do so, Max reloads the page, clicks the search button, and returns to the IDE. The coloring and call counts indicate that the code that registered the event handler, and the event handler itself, were both executed.



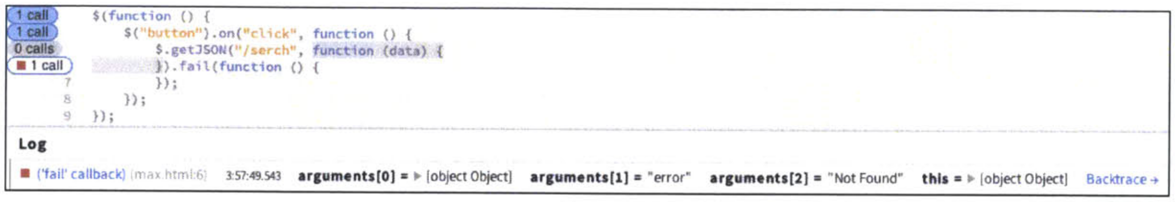
```
<script>
$(function () {
    $("button").on("click", function () {
    });
});
```

Next, Max needs to request the search results. He arrives at the code below by customizing a snippet he finds on the web. Max refreshes the page and clicks the search button again. From the coloring of the source code, he sees right away that the `success` event handler was never called.



```
$(function () {
    $("button").on("click", function () {
        $.getJSON("/serch", function (data) {
        });
    });
});
```

To figure out why, Max adds an empty error handler and saves the file. When he clicks the button again, he sees that the error handler was indeed called. He couldn't remember what arguments would be passed to the handler, but it doesn't matter. He clicks the 1 call pill next to the error handler, which adds the invocation of the error handler to the timeline so he can inspect the arguments.

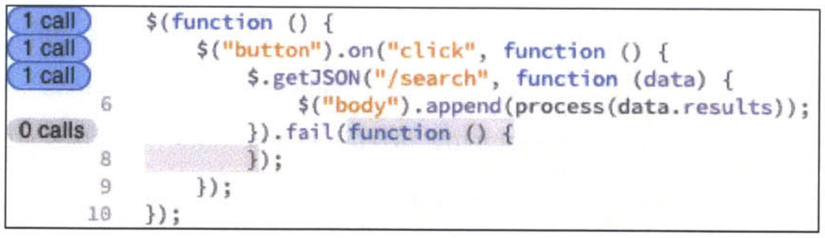


```
1 call    $(function () {
1 call        $("button").on("click", function () {
0 calls           $.getJSON("/serch", function (data) {
■ 1 call          }).fail(function () {
                  });
              });
          });
```

```
Log
■ ('fail' callback) (max.html:6)   3:57:49.543   arguments[0] = ▸ [object Object]   arguments[1] = "error"   arguments[2] = "Not Found"   this = ▸ [object Object]   Backtrace →
```

Max skims the arguments and sees that the string `Not Found` was passed as the third argument. This calls his attention to a typo in the URL (`serch` instead of `search`). He fixes it, refreshes the page, and verifies that the problem is fixed with a glance at the source code when all the call count pills turn blue except for the error handler.

To display the search results, Max needs to know what data is passed to the AJAX callback. He clicks the 1 call pill next to the callback function. He inspects the arguments to discover that the first argument contains the array of results. He gives a name to that argument in the source code and writes the code to display it on the page.



```
1 call    $(function () {
1 call        $("button").on("click", function () {
1 call            $.getJSON("/search", function (data) {
                      $("body").append(process(data.results));
0 calls           }).fail(function () {
                  });
              });
          });
```

3.3.1 Discussion

Theseus provides several forms of feedback that would have been difficult or tedious for Max to gather without it. He can see whether lines of code had executed using color, instead of sprinkling the file with breakpoints, log statements, or calls to `alert()`. He can correlate page events, such as AJAX responses, with events in his code. He can inspect the values of variables without explicitly instrumenting them ahead of time.

Chapter 4

System Design

Theseus consists of an extension for the Brackets editor, two modules that the extension uses to communicate with Chrome and Node.js, the JavaScript instrumentation library that is embedded in an HTTP proxy server and Node.js module loader, and the trace-collecting code that gets injected into the programs being debugged. The system is small, about 3,000 lines of code, half of which are devoted to the interface. It's also modular. The JavaScript instrumentation library *fondue* is packaged separately and has a stand-alone API. The composition of the system is summarized in Figure 4-1.

4.1 Trace Collection with *fondue*

fondue is the instrumentation library that was built to support Theseus' interface[1]. It has two components. The first is the code that modifies JavaScript source code to add hooks for capturing function calls, the values of expressions, etc. The second is the code that *fondue* prepends to the modified JavaScript that uses the hooks to collect trace data. That latter defines a global object named `tracer` with functions for collecting the trace (`traceReturnValue()`, `traceFunCall()`, etc) and accessing the trace data (`trackLogs()`, `backtrace()`, etc).

[1]Named 'fondue' because it's more pleasant to think of instrumentation as covering code in a delicious melted cheese than clogging it up with code that makes it run more slowly.

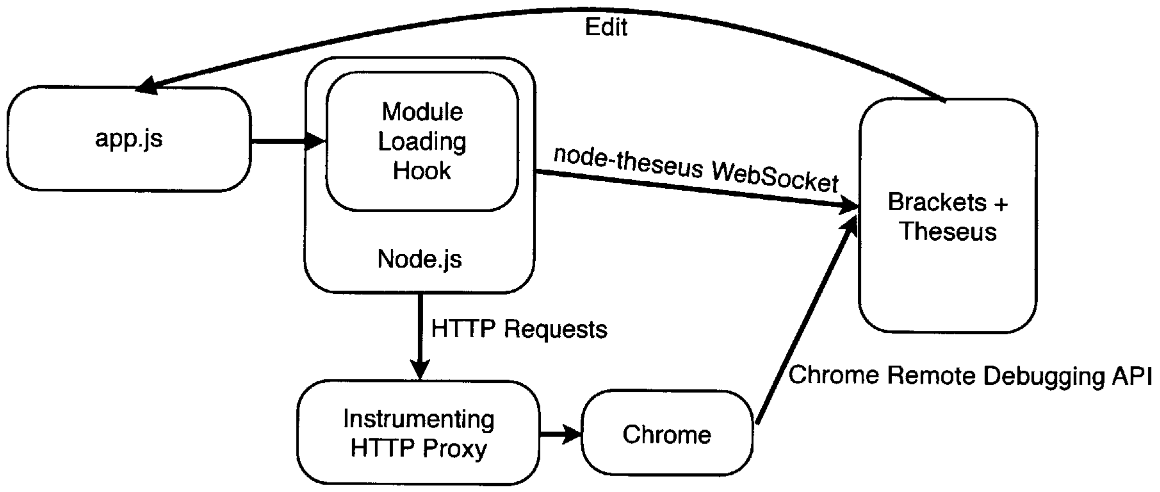


Figure 4-1: System design overview.

4.1.1 Nodes: Signposts of Execution Flow

Theseus is function-centric. The granularity of the inspection that users can perform with Theseus is at the function level. However, *fondue* was built to capture all information about control flow, so its data model supports generic trace points called *nodes*. Functions, conditional branches, loops, and individual expressions can be captured as node objects.

An "invocation" is an object representing the execution of a node. Just before evaluation of a function, branch, or expression, an invocation with a pointer to that code's node is placed onto a global stack and connected to the invocation on the stack above it, forming the call graph. The invocation is removed from the stack when evaluation of the function, branch, or expression completes.

Each node consists of

1. a unique identifier (which, for debugging purposes, includes the file path and position in the file),
2. its type (function, branch, etc.),
3. the path to its containing file, and
4. its position in the file as a pair of line/column coordinates for its starting and

Example JavaScript	**Generated Function Name**
function foo() { }	foo
(function foo() { })	foo
var foo = function () { }	foo
{ foo: function () { } }	foo
var bar = { foo: function () { } }	bar.foo
Bar.prototype = { foo: function () { } }	Bar.foo
Bar.prototype.foo = function () { }	Bar.foo
obj.on('event', function () { })	('event' handler)
setTimeout(function () { }, 100)	(timer handler (100ms))
setTimeout(function () { }, expr)	(timer handler)
bar(function () { })	('bar' callback)
baz.bar(..., function () { }, ...)	('bar' callback)

Table 4.1: fondue's JavaScript function naming convention. fondue assigns these human-readable names to functions as it walks the AST.

ending characters.

Nodes representing function definitions are also given names, which are generated according to the patterns represented in Table 4.1.

Since the unique identifiers given to each node are based on the file path and position in the file, they are subject to change due to irrelevant changes to the file. Since the active query is represented as a set of `nodeIds`, the query often needs to be reset after a file is saved. It would be better if the identifier were based on higher level properties of the code that wouldn't change due to irrelevant edits. Chrome's code replacement algorithm uses features like the number of arguments and the variables in the closure in order to find a mapping between code that is loaded in the VM and the code that it is being replaced with. It would also be useful for the editor to be able to deal with the file being opened after edits were made and stuff moved around, but the running program sends node information that is out of date with regard to where things are in the text.

4.1.2 Source Code Transformations

To collect information about how a block of code executes, *fondue* wraps it with code that traces how control flow arrived, passed through, and exited the block. The details are different depending on the type of node. The following two sections show how it works for function definitions, function calls, as they are the most intricate. Instrumenting branches works like instrumenting function definitions, and instrumenting expressions works like instrumenting function calls, so the details for those have been omitted. The third section shows how function creation is used to add asynchronous edges to the call graph.

Function Definitions

To capture the run-time call graph, *fondue* adds calls to a `tracer` object upon function entry and exit. To demonstrate, here is a simple JavaScript function definition:

```
function foo(a, b) {
    var c = a + b;
    return c;
}
```

fondue's transformation will add a call to `tracer.traceEnter()` to the beginning of the function's body, passing along a unique identifier for the function, an object containing the values of all the named arguments, a copy of the entire `arguments` array, and a reference to the function's call context (`this`). The original function body will be wrapped in a `try` block to capture any exceptions. If an exception is thrown, `tracer.traceExceptionThrown()` is called with a reference to all local variables (including function arguments) and the exception, then the exception will be re-thrown. If the function exits without a `return` statement, `tracer.traceExit()` will be called with a reference to all local variables. Any `return` statements in the function body are rewritten to pass the returned value to `tracer.traceReturnValue()` first.

This is what the code looks like after being processed:

```
function foo(a, b) {
    tracer.traceEnter({
        "nodeId": "/Users/tom/src/fondue/x.js-1-0-4-1",
        vars: { a: a, b: b },
        arguments: Array.prototype.slice.apply(arguments),
        this: this
    });
    try {
        var c = a + b;
        return tracer.traceReturnValue(c);
    } catch (e) {
        tracer.traceExceptionThrown({
            "nodeId": "/Users/tom/src/fondue/x.js-1-0-4-1",
            vars: { "a" : a, "b" : b, c: c }
        }, e);
        throw e;
    } finally {;
        tracer.traceExit({
            "nodeId": "/Users/tom/src/fondue/x.js-1-0-4-1",
            vars: { a: a, b: b, c: c }
        });
    }
}
```

The `nodeId` is only passed to `tracer.traceExceptionThrown()` and `tracer.traceExit()` for sanity checking. It could otherwise be derived by checking the top invocation on the stack.

Function Calls

Theseus also remembers the call site from which a function was called. For example, in this function, `bar()` is called two times and `baz.bar` called once:

```
function foo(a, b) {
    bar(a);
    bar(b);
    baz.bar(a + b);
}
```

fondue would know which invocation of `bar` was generated from which call site due to the transformation it performs on each function call. Instead of calling the function directly, the code will be rewritten to pass the function pointer to `tracer.traceFunCall()` along with a `nodeId` representing the call site. When the function has a context assigned (`baz.bar` above is executed in the `baz` context), that object is passed as well. The function body above would change to look like this:

```
tracer.traceFunCall({
    func: bar,
    nodeId: "/Users/tom/src/fondue/x.js-2-1-2-7"
})(a);
tracer.traceFunCall({
    func: bar,
    nodeId: "/Users/tom/src/fondue/x.js-3-1-3-7"
})(b);
tracer.traceFunCall({
    this: baz,
    property: "bar",
    nodeId: "/Users/tom/src/fondue/x.js-4-1-4-15"
})(a + b);
```

`tracer.traceFunCall` would push an invocation for the call site's node onto the stack, then call the function, setting its context explicitly if a value for `this` is provided.

Function Creation

Event callbacks are usually registered in JavaScript by providing a reference to a callback function. Often the callback functions are defined inline, as in this example that displays an alert after 1 second. The callback function is passed as the first argument to `setTimeout`:

```
function foo() {
    setTimeout(function () {
        alert('done!');
    }, 1000);
}
```

fondue will connect invocations of the callback function to the invocation of `foo` in which the callback function was created. That information is captured by wrapping all function expressions in calls to `tracer.traceFunCreate` like this:

```
tracer.traceFunCreate(function () {
    // this function body would also be instrumented
    alert('done!');
})
```

At run-time, `tracer.traceFunCreate` copies a reference to the invocation that is currently on top of the stack (the caller) and returns a shim containing a reference to the parent function and the callback function in its closure. When the shim is called, it saves a reference to the original parent invocation in `tracer`, then calls the original callback function. `tracer.traceEnter` will see the asynchronous caller and add an edge to it in the call graph in addition to the invocation that is on top of the stack.

4.1.3 Capturing Variable Values

fondue's call graph must store any values that the user might want to inspect later, such as function arguments and return values. Since JavaScript objects are mutable, if *fondue* stored only a reference, then the log entries generated after a mutation would reflect the new state of the object instead of the state at the time of the original invocation. To cope with that problem, *fondue* generates a shallow copy of all objects that it stores in the call graph. Creating copies is an expensive operation so the copies are only one level deep. If the user requests to inspect a nested object reference in Theseus, they are shown an error message. We are investigating ways to bypass this restriction.

4.1.4 Accessing the Trace

`tracer` offers a handful of public methods for accessing the trace data:

- `trackNodes()`, `newNodes(handle)`
- `trackHits()`, `hitCountDeltas(handle)`
- `trackLogs(query)`, `logDelta(handle)`
- `backtrace(invocationId, range)`

These methods accept and return plain JavaScript objects (objects containing only primitive data types that can be natively serialized) so that the arguments and return values can be easily transmitted as JSON (JavaScript Object Notation, the most convenient serialization format for JavaScript objects).

Since Theseus updates most information in real-time, the API is designed around a cursor design pattern: the `track*` functions return handles which can be used to periodically request updated information. As soon as a handle is created, `tracer` searches the execution history for all the information that satisfies the query that has been generated so far. From then on, information is added to the result set as the program runs. That results in overhead during execution proportional to the number of active handles, but allows every request for updated information to be satisfied by sending the data that has been saved so far and clearing the data associated with that handle. By default, Theseus polls these API functions 10 times per second to update the user interface.

`trackNodes()` & `newNodes(handle)` are used for retrieving information about all the nodes (functions, call sites, etc.) that exist in the instrumented program. Theseus uses this information to color dead code and place call counts. `trackHits()` & `hitCountDeltas(handle)` are used for retrieving the number of times that functions have been called. The data is returned as an object whose keys are `nodeIds` and the values are the number of times that the node has been reached since the last call to `hitCountDeltas()`.

`trackLogs(query)` is the first function that accepts options, namely the list of `nodeIds` for which to retrieve log entries. Every time the user changes the active query by clicking the call count next to a function definition, Theseus releases the old log handle (if there was one) and calls `trackLogs()` with the new set of `nodeIds`. `logDelta()` returns enough information to construct the log described in the previous chapter: a unique identifier for the invocation, the identifier for the parent invocation (if there was one and it is also in the query) the unique identifier of the node, the time at which the invocation occurred, and for functions, the arguments, return value, thrown exception, and context, if they are present. The log entries are always sent in chronological order.

`backtrace` returns an array of the nodes in a backtrace for the given invocation identifier. Backtraces cannot change over time, so this function does not return a handle.

4.2 Debugging with Theseus

4.2.1 Node.js

Users launch their scripts with the `node-theseus` command-line tool instead of with `node` directly. The `node-theseus` wrapper adds a hook to the Node.js module loading system to process all included JavaScript files with the *fondue* library as they are loaded.

`node-theseus` also listens for WebSocket[2] connections, which the editor extension periodically attempts to establish. When a connection is established, the editor sends requests consisting of the name of one of the `tracer` functions (`trackNodes`, `trackHits`, etc) and an array of the arguments to pass to that function. `node-theseus` invokes the function with those arguments and sends the result back. Data is serialized over the connection as JSON.

4.2.2 Chrome

The Theseus extension for Brackets comes bundled with an HTTP proxy server that rewrites the JavaScript contained on any page with *fondue*. It has two modes of operation. In one mode, the server serves a directory of static files from the user's computer. In the other mode, Theseus redirects all requests to another HTTP server running at a fixed address and port. Client and server can be debugged with the same Theseus instance by running the server with `node-theseus` and using the HTTP request forwarding mode to view the instrumented web page in Chrome.

The Brackets editor has a feature called Live Development, which uses Chrome's Remote Debugging API[3] to connect to an open tab so that changes to CSS that users make in the editor are reflected immediately in the browser, among other live coding features. The Remote Debugging API also supports features for opening a debugging connection to the page's JavaScript virtual machine. Theseus uses the ability to evaluate JavaScript expressions and retrieves the result to communicate with the global `tracer` object inserted onto the page by the proxy server.

[2]`http://dev.w3.org/html5/websockets/`

[3]`https://developers.google.com/chrome-developer-tools/docs/debugger-protocol`

Chapter 5

Evaluation

Theseus was developed as a series of prototypes over the course of a year, beginning at Adobe during the summer of 2012, and then at MIT for the following academic year. Theseus was designed iteratively using feedback from pilot tests and its design varied wildly during the first few months. In the spring of 2013, Theseus finally reached a level of maturity such that it became worthwhile to perform a more in-depth studies.

This chapter describes a lab study and a classroom study that we performed on the latest version of the software that has been presented in this thesis.

5.1 Lab Study

We conducted a lab study in order to answer several questions about how JavaScript programmers would use and perceive the utility of Theseus, and to determine whether Theseus could serve as an adequate replacement. Specifically, the study was designed to shed light on the five questions listed below. The first three questions concern the ways in which we think Theseus would make programmers more efficient:

RQ1. How would programmers find correspondences between code and program behavior with Theseus?

RQ2. How would programmers use Theseus to find where chains of callbacks break down?

RQ3. Would programmers use Theseus' structured log sort through tangled control flow problems?

The answer to the fourth question would shed light on what information Theseus should show by default in the log:

RQ4. How frequently do users inspect local variables, closure variables, and global variables?

5.1.1 Methods

We recruited 7 participants to a 90-minute lab study in which they completed programming tasks for $30 in compensation. The participants were all male undergraduate and graduate students of MIT. We screened the participants for JavaScript ability using a questionnaire whose results are shown in Table 5.1. During the study, the subjects were given 5 programming tasks: two 20-minute tasks and three 5-minute tasks. To facilitate within-subjects comparison, each participant was assigned to the Theseus or control condition for each task independently (but always with 2 tasks in one condition and 3 in the other). Subjects completed all of their control tasks first (using Chrome Developer Tools), then all of the Theseus tasks (during which most Chrome Developer Tools were disallowed[1]).

Participants completed the tasks on a provided MacBook Pro laptop with an external mouse in addition to the built-in trackpad. The screen was recorded, but not audio. Participants were asked to think aloud during the 20-minute programming tasks, but told to work as quickly as possible without worrying about communicating their thoughts during the 5-minute tasks.

The five tasks were as follows:

T1: Canvas Painter (20 minutes). Subjects were given the static HTML source code for a browser-based drawing site[2] with approximately 2,000 lines of JavaScript

[1]Users were allowed to use the DOM inspector and network request inspector, but not the breakpoint debugger or console, the tools Theseus is meant to replace.

[2]`http://caimansys.com/painter/` Accessed 2013-05-19.

Subject	Age	Gender	Programming Ability	JavaScript Ability	Freq. of JavaScript Use
S1	24	M	••●••	••••●	Daily
S2	23	M	••●••	•••●•	Daily
S3	20	M	••●••	••●••	Few days/wk.
S4	29	M	••••●	•••●•	Few days/wk.
S5	24	M	••••●	•••●•	Few days/mo.
S6	21	M	••••●	••●••	Few days/mo.
S7	39	M	••••●	••●••	Not recently

Table 5.1: Lab study pre-survey questionnaire. Programming Ability and JavaScript Ability are on a 5-point scale, with 1 labeled "Novice" and 5 labeled "Expert".

spread across 8 files. The line drawing tool required users to click and hold the mouse to draw lines. Participants were asked to change the program so that users could draw lines by clicking once at the start point and again at the end point of the line. As a painting application, Canvas Painter's event handling code was complex and the drawing logic spread across multiple files, making this task an appropriate test for RQ1.

T2: du (20 minutes). Subjects were given the skeleton for a Node.js command-line tool for calculating the total size of all files in a directory. The straight-forward implementation (calling du recursively for sub-directories) results in a thick web of callbacks that are very difficult to understand using breakpoints or log statements, making this task an appropriate test for RQ3.

T3: Laggy AJAX UI (5 minutes). Subjects were given an HTML file containing 25 lines of JavaScript that downloaded JSON from the server and displayed it in a popup. Subjects were asked to determine why it took so long for the popup to appear after clicking a button. The problem was a hard-coded delay in the server before it would deliver a response. We anticipated that being able to watch the code coloring change as the code executed with Theseus might allow users to quickly narrow down the asynchronous step that took the most time, addressing RQ2.

T4: Real-Time Chat (5 minutes). Subjects were given the code for the server (33 lines of Node.js) and client (31 lines of JavaScript on a web page) of a real-time chat site. The page was opened in two tabs and subjects were asked why messages from one tab did not appear in the other. The problem was that the name of the message used to transmit chat messages was different on the sending end from the receiving end, testing RQ2.

T5: Faulty Auto-Complete (5 minutes). Subjects were given the code for both the server (80 lines of Node.js) and client (63-line HTML file that was mostly JavaScript) of page that showed auto-completed search results from an address book. Subjects were asked why the results never displayed. The problem was a logic error on the client while processing the results. Most of the client code, where the error resided, was written inside one long function so that participants would be unable to inspect the offending variables with Theseus (which only allows inspecting parameters and return values). The breakdown of the event chain from the button click, to querying the server, to processing the results, to displaying the results, again tested RQ2.

The source code provided to the participants for tasks T2–T5 can be found in Appendix A.

We asked participants to use the Chrome Developer Tools in the control condition regardless of their usual programming environment. To determine whether this affected their usual debugging strategies, we asked "What would you have done differently to solve those problems if you were on your own computer?" after they completed the control condition tasks.

Logging Interface Actions

To answer RQ4, and to have a succinct summary of how each subject completed each task, the observer manually recorded all of the debugging-related user interface actions that the participants performed in both the control and experimental conditions. Some of the commands were common to both environments (editing the source code, adding a call to `console.log()`, etc.), but some were specific to Chrome Developer Tools and Theseus. Care was taken to choose actions that could be reliably counted by an observer. The complete list of user actions we recorded follows. First, the actions common to both experimental conditions:

Edit. The subject made a change to the source code. Consecutive editing actions were counted as a single action. Editing actions that counted as another type of action such as **+Log** were not counted as an **Edit** action.

Reload. The subject reloaded the web page or re-ran the Node.js script. The observer noted whether the action seemed to be performed to reset Theseus' call counts or to restore Theseus' connection to the browser.

+Log. The subject added a call to `console.log()`, which is the JavaScript logging statement. The observer noted the type of information that was printed from this list: 'got here' or equivalent, the current time, the arguments to a function, a local variable, the return value of a function call, 'this', a closure variable, a global variable, an object's property, or an array element. The number of times each of these types of logged expressions was tallied in order to answer RQ4. When a single log statement included expressions that fell into multiple categories (for example, a property of a global object), they were all counted.

Modify Log. The subject modified the arguments to a call to `console.log()`. The modified argument was tallied again according to the criteria described above.

–Log. The subject removed a call to `console.log()` from the code.

Inspect. The subject inspected the properties of an object or array. Given the difficulty of determining what the subject is reading in a log window or a debugging panel, this action was only counted when the subject expanded an object or array to see its constituent properties or items.

Some of the actions could only be performed in the control condition with the Chrome Developer Tools:

+Breakpoint. The subject added a breakpoint.

–Breakpoint. The subject removed a breakpoint.

Step. The subject used a step command in the debugger, such as "Step" or "Continue".

Finally, some actions could only be performed with Theseus:

+Pill. The subject added a function to the active Theseus query.

–Pill. The subject removed a function from the active Theseus query.

Backtrace. The subject viewed the backtrace of an entry in the log.

Watch counts. The subject watched the call counts and reachability coloring update as they interacted with the web page or Node.js script.

Post-Study Survey

At the conclusion of the study, we verbally asked five questions regarding their opinion of Theseus. The first two were open-ended:

1. What were the biggest differences between how you debugged with Theseus than you normally debug, if any?
2. What did you find Theseus most useful for? Least useful for?

The following three questions asked for opinions on a 5-point scale, though participants given the opportunity to clarify their responses with further discussion:

1. Did you find Theseus easy-to-use? (1: Very difficult, 3: Neutral, 5: Very Easy)
2. How likely would you be to use Theseus outside of this study? (1: Not at all likely, 3: Neutral, 5: Very Likely)
3. How likely would you be to recommend Theseus to a friend? (1: Very Unlikely, 3: Neutral, 5: Very Likely)

Subject	T1	T2	T3	T4	T5	Ease of Use	Would Use	Would Recommend
S2	•	🟦 •	🟦 Y	Y	🟦 Y	•••●•	●••••	●••••
S7	🟦 •	•	Y	•	🟦 Y	••●••	••●••	••••●
S5	🟦 •	•	Y	🟦 Y	Y	•••●•	••●••	••••●
S1	🟦 •	•	🟦 Y	Y	•	•••●•	•••●•	•••●•
S6	•	🟦 •	Y	🟦 •	🟦 •	••••●	••••●	•••●•
S3	Y	🟦 ?	🟦 Y	🟦 •	Y	•••●•	••••●	••••●
S4	Y	🟦 Y	🟦 Y	🟦 Y	Y	•••●•	••••●	••••●

Table 5.2: Summary of study results. The cells in the columns labeled T1–T5 contain 'Y' if the subject successfully completed the task. The cells are shaded blue if the task was completed with Theseus. The correctness of S3's solution for task T2 was unclear, so that cell contains a question mark.

5.1.2 Results

The results of the study are summarized in Table 5.2. Most participants could not complete the 20-minute tasks (T1–T2), but everyone completed at least one of the 5-minute tasks (T3–T5), and all but one participant completed at a majority of the 5-minute tasks. Because of the small number of participants, we were unable to establish any statistically significant relationships between participants' success rates and the tools they used. A chi-squared test found no relationship between using Theseus and the participant's ability to complete the tasks successfully ($\chi^2(1, N = 34) = .119, p = 0.73$). All participants but one claimed that they found Theseus easy to use and that they would be likely to use or recommend Theseus. However, the questions were asked verbally (which may have skewed responses to be more favorable), and many participants qualified their answers in ways that will be discussed in the section on the exit survey below.

One problem that undermined our ability to generalize the behaviors of the 7 subjects was that they demonstrated very different programming styles. If we examine

Table 5.4 for the actions we observed users taking as they tackled T1, we see that the four participants in the control condition exhibited four different debugging styles. S2 used no debugging tools except for one log statement at the very end; S3 used breakpoints as reachability tests for functions; S4 used breakpoints to step through and inspect variables; and S6 only inspected values with log statements. In the following sections, we will use observations of individual programmers to discuss each research question in turn.

RQ1: How might programmers find correspondences between code and program behavior with Theseus?

Participants frequently sought code correspondences using Theseus by keeping the call counts and code coloring on the screen as they interacted with the program they were working on. They were pleased with how much information they could absorb this way, an experience S1 described like this: "[Theseus] feels really interactive. [As opposed to breakpoints], it's more of a 'watch and see what happens' thing, which I like."

We recorded instances of the **Watch Counts** action in Tables 5.4—5.7. We did not observe any instances during T2 or T5, likely because T2 involved writing a non-interactive command-line tool and the problem in T5 resided in the logic of a single function, making it effectively invisible to Theseus. However, during T1, S1 and S3 used the **Watch Counts** strategy 6 and 3 times respectively at various times during the 20-minutes. 4 of the 6 participants used **Watch Counts** strategy during T3 and T4. The only participants who did not use **Watch Counts** strategy on T3 and T4 were S2 and S4. This may have been because they spent their first 20 minutes with Theseus working on T2, the non-interactive command-line tool.

There was some disagreement about whether the call counts were useful for finding correspondences when the user had no idea where to begin. S5 said, "how the call counts changed live when I interacted with the application ... was especially useful for Canvas Painter because it was a lot of source code and I didn't really know where to start." Their prediction of whether they would use Theseus outside the study (on a 5-point scale) depended on the size of the project: 4/5 if the code base is large, but only 1/5 if the code base is small. S1 had the opposite opinion, stating, "I felt like it was the least useful when I wasn't sure where the problem was. So in the canvas thing, I didn't know where the issue was, and there's not much of a global scope with Theseus. ... When I didn't know where to start, there was no way to find a global call stack and identify candidate starting points. ... [In short, Theseus is] more useful on a narrow scope, less useful on a global scope."

Participants were interested in the time at which the call counts changed if they were interacting with their application, but also the total number. A changing call count could alert the programmer to surprising or revealing information, such as when S3 watched the call counts during the T1 task. At one point, S3 thought aloud, "I get 2 mouse up actions [every time I click]. Huh." Then while watching the call counts and clicking a second time, they exclaimed, "Aha!" as the nature of the problem became more clear. S5 noted that they had become fixated on a handful of functions while trying to narrow down the location of some strange behavior because "it seems weird to me that I get 2 mouse ups every time I click, while I only get 1 mouse down. ... I'd expect the call counts to be the same for both of them, but they're not." S4 and S6 also used the fact that a function was called 17 times as verification that it was being called once for each file in the directory during T2, since they had checked that there were 17 files.

The call counts also turned out to be useful for verifying that a code change had had the desired effect. In S4's case, the fact that their change caused a function to be called a different number of times was encouraging. The call count seemed a reliable enough proxy for checking that the new behavior was correct that they performed no further tests.

RQ2: How might programmers use Theseus to find where chains of callbacks break down?

The problem of finding where chains of callbacks breakdown is an important subset of the problem of finding code correspondences. In JavaScript, functions typically cannot block, forcing the programmer to split computations into multiple functions with no guarantee that control will flow successfully from one function to the other.

We noted several points during the study when participants using Theseus were able to quickly (in some cases, immediately) locate the location of a broken call chain based on the code coloring and call counts. In one instance, S4 opened a source file and was immediately drawn to a network event handler that had never been called, becoming suspicious because it looked like a handler which should have fired several times had the page been working correctly. This was in contrast to S3's experience using a breakpoint debugger, in which they set breakpoints and reloaded the page 3 times before they finally guessed correctly about how much of the code had actually executed.

RQ3: Would programmers use Theseus' structured log sort through tangled control flow problems?

S4 named this as Theseus' most useful feature, saying that Theseus is most useful for "if you have recursion problems," referring to task T2 in which his solution involved recursive asynchronous operations. S3 dubbed the pills "automatic silent breakpoints" whose results he could "scroll through like a tree." S1 compared the log to typical `console.log`, saying, "[Theseus] is a lot more focused ... with `console.logs` it's global. ... [With Theseus] you can pick the scope you wanna look at on the fly." S4 summarized his opinion of the log like this:

> "It gives you what you would do if you were really careful and did console.log every function. Yeah, so I didn't have to console.log. This saves at least one or two iterations if the first thing you log is really the thing you need. If you need to go through and look more, then this can save a lot more iterations. ... This should be in Chrome. ... This should be in every JavaScript debugger. This is very useful."

S4 would often click the pills for several functions at once, saying, "all the time, the thing that I wanted to do first is select all the functions and then see the whole tree." Showing the asynchronous call tree for all the functions of interest in the file helped him to locate the points of interest. He cited the lack of a 'Select All Pills in File' command as the reason he rated Theseus' ease of use as 4/5 instead of 5/5. S6 felt similarly similarly, at one point saying aloud, "These are the four functions that are interacting," and without pausing, enabling the pills for those four functions to see how they related.

RQ4: How frequently do users inspect local variables, closure variables, and global variables?

Figure 5-1 summarizes the data we collected about the types of inspections that users performed *without* Theseus. There were only seven participants, and the numbers are conditioned on the tasks that the users performed, so we cannot claim that this distribution will hold universally. No participants were observed inspecting the values of global variables or the values of variables that were defined outside of the current scope (closure variables), but it certainly does happen. It's worth noting that 8 of the logged function call return values were invocations of `toString()` which were not necessary because `console.log` would have displayed the value anyway. Even so, most types of values that participants were interested in inspecting would have been available in Theseus' default log view.

Nearly all of the instances in the study where someone added log statements in the Theseus condition (4 total) were in order to inspect one of the types of values that are not automatically visible in Theseus. Extending the log to inspect intermediate values such as local variables and the values of expressions is discussed in Chapter 6, Conclusions & Future Work.

Usability Issues

As any good study of research software does, this study uncovered a laundry list of small bugs and usability snafus. Most of them are too mundane to mention here, but the following are significant enough to be guiding our continued research into debugging interfaces.

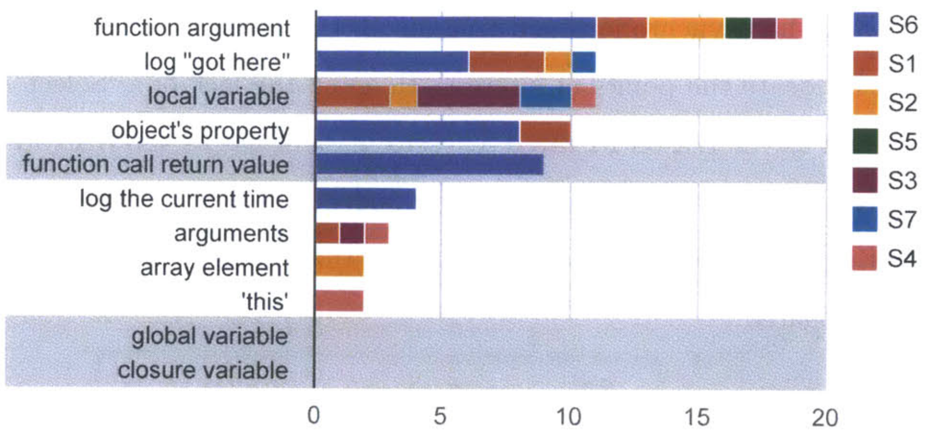


Figure 5-1: Types of values programmers inspect while using Chrome Developer Tools, using its breakpoint debugger and console (via `console.log`*). Information which is not visible by default in Theseus' log is shown with a gray background.*

One subject, S2, pointed out that the screen recording software from the study had slowed down the interface enough that he had become reluctant to perform more interface actions than necessary. No other subjects pointed this out, but it may have affected their behavior as well.

The **Refresh** action was given superscripts in Tables 5.4—5.7 in the cases when the participants refreshed the page or restarted the program solely in order to reset the call counts in the editor to zero. Several participants complained that the counts could not be reset from within the editor.

Watching a call count change requires some amount of working memory, especially when the user is tracking multiple counts simultaneously. S6 once read three call counts aloud to help remember their values over time as he interacted with page ("3 3 6, 4 4 8..."). A better interface would, in essence, remember those values for them, or take advantage of the fact that sometimes the changes are more important than the absolute values. S1 had a related problem, which is that the functions they were interested in tracking were not defined in the same part of the same file and wanted some way to collect their call count information into one location.

Several participants asked for a way to list the callers and callees of a function, but Theseus cannot yet do that.

Task T1: Canvas Painter

Without Theseus				With Theseus		
S2	**S3**	**S4**	**S6**	**S1**	**S5**	**S7**
edit	+breakpoint	+breakpoint	+log	refresh	+pill	edit
refresh	miss breakpoint	hit breakpoint	refresh	refresh^1	backtrace	out of time
edit	+breakpoint	step	mod. log	watch counts	refresh^2	
refresh	miss breakpoint	step	refresh	refresh^1	watch counts	
edit	hit breakpoint	step	mod. log	refresh^2	refresh^1	
refresh	+breakpoint	step	+log	watch counts	+pill	
edit	edit	step	+log	+pill	backtrace	
refresh	refresh	step	refresh	+pill	jump to function	
edit	hit breakpoint	step	+log	refresh^1	backtrace	
refresh	edit	step	+log	watch counts	backtrace	
edit	refresh	hit breakpoint	+log	refresh^1	watch counts	
refresh	hit breakpoint	step	–log	watch counts	edit	
+log	refresh	–breakpoint	–log	refresh	refresh	
refresh	hit breakpoint	+breakpoint	refresh	refresh^2	watch counts	
out of time	–breakpoint	hit breakpoint	mod. log	+pill	+pill	
	success	step	refresh	+pill	backtrace	
		step	+log	–pill	out of time	
		step	refresh	+pill		
		step	out of time	+pill		
		step		+pill		
		step		backtrace		
		step		+pill		
		step		+pill		
		inspect		+pill		
		inspect		–pill		
		–breakpoint		backtrace		
		edit		+pill		
		refresh		refresh^1		
		edit		watch counts		
		refresh		+pill		
		edit		+pill		
		refresh		watch counts		
		edit		refresh^1		
		refresh		refresh^1		
		edit		edit		
		refresh		refresh		
		success		edit		
				refresh^1		
				edit		
				refresh		
				edit		
				refresh		
				out of time		

Table 5.3: Actions performed by users during the Canvas Painter 20-minute task. refresh^1 indicates a refresh that was performed primarily to reset the call counts back to zero. refresh^2 indicates a refresh that occurred because a bug in Theseus caused the Chrome tab to crash.

Task T2: du

Without Theseus			With Theseus		
S1	**S5**	**S7**	**S2**	**S4**	**S6**
edit	edit	+log	edit	edit	edit
+log	refresh	refresh	refresh	+log	refresh
refresh	edit	−log	edit	edit	edit
edit	refresh	refresh	refresh	refresh	refresh
+log	edit	edit	edit	+pill	+pill
refresh	refresh	refresh	refresh	edit	+pill
edit	edit	edit	+pill	refresh	−pill
refresh	refresh	+log	inspect	edit	+pill
refresh	refresh	refresh	edit	refresh	−pill
+log	+breakpoint	edit	refresh	+pill	+pill
+log	step	+log	+pill	edit	−pill
refresh	step	refresh	edit	+pill	+pill
edit	step	edit	refresh	edit	−pill
refresh	edit	out of time	+pill	refresh	inspect
edit	refresh		+pill	+pill	+log
refresh	edit		edit	+pill	refresh
edit	out of time		refresh	+pill	edit
refresh			+pill	refresh	refresh
edit			inspect	+pill	+log
refresh			+pill	−pill	refresh
edit			inspect	+pill	+pill
refresh			edit	edit	edit
out of time			refresh	+pill	refresh
			+pill	+pill	out of time
			+pill	+pill	
			−pill	refresh	
			inspect	edit	
			edit	refresh	
			refresh	edit	
			refresh	refresh	
			edit	+pill	
			refresh	+pill	
			edit	edit	
			refresh	refresh	
			+pill	+pill	
			−pill	success	
			+pill		
			inspect		
			+log		
			−pill		
			refresh		
			+log		
			refresh		
			+pill		
			out of time		

Table 5.4: Actions performed by users during the du *20-minute task. refresh^1 indicates a refresh that was performed primarily to reset the call counts back to zero. refresh^2 indicates a refresh that occurred because a bug in Theseus caused the Chrome tab to crash.*

Task T3: Laggy AJAX UI

Without Theseus			With Theseus			
S5	**S6**	**S7**	**S1**	**S2**	**S3**	**S4**
success	+log	edit	watch counts	success	watch counts	+pill
	+log	refresh	+pill		edit	+pill
	+log	edit	+pill		+pill	+pill
	+log	network timeline	+pill		backtrace	+pill
	refresh	success	−pill		edit	+pill
	success		+pill		+pill	jump to function
			success		success	success

Table 5.5: *Actions performed by users during the Laggy AJAX UI 5-minute task.*

Task T4: Chat

Without Theseus			With Theseus			
S1	**S2**	**S7**	**S3**	**S4**	**S5**	**S6**
network timeline	+log	out of time	watch counts	+pill	success	watch counts
+log	refresh		edit	inspect		watch counts
refresh	success		refresh	inspect		+pill
+log			out of time	edit		+pill
refresh				refresh		+pill
+log				success		+pill
refresh						backtrace
+log						out of time
refresh						
+log						
refresh						
refresh						
edit						
refresh						
success						

Table 5.6: *Actions performed by users during the Chat 5-minute task. refresh^1 indicates a refresh that was performed primarily to reset the call counts back to zero. refresh^2 indicates a refresh that occurred because a bug in Theseus caused the Chrome tab to crash.*

Task T5: Name Directory

Without Theseus				With Theseus		
S1	**S3**	**S4**	**S5**	**S2**	**S6**	**S7**
network timeline	+log	+log	success	edit	+pill	refresh[1]
+log	refresh	refresh		refresh	refresh[1]	success
+log	inspect	edit		success	+pill	
refresh	+log	refresh			refresh[1]	
network timeline	inspect	success			+pill	
edit	edit				+pill	
+log	refresh				refresh[1]	
refresh	+log				+pill	
+log	edit				refresh	
refresh	refresh				refresh	
inspect	inspect				+pill	
inspect	success				refresh[1]	
edit					+pill	
out of time					−pill	
					+pill	
					out of time	

Table 5.7: Actions performed by users during the Name Directory 5-minute task. refresh[1] indicates a refresh that was performed primarily to reset the call counts back to zero.

5.2 Node.js Mini-Course

In order to observe programmers using Theseus in a more natural setting, I held a roughly 2-hour tutorial on Node.js for students of 6.813/6.831, User Interface Design and Implementation. Many of their final projects required a server component, so the tutorial was advertised as an opportunity to learn a server language that worked well for real-time web interfaces.

I prepared a 17-step introductory tutorial to Node.js. The first step described how to install Node.js, Google Chrome, the Brackets code editor, the Theseus extension for Brackets, and the `node-theseus` command-line tool for debugging Node.js programs with Theseus. Two of the remaining 16 steps described how to use Theseus (one for debugging Node.js servers and one for debugging JavaScript on a web page). The 14 remaining steps covered the following topics:

- Install Node.js and using the Node.js package manager
- Create a web server with the Express library, extending it with middleware
- Use socket.io for real-time client/server messaging
- Fetch JSON from the server using AJAX
- Store data in redis and PostgreSQL
- Password-protect a page using the Passport package

The tutorial began with a brief verbal introduction. A text file containing instructions for downloading the tutorial files and a link to an exit survey were projected on the screen with space for tips to accrue throughout the tutorial as the teaching assistants noticed recurring problems. Students could work at their own pace and leave at any time, whether they completed the materials or not. Using Theseus was encouraged as part of the introduction and by being featured prominently in the course materials, but was entirely optional.

The version of Theseus that was distributed to the students contained code that recorded basic editor actions, enough to get a sense of how they progressed through the tutorial, and how much they interacted with Theseus. Specifically, it reported when the user opened a file in Brackets so that it could detect when the tutorial files were opened, when Theseus connected to a Node.js or Chrome process for debugging, and when the user clicked call count pills to add or remove them from the query.

5.2.1 Observations

Approximately 30 students attended the tutorial and about 20 successfully installed all of the recommended software and ran the tutorial using Theseus. A summary of the students' interaction with Theseus is presented in Figure 5-2. Instead of following the progress of a few students closely, the facilitators assisted whichever students needed help, allowing us to paint a broad strokes picture of how Theseus worked in a classroom with many students.

Holding the tutorial taught three main lessons about Theseus. The first is that Theseus handles exceptions poorly. The extent to which Theseus calls attention to the presence of exceptional cases occurring in a program is showing exceptions in the log. That made them difficult to discover for many students. This is not a fundamental limitation of Theseus, just an engineering oversight.

The second lesson is that Theseus does not help students learn how asynchronous programming works. Experienced programmers understand how Theseus' asynchronous log works with very little instruction. They also quickly develop strategies to use the interface to solve problems with their code, as we saw in the lab study. However, students in the Node.js course who had little experience with JavaScript were not able to use Theseus to gain that knowledge. The experience helping students understand what went wrong with their tool highlighted the difference between tools like Whyline that attempt to explain to the user what's going on, tools that visualize what's going on, and tools like Theseus that are only useful for inspection. Tools in that final class are only helpful for people who have a good understanding of the system before they begin. They don't help programmers who don't yet have the model.

Thirdly, we learned that Theseus falls below the acceptable performance threshold of some students. According to the Brackets usage logs, 2 students disabled Theseus, at least one of whom reported doing so because restarting their application with Theseus took too long. Others may have simply stopped using Brackets or uninstalled the Theseus extension, neither of which would show up in the logs.

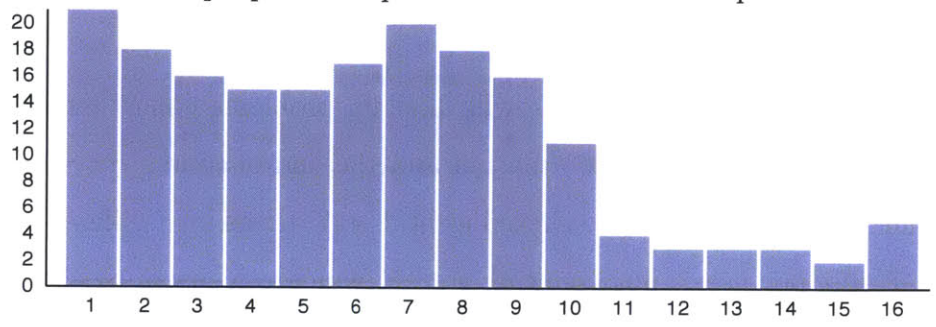
Since the instructors spent most of their time with the students who needed help, our information about the students who had no problems comes mostly from the automatically reported usage information and the end-of-course survey. The usage reporter indicates that pills were clicked a total of 35 times by 8 different users (min. 1, max. 7 pills per user), not counting step 5, which told users to click pills. The majority of the interactions took place during steps 8–10, when students were asked to piece together the client and server sides of a real-time chat site. The survey only received 6 responses, but in response to the question "What did you find Theseus most useful for? Least useful for?" students seemed to think that Theseus was useful (or theoretically useful):

- I didn't use it for that long, but I've ran into problems in Javascript with multiple event handlers firing more than once, or forgetting to unbind some event handlers. Theseus would be incredibly useful in that case.
- it was helpful for debugging! least useful....idk
- Most useful to see whether some code was getting executed. Sometimes it was difficult to actually understand the request/response object.

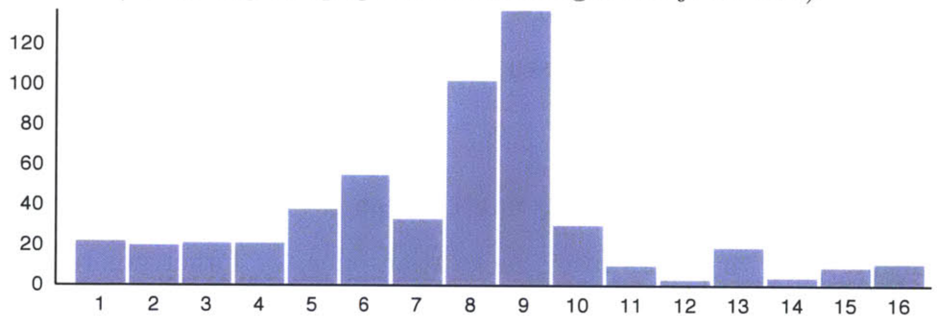
Our post-survey also asked, "How did you use Theseus to understand the code, if at all?" and the answers describe the types of activities we observed during the lab study:

1. To see which events got fired.
2. I looked at the count and log to see how the server and client were interacting.
3. I used it to see why something wasn't working - id go and check the call numbers next to the functions and those helped me find minor bugs
4. it helped me see when something was or was not getting executed

Total number of people who opened the file for each step of the tutorial:



Total Theseus debugging connections opened on each tutorial step by all users (refreshing the page and launching Node.js servers):



Total pill clicks on each tutorial step by all users:

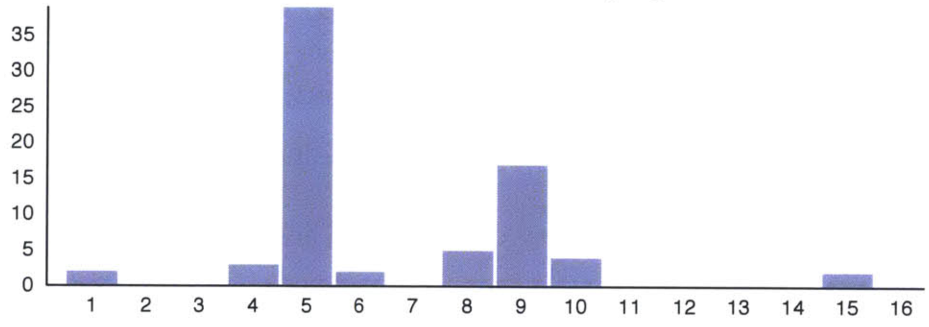


Figure 5-2: Node.js course activity. They were instructed to open each tutorial step in a way that caused a debugger connection to open, which is why the count is near 20 on steps 1–4, which come before they were introduced to Theseus. On step 5 the tutorial explicitly asked them to click pills to introduce Theseus. Step 8: connect with socket.io. Step 9: Send messages with socket.io. Step 10: send chat messages.

Tutorial Files Opened	Session Duration (minutes)	Pill Clicks
●○○○○○○○○○○○○○○○	0.0	0
●○○○○○○○○○○○○○○○	0.0	0
○○○○○●●○○○○○○○○○	0.4	0
●●○○○○○○○○○○○○○○	6.3	0
●●○○○○○○○○○○○○○○	9.1	0
●●●○●●●●●○○○○○○○	9.1	0
●●○○○○○○○○○○○○○○	12.7	0
●●●●●○○○○●○○○○○●	21.2	0
●●●●●○●○○○○○○○○○	23.1	0
●●●●●●●●○○○○○○○○	37.4	0
○○○○○●●●●●●○○○○○	37.8	0
●●●●●●●●●○○○○○○○	42.7	0
○○○○○○●●●●○○○○○●	44.9	0
●●●●●●●●●○○○○○○○	50.8	0
○○●○○●●●●●○○○○○○	54.3	2
●●●●●●●●○○○○○○○○	60.3	0
●●●●●●●●●●○○○○○○	62.7	0
●●●●●●●●●●○○○○○●	73.1	4
●●●●●●●●●○○○○○○○	77.0	0
●○○○○○●●●○○○○○○○	82.5	0
●●●●●●●●●●○○○○○○	86.7	7
●●●●●●●●●●●●●●○○	87.3	2
●●●●●●●●●○○○○○○○	89.9	5
●●●●●●●●●●●●●●●●	92.0	4
●●●●●●●●●●●●●●●●	108.2	5
○○○●○●●●●●○○○○○○	118.4	1

Table 5.8: Node.js course detailed activity summary. The duration is the difference between the time at which they first opened a file and the time at which they last opened a file. The number of pill clicks only counts those that occurred after *step 6, which asked users to click pills.*

5. just verified that stuff was called

When asked “What were the biggest differences between how you debugged with Theseus than you normally debug, if any?” respondents almost universally declared Theseus to have saved them from writing lots of print statements:

1. I didn’t have to place console.log statements in every event handler to figure out what got called.
2. Normally I would have written a lot of console.log statements to debug. But theseus allowed me debug without doing that.
3. it was a lot faster, since I typically type console.log statements to find out why and where things arent working - especially when there isnt an error thrown by the console
4. Didn’t have to add print statements everywhere
5. none

Chapter 6

Conclusions & Future Work

This thesis presented interfaces for displaying information about the run-time behavior of asynchronous code in the form of call counts, reachability coloring, and asynchronous call trees. Programmers in the presented studies liked Theseus and was able to use it with little training, solving programming tasks as well with Theseus as they did with established breakpoint debugging and logging tools. However, there are several research directions I plan to take which could make programmers even happier and more productive with their tools.

Theseus' scope is a single screen of code. Call counts and reachability coloring assume that the relevant code all appears on the screen at once. As some study participants noted, that is often insufficient. I believe that Theseus' visualizations may be useful if their scope were expanded to an entire file, or an entire project. Domain-specific knowledge of JavaScript such as whether code is executing as a result of a timer or a network request might be used to make navigating project-scale code coverage information feasible.

Theseus visualizes basic information about the past execution of their code inside the editor. As soon as the code changes, that information is invalidated because the program is now different. If we collected program traces that were complete enough to allow modified code to be executed inside a snapshot of past program states, programmers could be shown how their changes would have affected the execution of their program. Such a system could predict exceptions, or show how changes to conditionals affect what branches would have been taken, giving programmers immediate feedback that could prevent errors by visualizing potential program states. The same visualizations might be used for comparing the traces from multiple runs of the same code.

Theseus' log is simply an extension of call trees, with edges for asynchronous links, but such a visualization can only be used to answer *some* of the reachability questions programmers ask [14, 13]. Many of the remaining questions cannot be answered with Theseus because they are questions about classes of functions, such as all networking-related code. Showing all networking-related functions in Theseus' log would be overwhelming, so new approaches would be needed for a Theseus-like interface to work in those situations. Also, some reachability questions are unanswerable in Theseus because they concern *potential* situations, such as finding all possible ways that following a particular branch is possible. The Reacher tool, which uses static analysis, can answer many of those questions [15], but uses a completely different visualization from Theseus, and does not take advantage of run-time information to provide context. An extension of both interfaces seems desirable.

Theseus supports programmers in a variety of tasks simply by showing information in the right places, and providing an interface that makes investigating easy questions easy and investigating difficult questions possible. In the long term, I hope that this similar interfaces will eventually make understanding code possible for everyone.

Bibliography

[1] Brian Burg. Timelapse: Interactive Record/Replay for the Web. `http://homes.cs.washington.edu/~burg/projects/timelapse/research.html`.

[2] Christopher J. DiGiano, Ronald M. Baecker, and Russell N. Owen. Logomedia: a sound-enhanced programming environment for monitoring program behavior. In *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*, CHI '93, pages 301–302, New York, NY, USA, 1993. ACM.

[3] Paul V. Gestwicki and Bharat Jayaraman. JIVE: Java Interactive Visualization Environment. In *Companion to the 19th annual ACM SIGPLAN conference on Object-oriented programming systems, languages, and applications*, pages 226–227, Vancouver, BC, CANADA, 2004.

[4] Hani Z. Girgis and Bharat Jayaraman. JavaTA: A Logic-based Debugger for Java. In *16th Workshop on Logic-based Methods in Programming Environments*, 2006.

[5] Simon Goldsmith, Robert O'Callahan, and Alex Aiken. Relational Queries Over Program Traces. In *Proceedings of the 20th annual ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*, volume 40, pages 385–402, October 2005.

[6] Y.-G. Gueheneuc, R Douence, and N Jussien. No Java without caffeine: A tool for dynamic analysis of Java programs. In *Automated Software Engineering,*

2002. Proceedings. ASE 2002. 17th IEEE International Conference on, pages 117–126, 2002.

[7] Thorsten Karrer, Jan-Peter Krämer, Jonathan Diehl, Björn Hartmann, and Jan Borchers. Stacksplorer: Call Graph Navigation Helps Increasing Code Maintenance Efficiency. In *Proceedings of the ACM UIST 2011 Symposium on User Interface Software and Technology*, 2011.

[8] Jun Kato, Sean Mcdirmid, and Xiang Cao. DejaVu: Integrated Support for Developing Interactive Camera-Based Programs. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pages 189–196, 2012.

[9] MSI-Dr Andreas Kerren. Software visualization. *Journal of visual languages and computing*, 4(3):211–266, 1993.

[10] Andrew J Ko and Brad A Myers. Designing the Whyline: A Debugging Interface for Asking Questions about Program Behavior. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, volume 6, pages 151–158, 2004.

[11] Andrew J. Ko and Brad A. Myers. Debugging Reinvented: Asking and Answering Why and Why Not Questions about Program Behavior. *Human-Computer Interaction Institute*, pages 301–310, 2008.

[12] Jan-Peter Krämer, Joachim Kurz, Thorsten Karrer, and Jan Borchers. Blaze: Supporting Two-phased Call Graph Navigation in Source Code. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*, pages 2195–2200, 2012.

[13] Thomas D. LaToza. *Answering Reachability Questions.* PhD thesis, Carnegie Mellon University, 2012.

[14] Thomas D. LaToza and Brad A. Myers. Developers Ask Reachability Questions. In *2010 ACM IEEE 32nd International Conference on Software Engineering*, volume 1, page 185, New York, New York, USA, 2010. ACM Press.

[15] Thomas D. LaToza and Brad A. Myers. Visualizing Call Graphs. In *2011 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC)*, pages 117–124. Ieee, September 2011.

[16] Raimondas Lencevicius, Urs Hölzle, and Ambuj K. Singh. Query-Based Debugging of Object-Oriented Programs. In *Proceedings of the 12th ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*, pages 304–317, 1997.

[17] Henry Lieberman. A three-dimensional representation for program execution. In *Visual Languages, 1989., IEEE Workshop on*, pages 111–116. IEEE, 1989.

[18] Henry Lieberman. The Debugging Scandal and What to Do About It. *Communications of the ACM*, 40(4):26–29, 1997.

[19] Henry Lieberman and Christopher Fry. Bridging the Gulf Between Code and Behavior in Programming. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '95, pages 480–486, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co.

[20] Michael S. Meier, Kevan L. Miller, and Donald P. Pazel. Experiences with Building Distributed Debuggers. In *Proceedings of the SIGMETRICS symposium on Parallel and distributed tools*, pages 70–79, 1996.

[21] Microsoft. Debug Your App by Recording Code Execution with IntelliTrace. `http://msdn.microsoft.com/en-us/library/vstudio/dd264915.aspx`.

[22] Guillaume Pothier, Éric Tanter, and José Piquer. Scalable Omniscient Debugging. In *Proceedings of the 22nd annual ACM SIGPLAN conference on Object-oriented programming systems and applications*, volume 42, page 535, October 2007.

[23] Steven P. Reiss. Visualizing Program Execution Using User Abstractions. In *Proceedings of the 2006 ACM symposium on Software visualization*, volume 1, pages 125–134, 2006.

[24] Eric Schrock. Debugging AJAX in Production. *ACM Queue*, 2009.

[25] Jonathan Sillito, Gail C. Murphy, and Kris De Volder. Asking and Answering Questions during a Programming Change Task. *IEEE Transactions on Software Engineering*, 34(4):434–451, July 2008.

[26] Bret Victor. Learnable Programming. `http://worrydream.com/#!/LearnableProgramming`, 2012.

Appendix A

Source Code From the Lab Study

Participants were provided the following code for each of the lab study tasks.

A.1 Task T2: du

```
var fs = require('fs');

function du(path, callback) {
    callback(0);
}

du('./test-dir', function (size) {
    console.log('total size', size);
});
```

A.2 Task T3: Laggy AJAX UI

A.2.1 index.html

Some lines were wrapped to fit on the page.

```
<style>
```

```
body {
    background: #eee;
}
#popup {
  display: none;
  position: absolute;
  background: white;
  border-radius: 4px;
  padding: 8px;

  .name, .description {
    display: block;
  }

  .name {
    font-weight: bold;
  }
}
</style>
<h1>Home</h1>

<ul>
<li><a href="#" class="more-info" data-id="1">Shovel</a>
<li><a href="#" class="more-info" data-id="2">Basket</a>
</ul>

<div id="popup">
<span class="name"></span>
<span class="description"></span>
<span class="link"></span>
```

```
</div>

<script src="http://ajax.googleapis.com/ajax/libs/
jquery/1.7.2/jquery.min.js"></script>
<script src="main.js"></script>
```

A.2.2 main.js (included from index.html)

```
function fetchItemInfo(itemId, callback) {
  $.getJSON("/items/" + itemId, function (data) {
    callback(data);
  });
}

function popupItemInfo(x, y, info) {
  $("#popup").css({
    display: "inline-block",
    left: x,
    top: y
  });
  $("#popup .name").text(info.name);
  $("#popup .description").text(info.description);
  setTimeout(function () {
    $("#popup").hide();
  }, 4000);
}

$(document.body).on("click", ".more-info", function (e) {
  e.preventDefault();
  fetchItemInfo($(this).attr("data-id"), function (info) {
    popupItemInfo(e.pageX, e.pageY, info);
  });
});
```

A.3 Task T4: Real-Time Chat

A.3.1 app.js (Node.js server code)

```
var express = require('express')
  , app = express()
  , server = require('http').createServer(app)
  , io = require('socket.io').listen(server);

server.listen(3000);

app.use(express.static(__dirname + '/public'));

var messages = new Array()

Array.prototype.inject = function(element) {
    if (this.length >= 5) {
        this.shift()
    }
    this.push(element)
}

io.sockets.on('connection', function(socket) {
    socket.emit("init", JSON.stringify(messages));

    socket.on('msg', function(msg) {
        var message = JSON.parse(msg)
        messages.inject(message)

        socket.broadcast.emit('msg', msg)
    });

    socket.on('disconnect', function() {
    });
});
```

A.3.2 index.html

Some lines were wrapped to fit on the page.

```
<style>
#msgs {
  height: 300px;
  background: #f3f3ff;
  font-family: monospace, sans;
  overflow:auto;
}

.chat-title {
  color: white;
  background: #a2a2ee;
  font-weight: bold;
  font-size: 20px;
  height: 24px;
  padding: 2px;
}
</style>
<div>
    <p class="chat-title" onclick="javascript: toggleChat();">
```

```
        Real Time Chat</p>
    <div id="msgs"></div>
    <div id="form">
        <form id="chat" onsubmit="sendMsg(); return false;">
            <label for="username">Username: </label>
                <input name="username" type="text"><br/>
            <label for="msg"> Message: </label>
                <input id="msg" type="text" name="message"/><br/>
            <input type="submit"/>
        </form>
    </div>
</div>
<script type="text/javascript" src="http://ajax.googleapis.com/
ajax/libs/jquery/1.7.2/jquery.js"></script>
<script src="/socket.io/socket.io.js"></script>
<script src="main.js"></script>
```

A.3.3 main.js (included on index.html)

```
var socket = io.connect('http://localhost:3000');

socket.on('msg', function(data) {
    var msg = JSON.parse(data);
    appendMsg(msg);
});

socket.on('init', function(data) {
    var messages = JSON.parse(data)
    for (i in messages)
    appendMsg(messages[i])
});

function appendMsg(msg) {
    $('#msgs').append(function() {
        var div = $('<div>');
        div.html('<b>' + msg.username + ':</b> ' + msg.message);
        return div;
    });
    $('#msgs')[0].scrollTop = $('#msgs')[0].scrollHeight;
}

function sendMsg() {
    var msg = {};
    $.each($('#chat').serializeArray(), function(i,v) {
        msg[v.name] = v.value;
    });
    $("#msg").val("");
    appendMsg(msg);
    socket.emit('message', JSON.stringify(msg));
}
```

A.4 Task T5: Faulty Auto-Complete

A.4.1 app.js (Node.js server)

```
(function () {
    'use strict';

    var http = require('http');
    var connect = require('connect');
var url = require('url');

var host = '0.0.0.0';
var port = 3000;

var people = ["Amy Tobin", "Anthony Boling", "Olga Laine",
    "Harold Averett", "Melody Pettiford", "Vanessa Holloway",
    "Georgia Alfaro", "Jenny Hooper", "Sally Durden",
    "Jonathan Eubank", "Russell Owensby", "Michele Oconner",
    "Martin Overby", "Annie Slagle", "Gladys Sievers",
    "Dennis Deane", "Sue Simmons", "Joshua Montelongo",
    "Eva Bundy", "Craig Wargo", "Stanley Chaney",
    "Edward Ruhl", "Vickie Davison", "Hoggard",
    "Lillian Bigler", "Phillip Haynes", "Brandon Gilpin",
    "Renee Rodas", "Deborah Baxley", "Brandon Grissom",
    "Janie Twyman", "Gary Flack", "Phyllis Olmstead",
    "Curtis Farrington", "Charles Bowser", "Carl Robert",
    "Howard Elwell", "Ryan Hafner", "Arthur Budde",
    "Manuel Heywood", "Josephine Ardoin", "Cynthia Graham",
    "Thaxton", "Alicia Neilson", "Sharon Makowski",
    "Jack Mcnally", "Gwendolyn Richards", "Ryan Geter",
    "Peter Basile", "Lawrence Willingham", "Paula Lyons",
    "Antonio Earle", "Philip Sistrunk", "Edward Burkholder",
    "Helms", "Doris Brazil", "Elsie Blanchard", "Vicki Ko",
    "Antoinette Jett", "Larry Kirkwood"];
people.sort();

function search(term) {
    var results = [], i;
    for (i = 0; i < people.length; i++) {
        if (people[i].toLowerCase().indexOf(term.toLowerCase())
          !== -1) {
            results.push(people[i]);
        }
    }
    return results;
}

// because JSLint thinks "static" is a reserved word, but
connect disagrees.
connect.theStatic = connect['static'];

var app = connect()
    .use(connect.logger('dev'))
    .use(connect.favicon())
    .use(connect.theStatic('../'))
    .use(function (req, res) {
        res.setHeader('Access-Control-Allow-Origin', '*');
        var reqid = Math.random();
        var parsedUrl = url.parse(req.url, true);
        if (parsedUrl.href.indexOf('/search') === 0 &&
                parsedUrl.hasOwnProperty('query') &&
                parsedUrl.query.hasOwnProperty('s')) {
            var result = JSON.stringify(search(
                parsedUrl.query.s));
            var delay = Math.random() * 3000 + 500;
            console.log('Searched for ', parsedUrl.query.s,
                'responding in', delay, 'with', result);
            setTimeout(function () {
                res.end(result);
                }, delay);
            } else {
                res.statusCode = 404;
                res.end("not found");
            }
        })
        .listen(port, host);
    console.log("listening on " + host + " port " + port);
}());
```

A.4.2 index.html

```
<!doctype html>
<html>
<head>
<title>Company Directory</title>

<script src="jquery-1.7.js?prebug=no"></script>
<script>
(function () {
    'use strict';
    var resultsDiv;
    var spinnerDiv;

    var searchUrl = "http://127.0.0.1:3000/search";

    var search = function (term, callback) {
        $.getJSON(searchUrl, {s: term}, function () {
            callback.apply(this, arguments);
        });
    };
```

```
var hideSpinner = function () {
    spinnerDiv.hide();
};

var term = "";
var keyPressed = function () {
    if ($(this).val() !== term) {
        var thisTerm, i;
        term = $(this).val();

        if (term.length > 0) {
            spinnerDiv.show();
            resultsDiv.empty();
            search(term, function (results) {
                if (term === thisTerm) {
                    hideSpinner();
                    for (i = 0; i < results.length; i++) {
                        $("<li />").appendTo(resultsDiv)
                                   .text(results[i]);
                    }
                }
            });
        } else {
            resultsDiv.empty();
        }
    }
};

$(function () {
        $("body").append("Search: ");
        var textbox = $("<input />").appendTo("body");
        textbox.on('keyup', keyPressed);
        textbox.focus();

        spinnerDiv = $("<div />").appendTo("body")
                                .html("<img src='spinner.gif' />")
                                .hide();

        resultsDiv = $("<div />").appendTo("body");
    });
}());
</script>
</head>
<body>
</body>
</html>
```