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Readily Available Learning Experiences in Production Code

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## ABSTRACT

### Readily Available Learning Experiences in Production Code

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Online platforms for learning to code such as Coursera, CodeCademy, and CodeSchool attract millions of learners and significantly expand the pool of self-starting developers, yet critical gaps in knowledge and experience remain between inexperienced learners and professionals. With vast amounts of professionally-authored source code made readily available by the client-server architecture of the web, design patterns and implementation decisions found in source code can be used to provide on-demand learning experiences for users seeking to advance their skills in professional web development. Specifically, this thesis focuses on creating *Readily Available Learning Experiences* (RALE) for inexperienced learners who wish to become professional contributors but lack the means necessary to advance beyond their gaps in knowledge. The central claims of RALE are (1) surfacing hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites, (2) minimizing learning barriers while supporting personalized exploration of unfamiliar website code, (3) scaffolding mixed-initiative sensemaking to help users walk through unfamiliar complexities, and (4) scaling the conversion of examples into

learning resources without additional authorship or maintenance. Specifically, I propose to transform the entire domain of professional websites into opportunities for authentic learning. Professional websites offer rich details missing from training examples, providing real-world content and opportunities to think in the modes of the discipline. They embed programming concepts and implementation techniques that are used by professionals and are continually updated as new solutions arise. However, despite the abundant availability of web client source code, professional website source is complex and difficult for learners to understand. This thesis contributes three technical contributions to support RALE on the open web: (1) an API Harness for surfacing relevant code that modifies the DOM, (2) a Wisat architecture and Sleight-of-Hand technique to enable source instrumentation on production websites, and (3) a Serialized Deanonymization technique to expose hidden asynchronous links between logical JavaScript components. With these techniques for transforming websites into learning experiences, aspiring web developers have immediate opportunities to gain authentic practice in professional web development beyond what authored learning materials currently provide.



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## CHAPTER 1

### **Introduction**

With vast amounts of professionally-authored website source code made readily available by the client-server architecture of the web, implementation details and design choices found in source code can be used to provide on-demand learning experiences for users seeking to advance their skills in professional web development. This thesis introduces methods for (1) surfacing hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites, (2) minimizing learning barriers while supporting personalized exploration of unfamiliar website code, (3) scaffolding mixed-initiative sense-making to help users walk through unfamiliar complexities, and (4) scaling the conversion of examples into learning resources without additional authorship or maintenance.

Specifically, this thesis focuses on creating learning experiences for inexperienced web developers who wish to become professional contributors but lack the means necessary to advance beyond their gaps in knowledge. Many of these users can setup, read, and write basic JavaScript web applications but lack the conceptual knowledge of design patterns used in professional web solutions. Online platforms for learning to code such as Codecademy, Khan Academy, and CodeSchool attract millions of learners and significantly expand the pool of self-starting developers, yet these platforms primarily teach syntax or provide practice on constrained tutorial examples. Further, these platforms lack the authenticity required to support the progression from writing functional code

to writing professional-quality software. As a result, significant gaps in knowledge and experience remain between inexperienced developers and professional developers.

This thesis proposes to address conceptual knowledge gaps for inexperienced web developers by transforming the entire domain of professional websites into opportunities for authentic learning. Professional websites offer rich details missing from training examples, providing real-world content and opportunities to think in the modes of the discipline. They embed programming concepts and implementation techniques that are used by professionals and are continually updated as new solutions arise. However, despite the abundant availability of front-end code, professional examples are complex and difficult for learners to understand.

Deriving learning material from websites presents design and technical challenges due to the magnitude and complexity of the underlying source code. A simple UI interaction may require only ten lines of JavaScript, but modern web production engineering practices make use of libraries and build processes that can push front-end lines of code into the tens of thousands [6, 64, 70]. Bindings between HTML and JavaScript support an interaction, but it is difficult to determine how such bindings are constructed. A simple calendar widget, for example, could be created entirely in JavaScript and appended to the DOM with listeners, or it could be built in HTML and CSS with inline calls to JavaScript hooks. Embedding the widget amidst all its library or utility code in a minification build process blurs the location and scope of code most relevant to enabling the widget’s functionality.

JavaScript functions are often executed asynchronously, and visualizations of execution order provide little information about the conceptual structure of web programs. One

could understand the structure by walking through the entire execution path as they might when debugging, but this can contain thousands of steps for professional examples. Surfacing relevant information, such as the most-called functions, is a reasonable approach for identifying important functional components, but it can hide lower-level functions that become necessary bridges for understanding how components work together to produce a feature.

With prior systems [48, 59, 14, 25, 5], it is difficult to (1) differentiate relevance amidst JavaScript sources for a given interaction, (2) control the scope of JavaScript being analyzed, (3) identify the interplay between JavaScript and HTML that causes a visual change, (4) trim away inactive code and library code that get in the way of learning, (5) elicit code constructs and relationships with JavaScript sources, and (6) support a user’s sensemaking process through complex JavaScript artifacts. Our work on RALE overcomes these challenges to give users opportunities to learn authentically from professional websites.

### 1.1. Readily Available Learning Experiences

A RALE is defined as a learning scaffold created for a professional website that engages with a learner to support authentic practice with constructs and techniques used to compose the product. The purpose of RALE is to enable inexperienced learners to gain insights from professional products to bridge knowledge gaps in their journey of becoming a professional contributor. To advance this purpose, we argue that a RALE should:

- (1) Surface hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites.

- (2) Minimize learning barriers while supporting personalized exploration of unfamiliar website code.
- (3) Scaffold mixed-initiative sensemaking to help users walk through unfamiliar complexities in the surfaced resources.
- (4) Scale the conversion of examples into learning resources without additional authorship or maintenance.

Surfacing patterns, constructs, and relationships from professional websites (claim 1) helps inexperienced developers to overcome gaps in knowledge, shortcuts inefficient learning routes such as incomplete tutorials, and provides users with opportunities to learn authentically — in a personally meaningful way using multiple modes of the discipline (i.e. web application programming). Prior systems to RALE are able to surface information about a runtime but require the user to infer relationships and patterns for themselves. Without scaffolds in place, learning barriers often inhibit users from gaining meaningful insights from any information surfaced [45].

RALE calls for minimizing the effects of additional learning barriers that can be created by surfacing hidden details from software while still supporting in-depth exploration (claim 2). While there is a large body of work on the theme of extracting concepts from code, few address the risk that surfacing patterns, constructs, and relationships could overwhelm a user and present them with additional learning barriers. The studies presented later in this thesis reveal that learners are easily overwhelmed by overly detailed stack traces, verbose variable states, and complex nested program flows. However, there are times when learners seek these higher levels of detail. Thus, RALE supports personal in-depth exploration in its second claim.

RALE calls for techniques and affordances to scaffold learners in sensemaking, providing them with cues to engage in multiple modes of the web programming discipline such as architecture or implementation (claim 3). Further, by facilitating sensemaking as a mixed-initiative system, learners can work with the system toward their goal [37] to analyze, modify, and iterate on conceptual models of programming constructs. While prior tools [22, 8, 9] effectively support opportunistic sensemaking by leveraging context and online resources to provide relevant programming scaffolds, they are designed to support expert developers; they do not provide affordances to build on beginners' understandings [51] or help beginners reason about the structure of code [61].

With the first 3 claims in mind, a RALE must apply these claims while scaling continuously across its application domain without burdens of authorship or maintenance (claim 4). Tutorials and Q&A require authorship, or the manual creation of learning materials, and often leave learning gaps or fail to provide an adequate case library for each learner's goals. The underlying technologies enabling RALE should not require expert authoring for surfacing the underlying information from a runtime. With millions of active learners looking to the web for online learning and the fast pace of innovation in web programming, teachers and content authors meet only a small portion of the increasing demand for learning materials. The primary goal of this thesis is to transform inspiring professionally-produced websites into opportunities for learning without dependencies on authoring to bridge gaps in becoming a professional contributor.

## 1.2. Contributions: Three Systems Toward RALE

This thesis contributes three systems toward the goal of creating Readily Available Learning Experiences (RALE) for professional websites. Each system was developed sequentially in an effort to get closer to an overall goal of proving RALE on the open web. This section introduces the systems and their contributions toward RALE.

### 1.2.1. Unravel: Tracing, Organizing, and Identifying Relevant Runtime Code

*Unravel* is an extension of the Chrome Developer Tools for quickly tracing and visualizing HTML changes, JavaScript method calls, and JavaScript libraries. Unravel aids the reverse engineering of websites by providing comprehensive yet targeted views of JavaScript invocations, HTML changes, and included libraries (see Figure 1.1). Unravel enhances Google Chrome’s existing developer toolkit by linking all HTML and JavaScript components to their corresponding inspection panes for quick examination. Unravel works on all websites without interfering with existing functionality. For example, a developer can navigate to a landing page, record a parallax effect, and watch Unravel identify which lines of JavaScript were executed, which DOM elements were modified, and which attributes were modified per each element. Toward RALE, Unravel was the first system to surface code constructs in terms of relevance for a given website feature (founding claim 1) while lowering informational learning barriers (founding claim 2) and scaling to work across its domain without the need for external dependencies (founding claim 4).

The main conceptual contribution of Unravel is the idea of *tracing, identifying, and organizing the most relevant functions and DOM elements manipulated to support reverse engineering and understanding interactions on complex professional websites*. Unravel

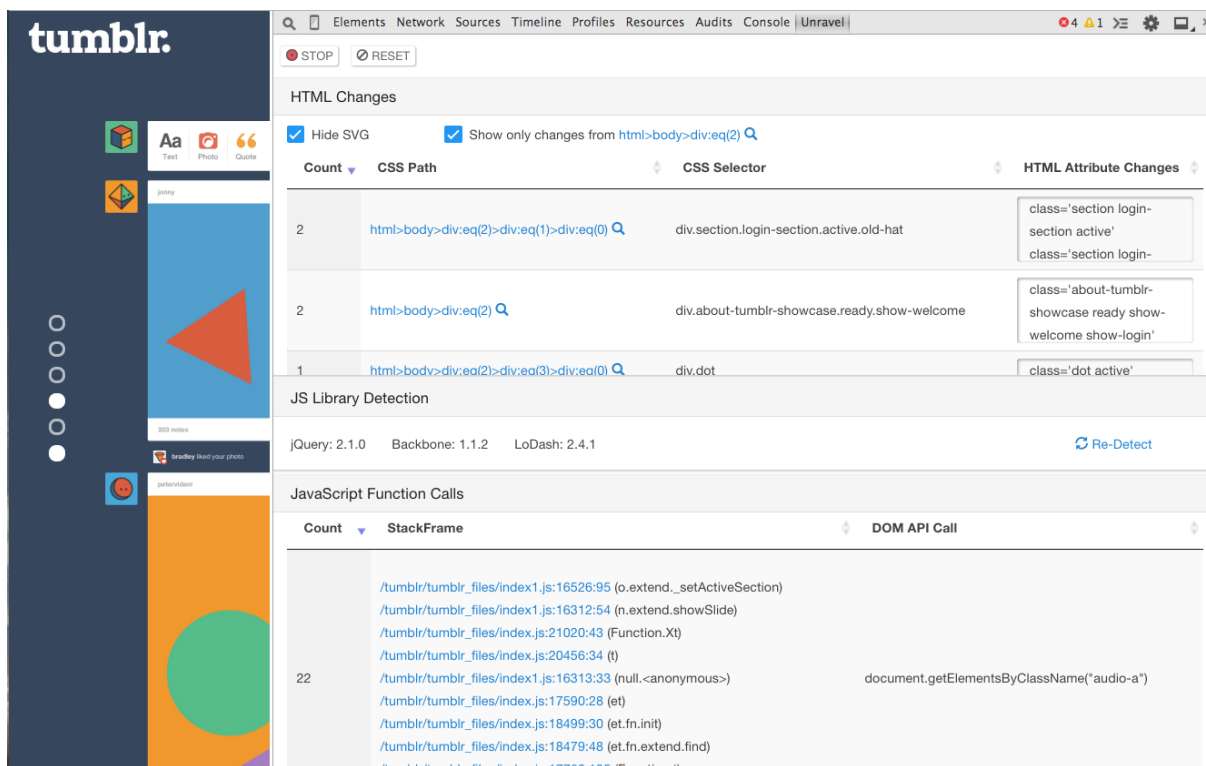


Figure 1.1. The Unravel recording interface consists of the HTML Changes pane (top), the JS Library Detection pane (middle), and the JavaScript Function Calls pane (bottom). Unravel has two controls for recording/stopping and resetting change detection (top). The HTML Changes pane shows the total count, CSS Path, CSS Selector, and HTML Attribute Changes for each element change. The JS Library Detection pane shows libraries detected. The JavaScript Function Calls pane shows the total count, stack frames, and DOM API call for each JavaScript call-stack recorded.

aggregates changes monitored from within a website and provides affordances to reduce, scope, and sort observations. Sources most frequently called become obvious choices for the user to examine. Complex UI features can invoke an enormous number of method calls and HTML changes. Navigating unstructured lists of change events for inspection is counterproductive. Unravel aggregates similar JavaScript call-stacks and HTML changes, increasing counts with each occurrence. While users frequently repeat an interaction to see



its effect, Unravel’s change panels are continually sorted by highest counts first, bubbling the most changed element or most called trace to the top.

Unravel is supported technically by a novel observation agent that deploys an API harness for observing and recording UI interactions from within a website. The API harness is an approach for monitoring an application’s interaction with an API through a removable recording adapter placed between the application and the API. Unravel’s observation agent publishes HTML changes and uses the API harness to monitor calls to the document API. While previous work was able to record and replay events, these solutions depended on access to a remote debugging API. Unravel’s observation architecture only depends on native JavaScript and HTML, widening its application domain to other UI inspection toolkits.

Unravel was evaluated with 13 web developers on 5 large-scale websites. The results included a 53% decrease in time to discovering the first key source behind a UI feature and a 32% decrease in time to understanding how to fully recreate a feature. In summary, Unravel can be applied to help developers find entry points into complex code quickly with lowered barriers of entry.

### **1.2.2. Telescope: Low-Barrier Learning Materials from Runtime Code**

*Telescope* is a platform that supports the discovery of website feature implementation by allowing the user to fine-tune a composite view of responsible JavaScript and explore visual links between JavaScript, HTML, and rendered UI components (see Figure 1.2). Telescope helps users generate low-barrier learning materials — less than two hundred lines of code — from tens of thousands of lines of complex website code. For example, a

curious user could discover how an interactive map component achieves its dragging effect in JavaScript and HTML by setting Telescope’s JavaScript detail level to minimum (DOM-modifiers only) and time constraints before and after the click-and-drag. By clicking call and query markers in the interface, visual lines connect JavaScript methods to queried DOM elements, and corresponding DOM components are highlighted in the website.

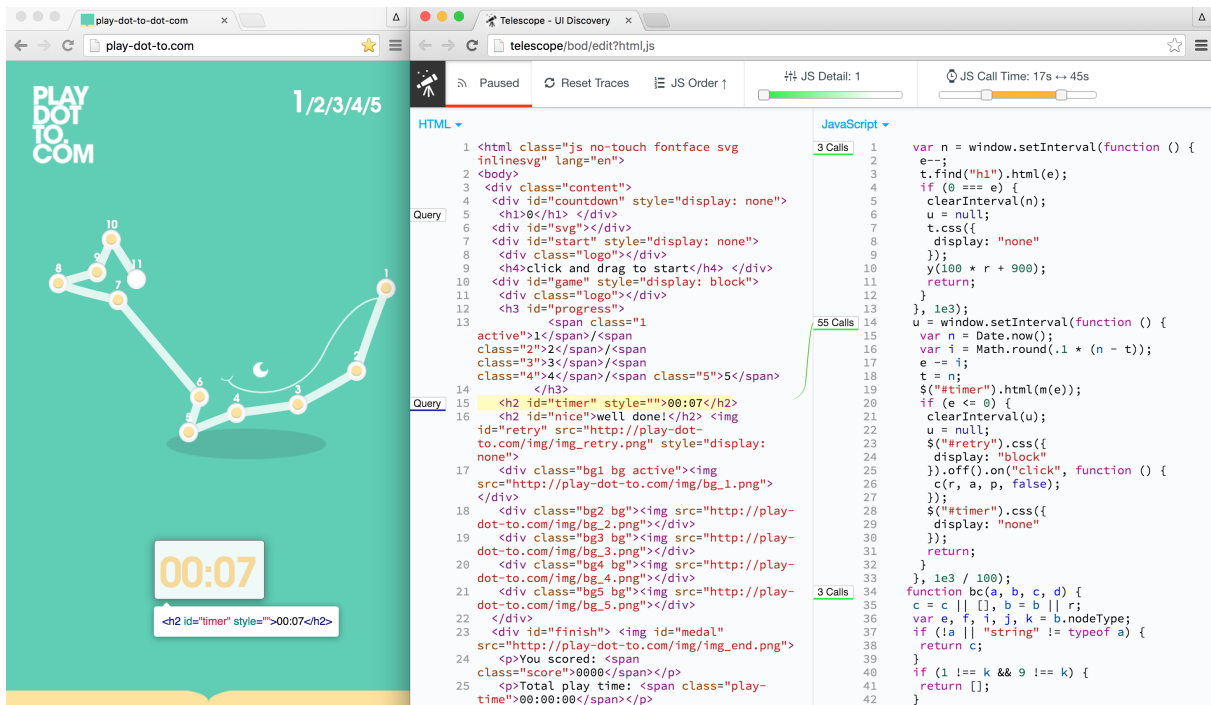


Figure 1.2. The Telescope interface is being used to discover how this HTML5 connect-the-dot game’s timer works. The interface is paused to freeze the current view. The detail level is set at minimum, and the JavaScript call time is constrained between the 17th and 45th second of execution. The left Telescope panel (middle) shows a filtered HTML view, where an active element is highlighted and query markers denote that JavaScript queried those lines during the chosen time window. The right Telescope panel shows the website’s JavaScript, filtered by time and detail. With the current settings, only the most relevant JavaScript is displayed: active non-library JavaScript which queried the DOM in the constrained time frame. A curved line is drawn to connect the JavaScript line to its DOM query.

Telescope surfaced hidden links beyond Unravel with its two-way visuals between HTML and JavaScript (extending claim 1). Telescope demonstrated the necessity of lowering additional information barriers while allowing for personalized exploration (extending claim 2). Further, Telescope provided a foundational architecture for scaling the conversion of examples into learning resources without additional authorship or maintenance (broadening claim 4).

The conceptual contribution of Telescope is the idea of *helping users understand complex website code by generating low-barrier learning materials*. Telescope introduces three design principles to support this idea:

- (1) *Single Composite View*: As a user interacts with a website, Telescope brings together relevant JavaScript for an interaction into a single, composite JavaScript view to resolve the challenges in finding all code relevant to a behavior in unfamiliar code [29]. Users can easily hide sources they deem irrelevant or alter the display order of script sources relative to their dependency load order.
- (2) *Detail and Time Controls*: The user can scope relevant Javascript by call time and control the amount of detail they wish to see, ranging from showing non-library DOM-modifying code only to showing all JavaScript present in the website. These controls address a critical need discovered through our human-centered design process, when we found users struggling to understand the code for an interaction when there is either too little or too much JavaScript to analyze.
- (3) *Visual Links*: Visual links connect active JavaScript to lines of HTML and website DOM components to expose end-to-end functionality.

The technical contributions supporting Telescope enable its ability to examine website UI interactions across the open web in real time. They include: (a) the *Wisat architecture*, which supports source code tracing and instrumentation as well as shared Telescope sessions on public websites and (b) the *Sleight-of-Hand method* (SoH), which swaps a website’s client-side implementation during runtime with its instrumented counterpart. The SoH method transitions websites from a non-traceable state to a fully instrumented state, supporting live interaction traces as a user interacts with their website. The Wisat architecture then transmits runtime traces used to decide which JavaScript is displayed in Telescope’s composite view and provides the linking data necessary for drawing connections between JavaScript, HTML, and website components. The third system, Isopleth, extends this architecture to enable mixed initiative sensemaking across the open web.

In a case study across seven popular websites, Telescope helped identify less than 150 lines of front-end code out of tens of thousands that accurately described the desired interaction in six of the sites. In an exploratory user study, users discovered difficult unfamiliar programming concepts by leveraging Telescope’s ability to reduce code while varying its detail display to provide deeper understanding when needed. In summary, Telescope can be applied to produce low-barrier learning materials for users to discover an accurate glimpse of how a website feature works, with support for them to explore much further.

### 1.2.3. Isopleth: Mixed-Initiative Sensemaking in Unfamiliar Code

*Isopleth* is a web-based platform that enables a mixed-initiative sensemaking process by combining system and user-generated facets and source code alterations to support

learners as they make sense of complex JavaScript features in professional websites (see Figure 1.3). Isopleth automatically identifies programming *facets*, or code constructs that are defined by their inputs and outputs, then exposes functional relationships and hidden asynchronous relationships in its call graph. In contrast to existing systems, our goal is to help users identify meaningful entry points into complex code and then interactively explore, label, and filter facets to produce their own understanding of its functionality. Isopleth supports mixed-initiative interaction by integrating newly created facets and labels into recalculated views. For example, a user could explore how autocomplete works by (1) selecting the “Keyboard” facet, (2) creating a new facet filter for the text of their autocomplete query, and (3) following asynchronous links between keyboard-related invocations and query-related invocations. Toward RALE, Isopleth surfaces hidden relationships and facets in the code (extending claim 1), minimizes additional coordination, design, and use learning barriers (extending claim 2), and is the first system to scaffold mixed-initiative sensemaking (founding claim 3).

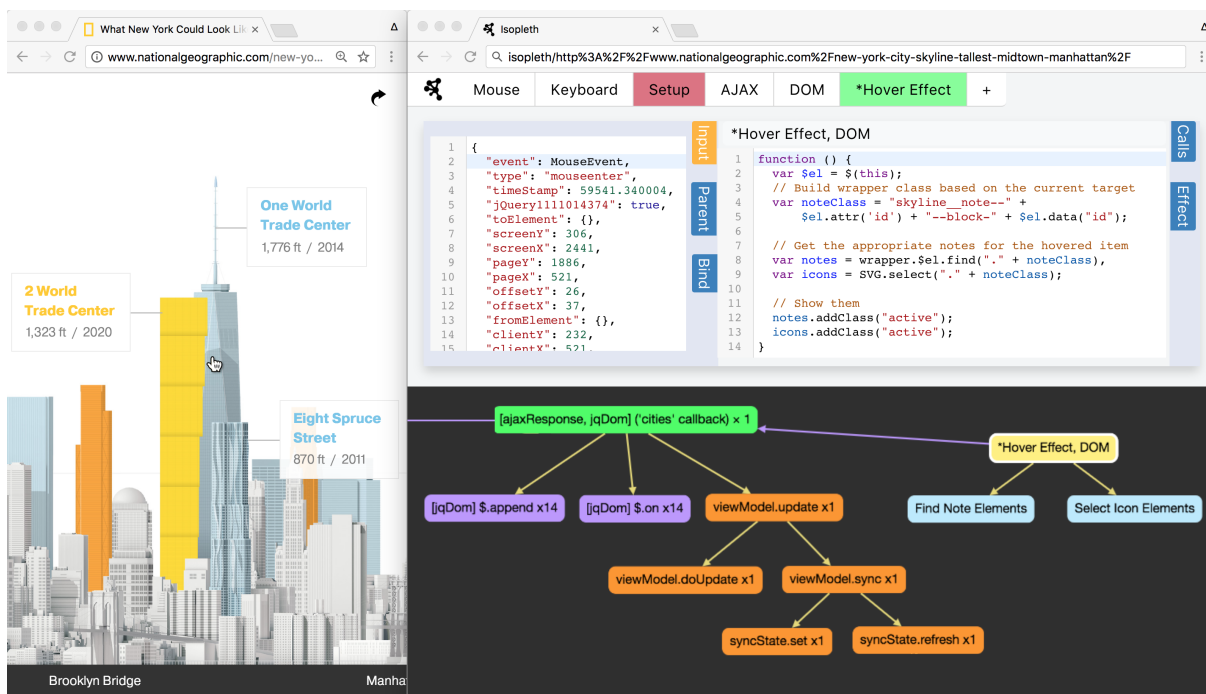


Figure 1.3. A learner is using Isopleth to understand JavaScript code constructs related to moving and scrolling their mouse on National Geographic’s New New York Skyline article. Isopleth opened in a new window after the user activated it on the website; it continuously updates with JavaScript activity. Facet filters (top) are used to filter display based on facet, or code constructs defined by their inputs and outputs. Source frame views (middle) display specific function invocation states in the runtime with their inputs and outputs, parent and child calls, asynchronous declaration context, asynchronous binding, and asynchronous effect if present. The condensed call graph (bottom) displays a collated, filtered, labeled, and color-coded JavaScript runtime call graph (See Figure 5.2). Users can apply **or** and **not** operators on the filters by left and right clicking, respectively. To support mixed-initiative sensemaking, users can add custom filters (See Figure 5.3), modify source frame and graph node labels, and add commentary in source code — the system reacts by integrating learner input into its views. Pictured here, a user has added a custom “Hover Effect”, altered source code, and updated node labels to make sense of smaller call trees.

The conceptual contribution of Isopleth is the idea of *scaffolding sensemaking of complex professional code by surfacing hidden relationships between code constructs and providing a mixed-initiative process to interactively explore, label, and identify system components and how they relate*. Distinct from function call filters, code detail levels, or web feature-location, Isopleth leverages automated techniques to surface facets, code construct defined by inputs and outputs, and expose hidden asynchronous relationships among function invocations. Users can engage in sensemaking by editing code, rearranging invocations, and composing their own invocation labels. As users explore connections between facets and code constructs, they can define new facet filters for the system to respond with newly surfaced facets and hidden relationships. By modifying and contributing filters to the system, users participate in a mixed-initiative flow, where the user and the system work together to support the user’s goal.

The technical contribution of Isopleth is *a Serialized Deanonimization (SD) technique that places unique identifiers in all functions in a web application’s JavaScript source to trace how functions are bound, passed, returned, and invoked asynchronously*. This technique provides the ability to take users beyond a UI feature’s binding to show them how the feature’s bindings was created. Related toolkits [48, 28] are limited to linking a function invocation to its declaration context, and therefore cannot expose where the function was bound, passed, or set as a callback. For example, imagine a web application that creates an anonymous function at line 13 of a source file and binds it as a click handler at line 93. When a user clicks, existing tools would point to line 13 and neglect line 93, thereby making it difficult for the learner to see how the function was used. SD provides missing links such as these by adding them to the call graph. This allows us

to see a complete picture of code activity between declaration and invocation, and thus surfaces crucial information for understanding how web features are implemented.

In a case study across 12 popular websites with rich user experiences, Isopleth supported sensemaking and the discovery of 20 different design patterns. It also surfaced common and distinct implementation approaches used across the 12 websites. In a user study with 14 participants, Isopleth was evaluated to analyze its ability in scaffolding sensemaking and informing conceptual models. Users with basic working knowledge of website programming were able to discover and explain design patterns they found in unfamiliar complex professional website code. Most users described either a newly formed or richly extended mental models of a website feature’s architecture. In summary, Isopleth was the first system to enable mixed initiative sensemaking for users seeking a deeper understanding of web feature implementation techniques.

#### **1.2.4. Thesis Statement**

Readily Available Learning Experiences on the open web surface hidden design patterns, code constructs, and relationships in professional websites to provide opportunities for inexperienced web developers to overcome learning barriers in unfamiliar professional website code, engage in structured sensemaking with complex artifacts, and bridge essential gaps in knowledge of developing professionally designed systems.

### **1.3. Thesis Overview**

- Chapter 2 establishes related work and presents how the contributions of this thesis both address and advance current research.



- Chapter 3 presents Unravel, the first system toward RALE, which aids the reverse engineering of websites by providing comprehensive yet targeted views of JavaScript invocations, HTML changes, and included libraries.
- Chapter 4 presents Telescope, the second system toward RALE, which supports the discovery of website feature implementation by allowing users to fine-tune a composite view of responsible JavaScript and explore visual links between JavaScript, HTML, and rendered UI components.
- Chapter 5 presents Isopleth, the third system toward RALE, which enables a mixed-initiative sensemaking process by combining system and user-generated content to support learners as they make sense of complex JavaScript features in professional websites.
- Chapter 6 discusses use cases for each system, reviews the design claims and evidence for RALE, and looks into how applications of RALE could be created for other domains.
- Finally, Chapter 7 reviews the contributions of this thesis and proposes future research for furthering the RALE vision.

## CHAPTER 2

### Related Work

This thesis extends and contributes to four main bodies of work around the central claims of RALE: (1) Surface hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites. (2) Minimize learning barriers while supporting personalized exploration of unfamiliar website code. (3) Scaffold mixed-initiative sensemaking to help users walk through unfamiliar complexities in the surfaced resources. (4) Scale the conversion of examples into learning resources without additional authorship or maintenance. We detail below the related work around each of these claims and what is necessary beyond prior work, so as to situate the contributions of this thesis.

#### 2.1. Surfacing Information from Code

RALE addresses a class of users who are both frustrated by their knowledge gaps in web development and limited by their ability to analyze complex professional code. Surfacing patterns, constructs, and relationships from professional websites helps users overcome gaps in knowledge, shortcuts inefficient forms of web foraging such as tutorials and Q&A, and provides them with opportunities to learn authentically — in a personally meaningful way using multiple modes of the discipline (i.e. web application programming). This section details prior works in surfacing information from source code.

### 2.1.1. Theseus, FireCrystal, and Scry

Systems including Theseus [48], FireCrystal [59], and Scry [14] provide techniques and affordances to surface JavaScript, HTML, and CSS feature source code. This thesis both addresses limitations and extends contributions from these works.

Theseus instruments and visualizes runtime information about JavaScript execution in a live editing environment [48]. Theseus was designed to address a programmer’s misconceptions by drawing attention to similarities and differences between the programmer’s idea of what code does and what it actually does. Theseus contributes an underlying framework called Fondue to instrument JavaScript sources for tracing, of which the Telescope (see Chapter 4) and Isopleth (see Chapter 5) directly extend. While Theseus helps developers address misconceptions and visualize execution, it lacks affordances to help users address additional learning barriers such as differentiating relevance in JavaScript, drawing links to interaction with the DOM, or exposing hidden relational links between facets in JavaScript. This thesis contributes these additional affordances while extending Theseus’ Fondue instrumentation techniques to support RALE on the open web.

FireCrystal allows users to record an interaction with a website and to replay the interaction with highlighting over sources that are active at each point in time [59]. This allows users to find specific JavaScript that ran during different frames of a UI recording. However, rich UI features can involve thousands of lines of JavaScript across multiple call frames, and FireCrystal’s interface requires users to replay through interactions to discover relevant sources via linear search, which becomes tedious and time-consuming at professional scale (i.e. thousands of lines of code). Like Theseus, FireCrystal’s design goal of visualizing execution through replay is limited to highlighting active JavaScript while

additional barriers in unfamiliar code inhibit ongoing discovery. However, FireCrystal’s contribution is a foundational component of the RALE vision.

Scry exposes program state and provides a timeline visualization for users to explore how state changes in response to JavaScript calls [14]. This allows users to find specific JavaScript, HTML, and CSS involved in changing the DOM at a specific point or frame in time. However, Scry adopts sequential workflows that require back-and-forth navigation from the interface to individual JavaScript files and limits its observation scope to JavaScript that interacted with the DOM. Further, Scry only provides one-way links from a DOM change to the JavaScript that operated on it. Supporting opportunistic discovery in RALE, this thesis contributes design characteristics such as two-way DOM-JavaScript inspection (see Chapter 4) and extensible facet filters (see Chapter 5) to view JavaScript in more ways than its relative proximity to querying the DOM.

### 2.1.2. Visual Tools and Web Inspectors

Prior tools in source code visualization were mainly designed to help experienced developers surface debugging information and enable inspection to solve problems in their applications efficiently. This thesis extends and applies techniques from these works to help inexperienced developers discover design patterns and constructs supporting web UI features. Glimpse provides animated transitions between the rendered UI and its source; Telescope (Chapter 4) extends this idea to link JavaScript to its queried elements in a browser’s web page. Mimic and Theseus log analytics and invocation counts from recordings of UI interactions; Unravel (Chapter 3) and Telescope extend this idea to help users differentiate which lines of code were more active than others. Telescope and Isopleth

(Chapter 5) surface calls to library and REST API's, building from ideas in RESTful service extraction [72]. Beyond this body of work, this thesis contributes filterable views of function invocations, compositing relevant JavaScript and HTML together with visual links, and visualizing the JavaScript call graph with invocations, relations, and labels.

Web developer tools included in major browsers help experienced developers build and debug their applications but can be overwhelming for learners trying to gain insight into professional development patterns. Chrome Developer Tools (CDT), Firebug, and Safari Web Inspector provide rich suites of tools for debugging, inspecting, and live-editing methods. DOM breakpoints trigger direct navigation to responsible JavaScript methods when elements in the DOM are dynamically changed [5, 41, 38], which provides an entry point into searching for the logic responsible for updating the DOM. While these inspectors offer robust debugging workflows, the primary limitation of these tools emerges as a barrier to learning, where too much source code obscures how constructs of the language are used to achieve an effect. Complex websites often have thousands of lines of JavaScript bundled in minified form for optimized transfer. Beyond overwhelming amounts of code, these inspectors are designed to support debugging workflows instead of opportunistic discovery. Using the tools to gain professional experience involves tediously following long call chains and reverse engineering complex asynchronous event-binding networks. The event-driven asynchronous nature of JavaScript obscures how logical components are related to react to the UI from the user's point of view. This thesis both augments and extends the CDT environment to transform websites into learning materials.

### 2.1.3. Surfacing Call Graphs

Computing a well-defined call graph of a program’s internal constructs, relationships, and function invocations helps construct accurate and comprehensive learning materials in RALE. Prior tools use forms of instrumentation to help inform developers how software works but typically use either static analysis or limited runtime analysis to determine program flow, leaving complex asynchronous operations unobserved. The contributions in Chapter 4, Telescope, rely on Fondue’s [48] ability to surface an accurate call graph. Telescope traverses the call graph to calculate which sources to display in its composite view (e.g. library code, invoked-JavaScript, and DOM-querying JavaScript).

The call graph contributions in Chapter 5, Isopleth, support advanced calculations used in its scaffolded sensemaking affordances. Isopleth sits in a unique space, focusing on dynamic asynchronous call-graph navigation for comprehension. Its call graph calculation is inspired by Lencevicius et al’s work on query-based debugging [47], but instead of requiring users to query traces, Isopleth’s facets provide low-effort ways to reshape the graph while providing a simple abstraction for defining new facets. WhyLine’s tracing techniques [44] are similar to Isopleth’s serialized deanonymization technique, but Whyline cannot capture the important asynchronous connections often present in web applications. Isopleth uses the ID’s from each method to backtrace complex asynchronous relationships, then provides affordances to visualize the complex relational links.

## 2.2. Minimizing Learning Barriers

Programmers often experience barriers in learning new programming concepts, and a primary claim of RALE is to minimize information barriers while supporting personalized

exploration of professional website code. Specifically, the three systems in this thesis help users overcome three of Ko et al’s Six Learning Barriers: Design, Coordination, and Information [45].

The Design barrier involves the inherent cognitive difficulties of solving a programming problem, the Coordination barrier involves determining how to combine constructs or technologies to achieve an outcome, and the Information barrier involves knowing where to look for clues about a program’s internal behavior. In Chapter 3, Unravel contributes a technique to overcome the Information barrier by filtering and promoting relevant JavaScript and HTML to inspect. In Chapter 4, Telescope provides a way to overcome the JavaScript/HTML coordination barrier by visually linking JavaScript and HTML if they are logically connected. In Chapter 5, Isopleth helps users overcome the design barrier by providing mixed-initiative scaffolds to help make sense of complex feature implementations.

Further, this thesis explores strategies, interfaces, and methods for developers to quickly and easily overcome barriers caused by the unfamiliarity of code. This includes mental barriers that Gross and Kelleher describe such as memory failure, method interpretation, and lack of temporal reasoning [29]. Developers trying to overcome these barriers currently turn to web foraging for speed and ease in finding help [9] but can become frustrated with outdated or incomplete results. Following Gross and Kelleher’s guidance on designing systems to identify functionality in unfamiliar code, we designed Telescope to “connect code to observable output” and “provide interactions to fully navigate code” (see Chapter 4). The event-based, asynchronous, and often overly-complex

nature of JavaScript implementations [2] increases these barriers, further discouraging those trying to learn from JavaScript source.

### **2.2.1. Visual Techniques to Overcome Barriers**

Visual learning techniques help users to easily see the dynamic effects of their code to understand the properties of a program’s external behavior relative to its internal constructs. For example, Gliimpse [20] provides animated real-time visuals that transition between markup languages and their rendered output. Users can see their code transform into its visual rendering as they modify it. PyTutor [32] provides users with a simple Python interface while showing them a visual display of internal program state and operations as they modify code in the interface. Bret Victor’s “Learnable Programming” [73] allows users to interact with a running program, modify its underlying code, and see the effects of modifications as they are made. Most modern web browsers provide affordances for users to find responsible source code through visual breakpoints in the DOM [5], JavaScript beautifiers [25], and HTML change highlights [26]. This thesis addresses remaining difficulties in forming accurate mental models of design patterns and techniques used to create professional web code, such as breaking down complex function relationships, visualizing JavaScript operations on the DOM, or minimizing the overwhelming effects of large volumes of code.

### **2.2.2. Interactive Techniques to Overcome Barriers**

Existing tools contribute design techniques to highlight, filter, and curate parts of code responsible for an effect. Theseus [48] provides “hit-counts” and detailed call stack logs



for lines of JavaScript in an extended Brackets IDE. FireCrystal [59] records UI interactions and plays them back in a view coupled with a JavaScript inspector that highlights active lines per each frame in time. Scry [14] extends the Safari browser to record UI interactions, then provides a timeline view where users can view DOM state changes and the JavaScript/CSS trace involved in each change. Clematis [2] visualizes episodes of cause-effect JavaScript events and their effect on DOM state through an expandable timeline view. Tutorons [33] automatically generates context-relevant, on-demand micro-explanations of code in an editor. Gidget [46] interactively coaches players learn programming by working with a bot named Gidget to debug problematic code. WebCrystal [16] gives users a way to quickly access HTML and CSS information from a webpage by selecting questions regarding how a selected element is designed. Whyline [43] allows users to ask questions about a runtime then visualizes answers in terms of runtime events directly relevant to a programmer’s question. Dinah [30] supports beginners in selected code causing graphical output through statement replay and temporal navigation.

### 2.3. Scaffolding Mixed-Initiative Sensemaking

The third primary claim of RALE is that it should scaffold mixed-initiative sensemaking to help users walk through unfamiliar complexities in the surfaced resources. This calls for techniques and affordances to support learners during their sensemaking process while providing them with cues to engage in multiple modes of the web programming discipline such as architecture, implementation, and refactoring.

### 2.3.1. Sensemaking and Learning Scaffolds

In order to build new understanding from a programming example, a learner must first make sense of the code structure and functionality. In the learning sciences, sensemaking refers to the process of understanding a new example or artifact by generating representations that explain what is known or understood [75, 62]. While experts leverage templates and formal representations of programming constructs to make sense of and solve problems, these patterns are not apparent to beginners [1, 76, 52, 56, 17, 18, 19]. Furthermore, learning from complex examples requires understanding not only the individual components, but also how they coordinate to solve a problem [45]. This requires both conceptual knowledge and expert strategies for constructing an understanding of a problem by examining evidence, testing hypotheses, and reflecting on findings [79, 78].

The learning sciences provide guidelines for scaffolds in RALE (supports and affordances) that can help beginners bridge this knowledge gap to make sense of complex examples. This literature suggests that tools designed to support sensemaking should build on learners' intuitive understanding by using representations and language that connect to their knowledge [51, 62]. Tools should also be organized around the semantics of the discipline [62] and provide opportunities for learners to reason about the structure of code, and not just how it works [61]. Finally, tools should provide opportunities for learners to inspect professional code in different ways [62]. Providing multiple ways to visualize the code helps learners build dense, interconnected conceptual representations [10, 65, 3]. In Chapter 5, these learning goals are implemented in Isopleth to enable RALE for professional websites.

### 2.3.2. Program Comprehension

The design of RALE extends a rich body of research in computer program comprehension by contributing new interaction techniques to code comprehension. Specifically, this body of work examines how programmers support cognitive tasks such as thinking and reasoning about the structure of code [71, 12, 69, 74, 68, 60]. Several comprehension theories classify how programmers understand new code, such as (1) top-down from domain to source code [12], (2) bottom-up from statements to abstractions [68], (3) beacons from familiar code with plan decomposition in unfamiliar code [69], and (4) bottom-up through control-flow abstraction from microstructures to macrostructures to form a situational model [60]. Most similar to Pennington’s theory [60], detailed in Chapter 5, Isopleth allows users to navigate and filter pre-labeled microstructures and follow control-flow through relational links in a graph. Isopleth’s sensemaking affordances aid the formation of Pennington’s macrostructures by breaking down complex website logic into consumable pieces and allowing users to explore and modify these pieces in a personally meaningful way. Similar to Soloway’s theory [69], Telescope aids program comprehension by providing learners with visual line connectors between modified DOM elements and active JavaScript functions (see Chapter 4). Telescope’s visual line affordances draw a learner’s attention to certain code constructs in HTML and JavaScript, acting like Soloway’s beacons for discovery.

## 2.4. Scaling Learning Resources

With millions of active learners looking to the web for online learning and the fast pace of innovation in web programming, teachers and content authors meet only a small

portion of the ever-expanding demand for learning materials. The primary goal of RALE is to transform inspiring professionally-produced websites into opportunities for learning with no dependencies on authoring. This section details related work around RALE’s fourth claim to scale the conversion of examples into learning resources without additional authorship or maintenance.

#### 2.4.1. Technical Dependencies

Chapter 3 and Chapter 4 introduce the API Harness and Wisat architecture to capture JavaScript functionality on the open web, but unlike related methods they require few dependencies or user installation to scale. The Mozilla Remote Debugging Protocol [57] allows developers to access the JavaScript event loop and observe execution, but the Mozilla RDP does not store a full history of function invocations, which is necessary for call graph calculation in Telescope and Isopleth. Lieber et al’s Fondue instruments all functions in the JavaScript source to monitor execution, but requires users to override their system settings to allow a proxy server to intercept website sources [48]. While Unravel is limited in its abilities to surface runtime information (i.e. DOM-modifying JavaScript only), a core design characteristic of Unravel is to be lightweight and immediately usable on public websites. Similar to Unravel, Maras et al’s source extraction technique and Burg et al’s Scry offer limited views of JavaScript based on static analysis of dependencies and DOM-querying JavaScript, respectively [55, 14]. Alternatively, the Wisat architecture surfaces complete runtime information about all JavaScript functions via one-click user activation to provide accurate scaffolds and fully comprehensive views into source code (used in Chapters 4 and 5).

### 2.4.2. Extending Web Foraging

One set of tools has been designed to support professional developers as they make sense of complex code using resources provided continuously via the web. Brandt et al explored how programmers leverage online resources to support the development process, opportunistically transitioning between web foraging, learning, and writing code [9]. They built on this work to develop Blueprint, a web search interface integrated into a development environment to support searching for relevant code examples efficiently [8]. Fast and Bernstein designed Meta, a Python language extension that allows programmers to share and compare their implementation approaches and provides recommendations for improvements based on crowd data [22]. These approaches effectively support opportunistic sensemaking by leveraging context and online resources to provide relevant programming scaffolds. However, they are designed to support expert developers; they do not provide affordances to build on beginners' understandings [51] or help beginners reason about the structure of code [61].

## CHAPTER 3

**Unravel: Rapid Web Application Reverse Engineering**

This chapter presents the first application in RALE, the Unravel system, which provides techniques in overcoming challenges in finding relevant HTML and JavaScript code for a UI feature in a complex professional website. This chapter has adapted, updated, and rewritten content from a paper at User Interfaces Systems and Technology 2015 [34]. The source code for Unravel is openly available <sup>1</sup>. All uses of “we”, “our”, and “us” in this chapter refer to coauthors of the aforementioned paper.

Professional websites with complex UI features provide real world examples for developers to learn from. Yet despite the availability of source code, it is still difficult to understand how these features are implemented. Existing tools such as the Chrome Developer Tools and Firebug offer debugging and inspection, but reverse engineering is still a time consuming task. We thus present Unravel, an extension of the Chrome Developer Tools for quickly tracking and visualizing HTML changes, JavaScript method calls, and JavaScript libraries. Unravel injects an observation agent into websites to monitor DOM interactions in real-time without functional interference or external dependencies. To manage potentially large observations of events, the Unravel UI provides affordances to reduce, sort, and scope observations. Testing Unravel with 13 web developers on 5 large-scale websites, we found a 53% decrease in time to discovering the first key source

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<sup>1</sup>Unravel Github <https://github.com/NUDelta/Unravel>

behind a UI feature and a 32% decrease in time to understanding how to fully recreate a feature.

### 3.1. Motivation and Contributions

Developers can learn from professional websites, but the barriers to understanding unfamiliar code [45] hinder the potential for authentic learning [66]. Without documentation for UI features of complex websites, one must search for curated examples or attempt to reverse engineer the website to discover how a feature works. Examples may not be available for unique features or may only provide partial solutions. Professional websites combine many web technologies to present unified interfaces that are not straightforward to disassemble. Reverse engineering UI components such as a photo carousel, search autocomplete, or table filter is difficult, because it involves cyclical HTML inspections to follow element changes and find-all queries in JavaScript files for references to DOM elements. JavaScript often execute asynchronously out of order, making it difficult to identify which lines of JavaScript to start examining [2].

Current approaches including record & replay in the DOM and JavaScript tracing have inspired this chapter (e.g. [5, 11, 13, 20, 59]) as they showed that recording and tracing changes in-context gives developers a better understanding of what’s happening in the source code [13, 30]. With some context clues about where to begin looking, junior developers are more likely to overcome barriers that would otherwise prevent them from beginning a first attempt at reverse engineering [45]. But beyond source exposition, existing tools lack affordances to show the most relevant lines of source code. Complex features may consist of hundreds or thousands of recorded function invocations; without

additional affordances, the inefficient process of searching, inspecting, and debugging to gain understanding is tedious and time-consuming.

*Unravel* aids the reverse engineering of websites by providing comprehensive yet targeted views of JavaScript invocations, HTML changes, and included libraries (see Figure 3.1). *Unravel* enhances Chrome’s existing developer toolkit by linking all HTML and JavaScript components to their corresponding inspection panes for quick examination. *Unravel* works on all websites without interfering with existing functionality. For example, a developer can navigate to a landing page, record a parallax effect, and watch *Unravel* identify which lines of JavaScript were executed, which DOM elements were modified, and which attributes were modified per each element.

The main conceptual contribution of *Unravel* work is the idea of *tracing, identifying, and organizing the most relevant functions and DOM elements manipulated to support reverse engineering and understanding interactions on complex professional websites*. *Unravel* aggregates changes monitored from within a website and provides affordances to reduce, scope, and sort observations. As users repeat their desired interaction, call counts related to their feature bubble up, turning relevant sources into obvious choices for the user to examine. Complex UI features can invoke an enormous number of method calls and HTML changes. Navigating unstructured lists of change events for inspection is counterproductive. *Unravel* aggregates similar JavaScript call-stacks and HTML changes, increasing counts with each occurrence. *Unravel*’s change panels are continually sorted by highest counts first, bubbling the most changed element or most called trace to the top. Affordances are provided to constrain observation scope to specific DOM sub-trees and



throttle large sets of function invocations generated in loops, such as scaling an image on each pixel scrolled.

The fundamental technical contribution of Unravel is *an observation agent that deploys an API harness for observing and recording UI interactions from within a website*. The API harness is an approach for monitoring an application’s interaction with an API through a removable recording adapter placed between the application and the API. Unravel’s observation agent publishes HTML changes and uses the API harness to monitor calls to the document API. While previous work was able to record and replay events, these solutions depended on access to a remote debugging API. Unravel’s observation architecture only depends on native JavaScript and HTML, widening its application domain to other UI inspection toolkits.

In the rest of this chapter, we introduce Unravel and its main components for tracking HTML changes, tracing JavaScript method calls, and identifying libraries. We detail the observation agent and techniques for organizing and presenting trace information; evaluate the benefits of reverse engineering with Unravel; and conclude with a discussion of design principles, limitations of our approach, and a brief look at the next chapter.

### 3.2. Unravel

Unravel is a Chrome Developer Tools extension that provides affordances for discovering and navigating relevant UI source code through three main activities: recording source code activity triggered by a user’s interaction with a web page, refining the scope of source code under observation, and linking lines of source code to corresponding inspection and debugging panes for further analysis (see Figure 3.1).

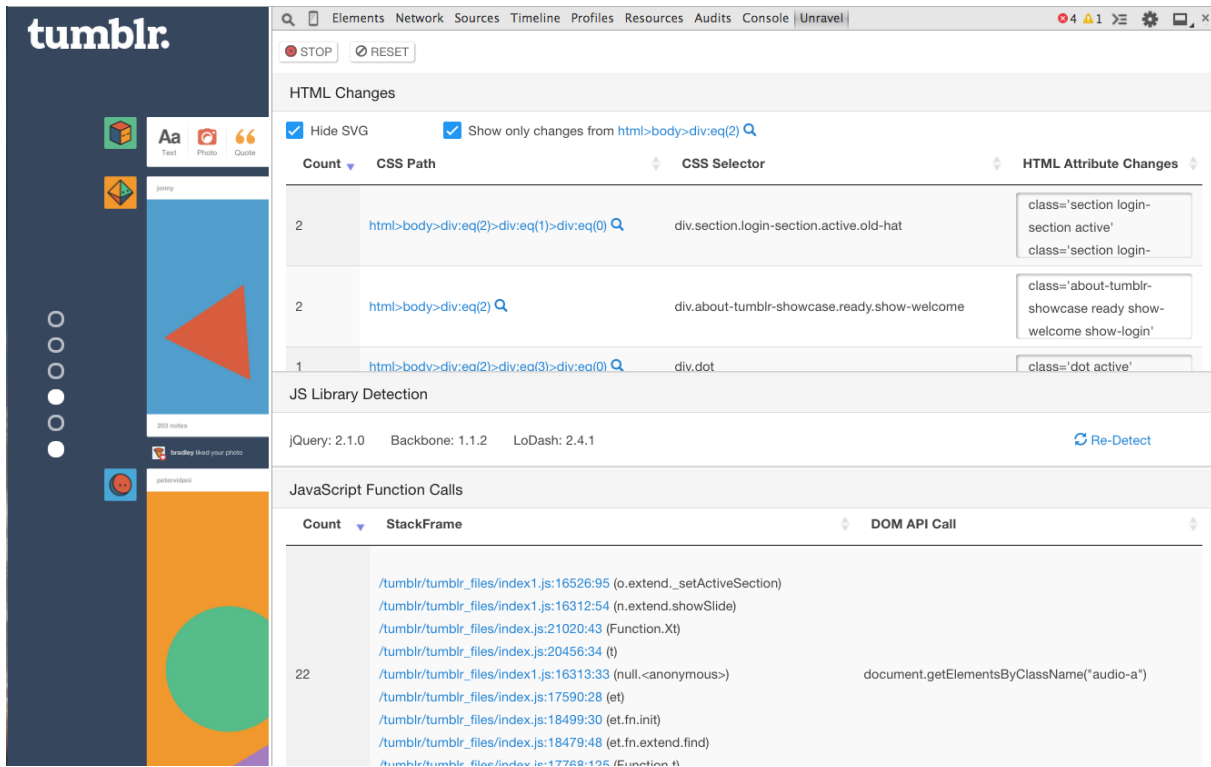


Figure 3.1. The Unravel recording interface consists of the HTML Changes pane (top), the JS Library Detection pane (middle), and the JavaScript Function Calls pane (bottom). Unravel has two controls for recording/stopping and resetting change detection (top). The HTML Changes pane shows the total count, CSS Path, CSS Selector, and HTML Attribute Changes for each element change. The JS Library Detection pane shows libraries detected. The JavaScript Function Calls pane shows the total count, stack frames, and DOM API call for each JavaScript call-stack recorded.

### 3.2.1. Unravel Feature Design

To inform the design of Unravel, we conducted a small exploratory study that observed the existing approaches for reverse engineering web pages. The study consisted of two senior and two junior developers for 20 minutes each, who were asked to reconstruct an animated feature from Tumblr on their own page. We observed participants repeating the animation frequently while inspecting the HTML to see changes. We watched participants slowly

scan through numerous JavaScript files to discover source code causing the animation. One participant said, “I just want to know how they achieved the effect, but it’s not entirely clear from the web inspector.”

Unravel’s features were designed to help address frustrations and inefficiencies expressed by the test participants. The Unravel HTML Changes feature was designed to record and present modifications to lessen repeat behavior (see Figure 3.2). The JS Function Calls feature was designed to capture JavaScript traces with links to executed line numbers in JavaScript files, making it easier to skim active source code (see Figure 3.3). While no inefficiencies were observed related to JavaScript libraries, we noticed many non-native functions appearing in JavaScript traces. We decided to add library detection to inform the user about the presence of frameworks, polyfills, shims, or syntactic sugar (see Figure 3.4). Unravel’s three views are presented as one inspection interface to highlight relevant source code supporting a feature.

### 3.2.2. Tracking HTML & CSS Changes

Without Unravel, current methods for detecting changes in HTML elements involve setting DOM breakpoints or watching for changes in element inspectors. Stepping through hundreds of attribute changes and looking through a DOM tree becomes time consuming. Unravel aims to streamline searches by providing a list of changes instead.

The Unravel extension begins to track HTML changes that occur in the website as a user starts a new recording. With each user interaction in the website, changes are streamed into the Unravel console under the HTML Changes section (see Figure 3.2). A DOM element’s attribute and sub-tree modifications are then viewable in list form with

HTML Changes	
<input checked="" type="checkbox"/> Hide SVG	<input checked="" type="checkbox"/> Show only changes from <code>html&gt;body&gt;div:eq(1)</code> 🔍
Count ▼	CSS Path 🔍
2	<code>html&gt;body&gt;div:eq(1)&gt;div:eq(1)&gt;div:eq(0)</code> 🔍
1	<code>html&gt;body&gt;div:eq(1)&gt;div:eq(2)&gt;div:eq(1)</code> 🔍

Figure 3.2. Within the Unravel HTML Changes pane, users can opt into hiding changes from SVG elements (top left). Users can constrain Unravel’s observation scope by selecting an HTML element to observe (top right).

direct links to structural and CSS inspection in the CDT elements pane (see Figure 3.1). While Unravel does not capture preloaded CSS or CSS pseudo-classes like `:hover`, it monitors CSS class and style changes in HTML attributes such as changing opacity, toggling a class, or modifying WebKit attributes.

**3.2.2.1. An Unravel HTML Change Record.** Each record in the HTML Changes in the Unravel tool contains:

- Change Count: how many changes were recorded for the HTML element
- CSS Path: a unique CSS selector based on the element’s DOM tree location that links to the corresponding node in the CDT Elements Pane
- CSS Selector: a CSS selector based on common query patterns including id, class, and name

- **HTML Attribute Changes:** a list of changes to the element's attributes ordered oldest first

An example user Alice wishes to discover how a modal window is hidden after clicking an  $\times$  icon. She clicks *record* in Unravel and watches for changes while clicking the  $\times$ . Alice stops the recording and looks at the changes listed in the HTML Changes Pane of Unravel. She notices that the list is presorted by highest count of changes first. The first record shows a div with CSS selector `div#modal`. She clicks on the record to see what it is referencing in the actual website and elements panel. Chrome highlights the element in the panel and in the website. Alice confirms it is her element and examines the attribute changes, listed as `class="modal-front"` followed by `class="modal-hidden"`. Alice learns that removing class `modal-front` and adding class `modal-hidden` caused the desired effect.

### 3.2.3. Tracing JavaScript Method Calls

The bottom panel of Unravel lists JavaScript call-stacks captured while recording (see Figure 3.3). Unravel listens for calls to `window.document` and reports JavaScript traces involved in querying and manipulating the DOM. Every stack frame of each call-stack is linked to its corresponding file and line number in the CDT JavaScript inspector.

Each record in the Unravel JavaScript Changes pane contains:

- **Call Count:** how many times a call-stack was invoked
- **Stack Frame(s):** the call-stack leading to a document query
- **DOM API Call:** which document API method was invoked

JavaScript Function Calls	
Count ▲	StackFrame
22	/tumblr/tumblr_files/index1.js:16526:95 (o.extend._setActiveSection)
	/tumblr/tumblr_files/index1.js:16312:54 (n.extend.showSlide)
	/tumblr/tumblr_files/index.js:21020:43 (Function.Xt)
	/tumblr/tumblr_files/index.js:20456:34 (t)
	/tumblr/tumblr_files/index1.js:16313:33 (null.<anonymous>)
	/tumblr/tumblr_files/index.js:17590:28 (et)
	/tumblr/tumblr_files/index.js:18499:30 (et.fn.init)
	/tumblr/tumblr_files/index.js:18479:48 (et.fn.extend.find)
	/tumblr/tumblr_files/index.js:17768:125 (Function.t)

Figure 3.3. The Unravel JavaScript Function Calls pane has captured a call-stack that was executed 22 times. A stack frame with a method called `_setActiveSection` on object `o.extend` initiated the call-stack (top), which arrived at a document query for elements with class “audio-a” (shown in Figure 3.1 bottom right).

An example user Carol wishes to better understand how a web application’s card-flip effect reveals new data when scrolling down in the interface. Carol initiates a new recording session in Unravel and begins to see stack frames captured in the JavaScript changes pane. Carol stops the recording and notices a call-stack was captured. Carol clicks the first frame in the call-stack and is linked to the CDT JavaScript inspector for `index1.js` at line 16526:95. She immediately notices a function `_setActiveSection` that contains logic to change the `translate3d` style attribute of a `div` element. With the first clue,



Figure 3.4. The Unravel JS Library Detection pane requests detection for libraries when Unravel starts and as users select re-detect (right). Re-detection is an affordance provided for libraries added after the initial page load. In this figure, jQuery, Backbone, and LoDash were detected.

Carol returns to Unravel to search for how data is loaded. Carol skims the methods and arguments of additional stack frames and finds a method called `fetchCard`. She clicks the stack frame and discovers an XHR request contained a callback that triggered `_setActiveSection`.

### 3.2.4. Identifying JavaScript Libraries Used

As a precursor to examining source, a list of libraries active in a website prepares the user to understand source in context with the libraries. This may help them to reproduce code for their own use without the frustration of missing libraries. Further, this provides users with clues to how features are implemented using the libraries.

Unravel detects JavaScript Libraries immediately upon launch and lists the libraries with their corresponding versions (see Figure 3.4). An option to re-detect libraries is provided for websites that use a lazy-loading strategy for installing libraries into the application scope.

An example user Bob wishes to discover how a stock-ticker web application easily reformats numbers in many variations. He opens Unravel and finds many sources using

a `numeral()` function. If Bob tried to invoke `numeral` in his own application, he would discover that it is not included in native JavaScript. Using Unravel’s library detection, Bob sees that Numeral.js version 1.5.3 is present in the stock-ticker web application. Bob includes the numeral library in his application and is now able to use the same numeral conversion methods as the stock-ticker application.

### 3.3. Organizing and Tracing Relevant Source Code

#### 3.3.1. Organizing Large Volumes of Trace Information

Complex UI features can generate large volumes of HTML changes and JavaScript traces. Navigating through long lists of changes and traces fails to resolve the *Information Learning Barrier* [45], because the program’s internal behavior may remain unclear despite a wealth of information. This section discusses four strategies Unravel provides to counter information overload: DOM Tree Scoping, CSS Path Aggregation, SVG Hiding, and Call-Stack Aggregation.

**3.3.1.1. DOM Tree Scoping.** Without affordances to reduce observation events, simultaneous UI effects can cause confusion. As a user records an interaction, other dynamic behaviors in the application could highlight source code not relevant to the user’s interests. After selecting an HTML element to observe, users can opt for Unravel to scope future recordings to a single element and its subtree (see Figure 3.2). With the focus option selected, changes outside the scope of selection will be ignored.

**3.3.1.2. CSS Paths and Selectors.** HTML changes are recorded and reduced in real-time to the unique DOM tree path of an element. Continuous changes to one element’s



attributes are rolled up under a single record in Unravel’s HTML change pane (see Figure 3.2). Elements with the most changes bubble to the top. While DOM tree paths can be queried, they can become quite long and difficult to read. Unravel provides simpler selectors by combining the elements tag, id, class, and name if present (see top middle of Figure 3.1).

**3.3.1.3. Throttling Repeat Calls.** During a preliminary study with an Unravel prototype, we discovered that users were being shown too many irrelevant HTML changes for pages that made use of animations. The users weren’t interested in the animation logic itself, but rather DOM elements and interactions surrounding the animation. In the HTML Changes pane, users can select an option to hide superfluous animations (e.g. SVG transitions) (see Figure 3.2).

**3.3.1.4. Call-Stack Aggregation.** Similar to the HTML Changes feature, JavaScript traces are recorded and reduced by unique call-stack. Continuous calls through the same set of methods are logged by increasing the call-stack count. During our pilot study, we observed users repeating interactions and leveraged this usage pattern to surface relevance in code. As users repeat actions, DOM elements that were changed and functions that were invoked bubble up a sorted list. Users then can sort lists by highest count first with stack frames ordered top-down. All of Unravel’s columns are sortable, allowing users to quickly navigate through different perspectives of their recordings.

## 3.4. Implementation

In building Unravel, we sought to improve upon architecture from related systems to provide a scalable and portable implementation. Systems like FireCrystal and that of

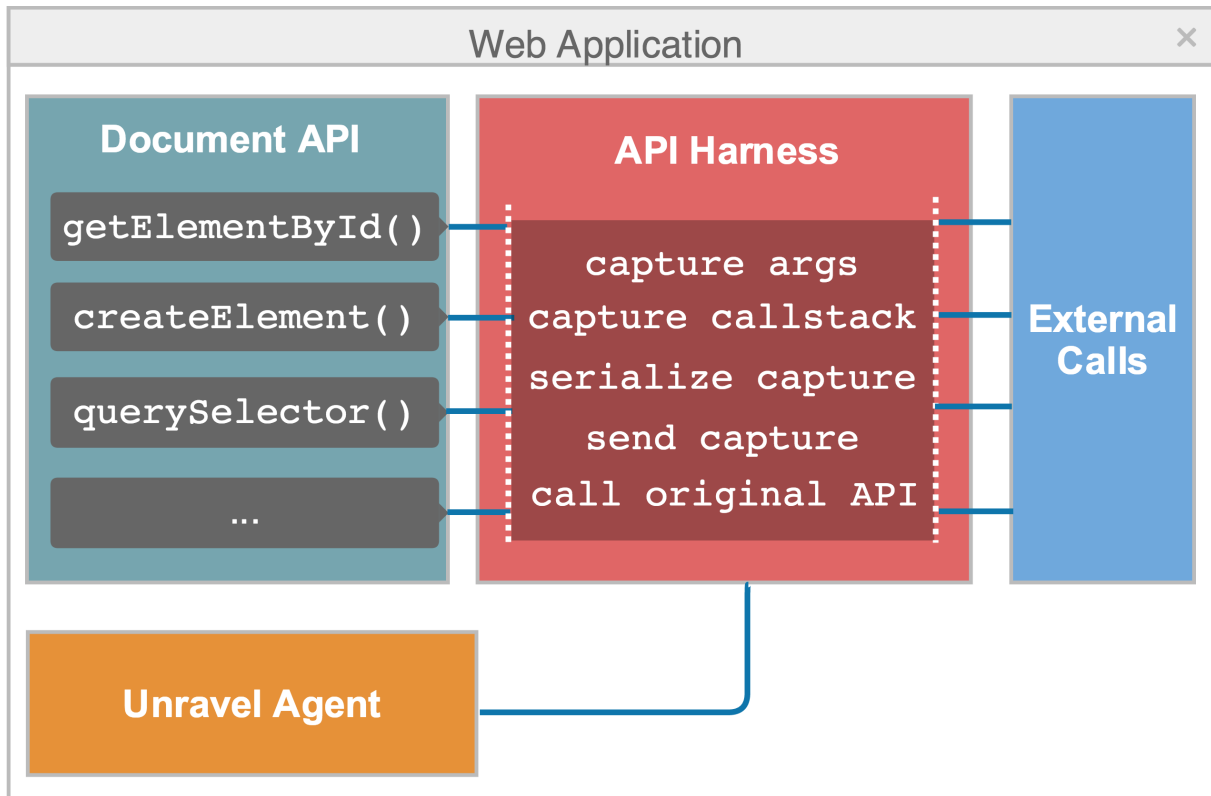


Figure 3.5. An API harness is placed on the document API. Unravel captures and serializes call-stacks and arguments made to the API. Normal interaction with the API resumes after the details of a method call are broadcast.

Maras et al depended on the Firefox Debugging API to query for sources involved behind UI feature [54, 59]. Both the scalability and portability of this strategy are limited to the constraints of the Firefox Debugging API. Theseus proposed a global method-wrapping policy for monitoring JavaScript traces that depended on a third-party server to alter sources [48]. We strived to build Unravel without any dependencies on external servers or environmental APIs so that it could scale to handling larger UI changes and share a reusable architecture for implementations in other UI toolkits.

**3.4.0.1. API Harness.** We introduce an API harness as a novel method for monitoring all interactions with an API by placing a removable recording adapter on top of the API. Unravel’s agent applies the API harness to monitor call-stacks and arguments to `window.document` when the user begins a recording and removes it when the user stops a recording. By monitoring the document API, we can see the execution route and arguments of functions asking to query and change the DOM (see Figure 3.5). Data from the harness is sorted and reduced prior to appearing in the Unravel’s JavaScript Function Calls view. Technical details are discussed in the next section.

### 3.4.1. API Harness

The API harness is a removable device installed during runtime that captures JavaScript method traces and arguments (see Figure 3.5). The harness implementation is straightforward: for each method in the API, save a reference to the original method and temporarily replace it with a new method that implements the following:

- (1) Capture the call-stack invoking an API method.
- (2) Capture arguments passed to the API method.
- (3) Serialize the captures for transport.
- (4) Propagate the capture to subscribers.
- (5) Call the original API method with the incoming arguments.

Captures are broadcast from the harness without modification as method calls are made to the API, giving subscribers flexibility in processing the data. Unravel’s API harness call-stack captures implement the JavaScript `Error` interface. As each method call is made to the document API, an error object containing a snapshot of the call-stack

is thrown and caught. This snapshot captures comprehensive execution traces from event handlers down to document queries. Unravel reduces and sorts its captures to simplify inspection for the user (discussed earlier). When a recording is finished, the API harness is removed by restoring the original methods to their respective endpoints in the API.

Alternative approaches to implementing an API harness either require external dependencies or aren't designed to monitor program execution. The Mozilla Remote Debugging Protocol [57] allows developers to access JavaScript threads and observe their execution but it is only available to extensions of Firefox. Lieber et al's Fondue wraps all functions in the JavaScript source to monitor execution, but exists as a separate proxy server that modifies a web page's JavaScript as it passes through [48]. Eagan et al's Scotty enables modification to non-extensible components during runtime, but it does not monitor interactions with those components [21].

Engineering trade-offs limit the capabilities of the API harness but give portability to its implementation. The harness must be able to modify public methods of the original API, it must be able to store references to the original method implementations, and it must be able to access callers and arguments. For example, an API harness would not be able to monitor an API reference that was closed in a private variable, because the harness requires public access to API methods. Despite these limitations, the API harness inspects program activity from within a program and operates without external dependencies. With minimal performance overhead, the API harness scales with API demand without causing interference.

### 3.4.2. HTML Observer and Library Detection

Unravel’s HTML observation implements the JavaScript MutationObserver interface. When the observation scope is changed in the Unravel UI, new MutationObservers are created to monitor the corresponding subsections of the DOM tree. As the observers notice events, they are propagated to Unravel’s sorting and reduction implementation. When each observation is received, its element’s CSS path is calculated by determining the DOM tree location relative to parent and sibling nodes.

The JavaScript libraries are detected by a simple interface detection strategy: for each known library, the Unravel agent tries to invoke published interface methods from the library. We began with Hidayat’s try-catch detection strategy [36], but extended it as we discovered libraries with identical identifiers and overlapping interface methods such as Underscore.js and lodash.js, both of whom have array methods like `_.reduce()`. If the test is successful, the agent detects the library version and returns the name and version number. There are many JavaScript libraries available, yet there is no published standard for declaring the library name and version from within the library. To detect all JavaScript libraries and display information about them is beyond the scope of Unravel, so we tested Unravel with support for the top 20 JavaScript libraries [7].

Website	UI Feature	Trigger
Tumblr	Card Flip View Change	Scroll, Click
Apple iPad	iPad Cover Change	Click
Flickr	Effect Sync to Video	Scroll, Click
Amazon	Product Carousel	Interval, Click
Kickstarter	Photo Carousel	Interval, Click

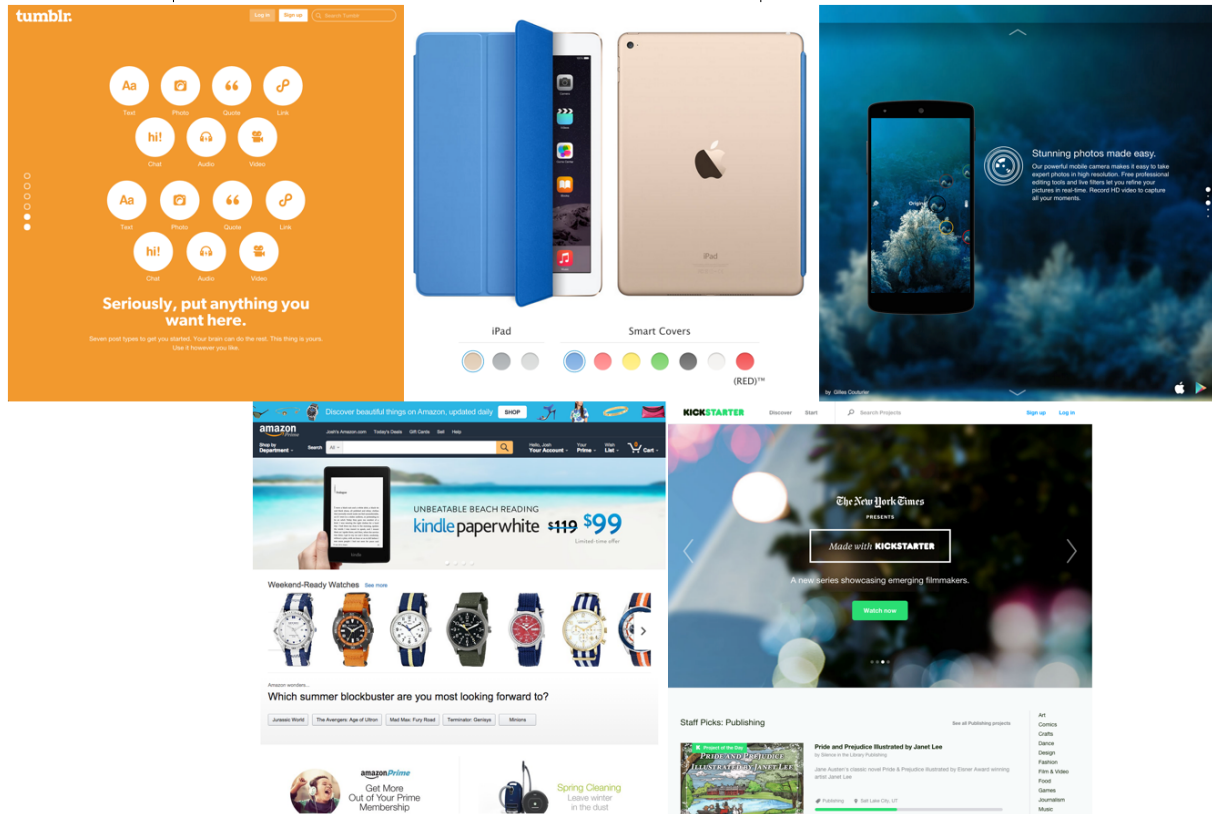


Figure 3.6. Participants reverse engineered 2 UI features from a set of 5. The top table lists each website with its corresponding feature and trigger under inspection. The screen-shots are of Tumblr, iPad, Flickr, Amazon, and Kickstarter (mid left to bottom right).

### 3.5. Unravel User Study

#### 3.5.1. Method

Our study aims to answer the following research questions:

**RQ1** How does a user’s strategy for reverse engineering a web application UI feature differ with and without Unravel?

**RQ2** How does Unravel affect the amount of time it takes a user to reverse engineer a web application UI feature?

**RQ3** Which features in Unravel are the most effective while reverse engineering a web application UI feature?

**RQ4** How do junior developers’ use of Unravel and reverse engineering strategies differ from senior developers?

The target users of our study are junior web developers with less than one year of professional experience and senior web developers with greater than five years of professional experience. The study is a within-subjects design, where each user was asked to reverse engineer a UI feature in each of two websites from a pool of five, one website with CDT and one with CDT + Unravel (see Figure 3.6). CDT as the control requires no training or installation, and our initial study showed that both junior and senior developers could discover key sources using just CDT. 13 web developers, 6 junior and 7 senior, participated in study sessions lasting 45 minutes. Time was limited to 15 minutes each for each reverse engineering task with a 15-minute follow-up discussion. Each participant was compensated \$20. The assignment of websites to participants was randomized, and the order of using Unravel first was reversed for half of the participants.

We chose UI features from five popular professional websites: Tumblr, Apple, Flickr, Amazon, and Kickstarter. While widely used, each contains a clever implementation. When scrolling down on Tumblr’s homepage, a card flip effect peels away each page view. Selecting different iPad covers on Apple’s product page fades through user choices without changing the iPad image. Flickr’s mobile demo synchronizes changes on its virtual phone screen with background fades. Amazon animates its product carousel with easing transitions based on user selection. Kickstarter flips through its banner carousel with fades during pre-programmed intervals. Though not obvious, functionality in these features consists of changing CSS classes, modifying HTML positioning attributes, and loading media in subtle ways.

We taught users about the tool, verified their background, and recorded their tests to ensure result accuracy. Before starting the test, participants were asked to watch a two-minute demo to help them become familiar with how to use Unravel. While participants were recruited by the experience on their CV, they were asked to confirm their amount of professional engineering experience before starting the experiment. Each participant provided a screen recording with audio and click history for the entire experiment.

We tracked three key milestones for reverse engineering. The milestones correspond to events happening at certain times, but participants were encouraged to proceed at their own pace throughout the tests.

M1. Time to finding the first key source.

M2. Time to finding the second key source.

M3. Time to fully understanding how to recreate a feature.



These milestones were tracked via each participant’s screen recording to assess understanding. A key source is defined as a high-level code snippet that provides critical-path functionality for a behavior such as a click handler that adjusts the opacity of a div. Some participants had enough experience to describe a solution without reverse engineering, but they were required to find sources to support their claims. Prior to performing the study, the test set of five UI features were fully reverse engineered to identify significant methods, line numbers, classes and variable names in JavaScript, CSS, and HTML. For each solution, two key sources were identified that users must find for each UI feature in order to fully defend how the behavior is functioning. Timestamps for M1 and M2 were logged if a user displayed a key source in view for three or more seconds. M3 was logged when a participant gave notice of complete understanding.

Study pre-tests revealed inconsistency between web applications caused by source minification and obfuscation. Some users knew of the Chrome Dev Tools “Pretty Print” feature that reformats JavaScript source to be readable, while others were confused by large undecipherable blobs of JavaScript. To remedy source minification, we cloned versions of the popular web applications, manually unminified their sources, and hosted them on a private mirror. Subsequent tests showed that mirroring unminified versions resolved the testing inconsistency.

Participants were given a short follow-up discussion to assess how using Unravel altered their strategy and understanding of web application engineering. Questions about specific features of Unravel were included to assess their qualitative value and provide opportunities for feedback on feature usability. Survey results were compiled into four categories: useful features, improvements, learning, and strategies.

Data recordings from each participant were analyzed for statistics on 25 distinct user activities in CDT and Unravel and the time signatures of the major milestones. User activities include actions with similar complexity to switching an inspector pane, inspecting an event handler, or setting a breakpoint. Paired t-tests for with-Unravel vs without-Unravel were performed across all the coded data in the screen recordings to check for significant differences. Distributions were analyzed on an aggregate to determine average milestone times and activity counts.

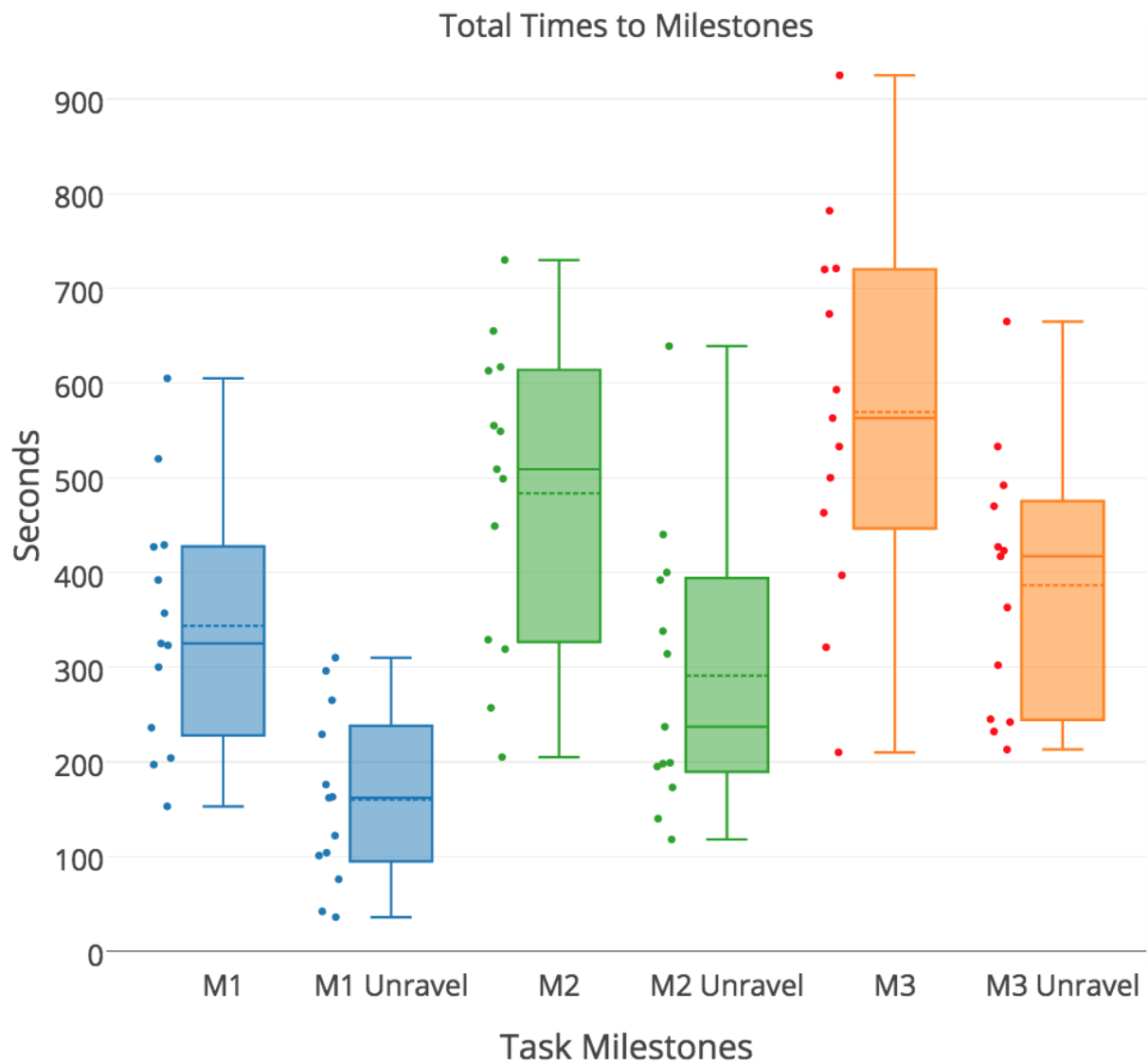


Figure 3.7. Results of the user study are compared in total times to milestones. Boxes indicate interquartile range. Means are shown as dotted lines and medians are solid lines. The box whiskers indicate range including outliers. There is a significant difference in each of total times for M1, M2, M3.

### 3.6. Study Results

#### 3.6.1. How did Unravel affect task completion times?

Unravel significantly decreased time to all three milestones (see Figure 3.7). Developers achieved milestone I, finding their first key source responsible for the UI interaction roughly twice as fast with Unravel (53.4% time decrease,  $t(13) = 4.2, p = 0.0012, \mu_1 = 184s, \mu_2 = 344s$ ) where  $\mu_1$  is CDT + Unravel. Developers achieved milestone II, finding their second key source 39.8% faster with Unravel ( $t(13) = 4.533, p = 0.0007, \mu_1 = 291s, \mu_2 = 484s$ ). Developers achieved milestone III, reaching full understanding 32.1% faster with Unravel ( $t(13) = 3.81, p = 0.0025, \mu_1 = 386s, \mu_2 = 569s$ ).

No significant difference was found in the split times between M1, M2, and M3 (see Figure 3.8). Developers had no significant difference between M1 and M2 ( $t(13) = -0.24, p = 0.81, \mu_1 = 131, \mu_2 = 140s$ ) where  $\mu_1$  is CDT + Unravel. Developers had no significant difference between M2 and M3 ( $t(13) = 0.33, p = 0.75, \mu_1 = 95s, \mu_2 = 86s$ ).

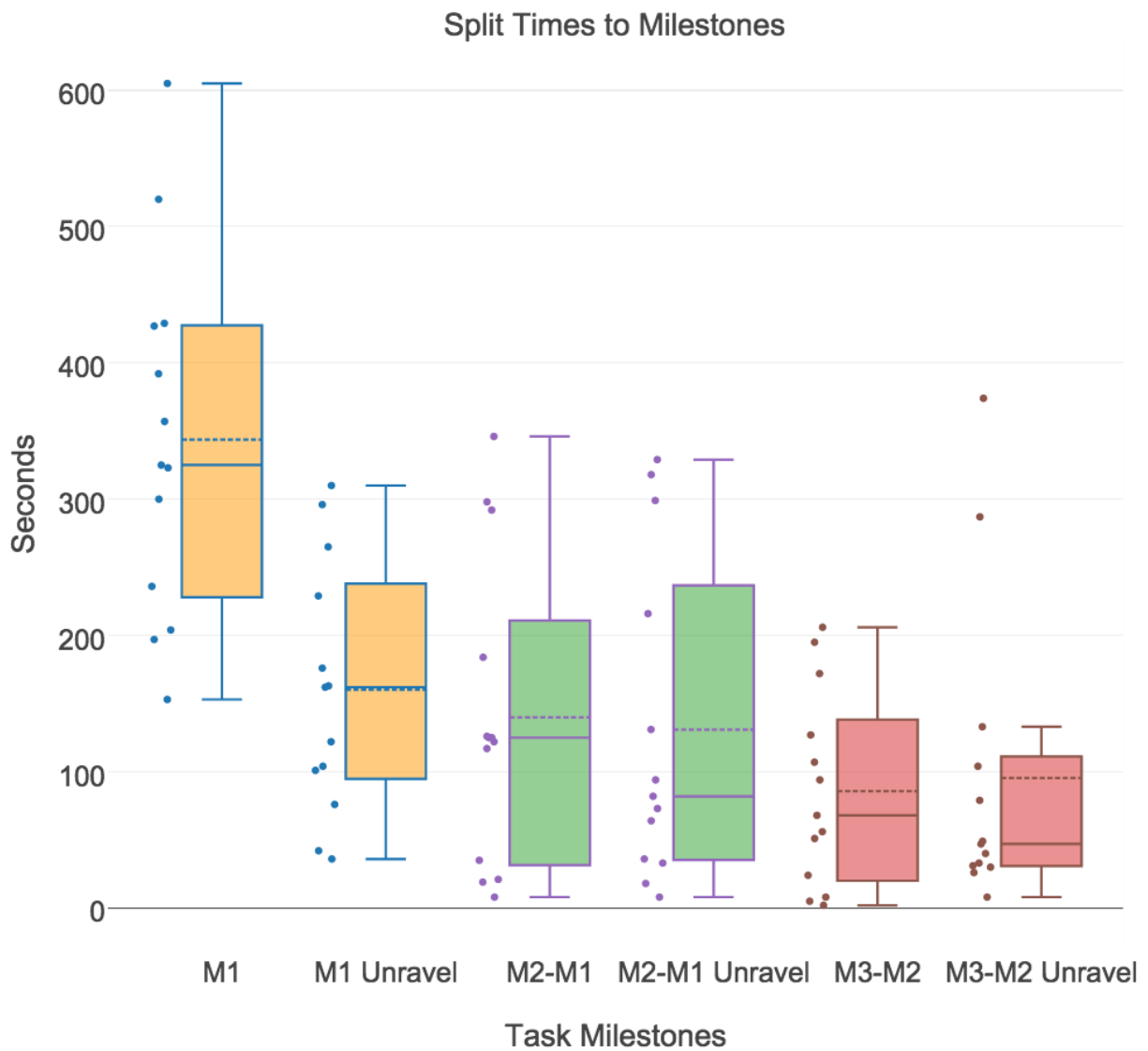


Figure 3.8. Results of the users study are compared in split times between milestones. There is a statistically significant difference between M1 and M1 with Unravel. However, there was no significant difference for the M2 or M3 split times. This means that Unravel was most effective for decreasing the time to first key source.

Differences in milestone times with and without Unravel are explained by variations in user interactions. Developers noted difficulty in finding a starting point during tests without Unravel, which increased their time to M1. Without significant differences in M2-M1 and M3-M2, some participants may have altered their strategy to depend on existing developer tools to find related sources. Total times to M2 and M3 show that no major inefficiencies affected overall time savings by using Unravel.

### 3.6.2. How did Unravel affect reverse engineering strategy?

Unravel significantly altered the reverse engineering strategy developers used when completing their tasks. Developers browsed an average of 2 JavaScript source files with Unravel compared to 10 without Unravel ( $t(13) = 2.84, p = 0.015$ ). Developers searched for text in sources an average of 1 time with Unravel compared to an average of 9 times without Unravel ( $t(13) = 5.6, p = 0.0001$ ). Developers focused on an element for inspection an average of 1 time with Unravel compared to 10 times without Unravel ( $t(13) = 4.67, p = 0.0005$ ). Developers recreated the UI interactions an average of 5 times with Unravel compared to 11 times without Unravel ( $t(13) = 3.45, p = 0.0048$ ).

### 3.6.3. How do junior developers compare to senior developers?

Six junior developers reached M1 without Unravel faster than seven senior developers and had no significant difference in other areas ( $t(13) = 2.24, p = 0.05, \mu_1 - \mu_2 = 141s$ ), where  $\mu_1$  is for senior developers. Differences with less statistical significance include: senior developers set more breakpoints ( $t(13) = 1.99, p = 0.09, \mu_1 - \mu_2 = 4$ ), senior developers were more likely to inspect network ( $t(13) = 2.29, p = 0.06, \mu_1 = 1, \mu_2 = 0$ ),

senior developers inspected more elements ( $t(13) = 1.8, p = 0.11, \mu_1 - \mu_2 = 6$ ), and senior developers inspected more event handlers ( $t(13) = 1.84, p = 0.11, \mu_1 - \mu_2 = 3$ ). While senior developers used different CDT interface controls to reverse engineer, they desired a broader understanding of the UI feature in the context of the website. A senior developer stated, “I had an idea of how the feature worked before I started, so I wanted to see how the feature was situated in the application first.”

#### **3.6.4. Which features of Unravel were the most effective?**

In the follow-up discussion, all 13 participants were interviewed for their opinion on Unravel’s features, Unravel’s weaknesses, reverse engineering strategies, and concepts learned. 10 out of 13 developers stated the JavaScript method traces were most helpful for them to understand a solution. The remaining 3 out of 13 developers stated the HTML changes pane was most helpful. 5 out of 13 developers found the library detection pane useful, while the other 8 stated it did not provide any help. 4 out of 13 participants noted that Unravel could be improved by integrating library detection into the JavaScript stack-traces to highlight the difference between library vs non-library source. 7 out of 13 participants stated a new programming concept they learned while reverse engineering with Unravel, such as using class-toggling to animate objects off screen or using scroll-to thresholds to activate events on a page. 5 out of 13 participants found constraining the scope of observation useful.

### 3.7. Limitations

Unravel only provides recordings of client-side traces and execution. Server-side source code typically isn't made available for external inspections, but there is an effort to study how to expose API endpoint and behaviors from front-end source [54]. Further, professional websites typically use source-code minification techniques to decrease the size of their files an average of 20% [70]. For our user tests, sources were manually unminified for participants. This feature can be added to Unravel with the use of JavaScript libraries like js-beautify [49], where sources would be parsed and reloaded in unminified form.

Our study did not attempt to identify UI features for which Unravel is not able to provide meaningful information. Unravel only observes JavaScript and HTML pertaining to changes in the DOM. Other JavaScript activity such as data-management, storage, and retrieval would not be visible in Unravel unless a DOM-query was involved in the same call stack (e.g. Unravel would surface functions appending data to the page from an AJAX response, but not the prior AJAX request). In our preliminary study, we discovered shortcomings from SVG transitions where elements had hundreds of positioning attribute changes each second. This flood of changes carries a risk of burying relevant sources. Pseudo-elements and CSS pseudo-classes are outside Unravel's scope of observation but can be easily discovered with existing inspection tools.

In-memory state storage techniques are outside the observation scope of Unravel. Unravel's API harness will not be able to monitor communication with privately closed references to an API. If a web application is designed to preload DOM API queries into memory on page load, Unravel will not capture the query in its API harness if it was not



actively recording at page load. A potential workaround is to detect these behaviors and inject the API harness and observation agents prior to page load.

### 3.8. Conclusion

Having demonstrated the effectiveness of Unravel for helping web developers reverse engineer professional websites quickly, we revisit techniques that contribute to Unravel’s effectiveness.

#### 3.8.1. Organizing and Presenting Large Volumes of Traces

Compared to the performance and interfaces of other source-tracking systems, Unravel is distinguished by its abilities to reduce, scope, and filter large amounts of source detection information in a way that highlights relevant data for the user. A participant stated, “Unravel was way easier to locate specifically where and when in the files the code was executed.” We observed through the study that participants found relevant sources by looking at the top items in the HTML JS tracking panels in Unravel. A different participant stated, “Without a doubt I prefer Unravel over sifting through element changes in the Chrome Inspector.”

#### 3.8.2. Tracing UI Features to Relevant Sources

Advancing related work [59, 54, 16, 11, 13, 30, 72], Unravel introduces a reusable architecture that is both portable and scalable. Unravel serves as a recorder and reducer of meaningful information, with detailed inspection delegated externally. The implementation for this chapter was in CDT, but a participant asked, “Could we have this for Node.js?” While there isn’t a DOM to observe, Unravel’s JavaScript source tracing

and library detection would work in Node.js. For example, an API harness placed on the HTTP API could capture meaningful traces supporting a GET or POST request. The API harness and application agent allow Unravel’s architecture to be reused in any JavaScript environment. The scalable nature of Unravel’s architecture allows it to accommodate long recordings of complex features. A participant stated, “I don’t even need to inspect, I just hit record and it goes. That by itself is great.”

### **3.8.3. Toward Fine-Tuned Discovery in Web Applications**

This chapter provides a contribution towards helping users quickly identify relevant HTML and JavaScript supporting a web feature, however the user discovery interaction involves back-and-forth navigation and only provides one-way inspection pointers into front end code. Unravel quickly helped users identify responsible source code, but its study reveals that Unravel had no noticeable effect in decreasing the amount of time to reaching understanding of the source code (M2 and M3). Returning to the goal of creating Readily Available Learning Experiences from production websites, the next chapter introduces the Telescope system to overcome Unravel’s limitations and expand upon its contribution. Telescope provides users with composite views of low-barrier learning materials with support for two-way source discovery between the website feature and its relevant source code.

## CHAPTER 4

**Telescope: Fine-Tuned Discovery of Web Feature Source Code**

This chapter presents the second application towards RALE, Telescope, which is an interactive platform for discovering how JavaScript and HTML work *together* to support a web feature interaction. This chapter contributes a technique to overcome limitations in Unravel’s back-and-forth inspection style through dynamic links and interactive time and detail filtering. This chapter has adapted, updated, and rewritten content from a paper at User Interfaces Systems and Technology 2016 [35]. The source code for Telescope is openly available <sup>1</sup>. All uses of “we”, “our”, and “us” in this chapter refer to coauthors of the aforementioned paper.

Professional websites contain rich interactive features that developers can learn from, yet understanding their implementation remains a challenge due to the nature of unfamiliar code. Existing tools provide affordances to analyze source code, but feature-rich websites reveal tens of thousands of lines of code and can easily overwhelm the user. We thus present *Telescope*, a platform for discovering how JavaScript and HTML support a website interaction. Telescope helps users understand unfamiliar website code through a composite view they control by adjusting JavaScript detail, scoping the runtime timeline, and triggering relational links between JS, HTML, and website components. To support these affordances on the open web, Telescope instruments the JavaScript in a website without request intercepts using a novel *sleight-of-hand* technique, then watches

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<sup>1</sup>Telescope Github <https://github.com/NUDelta/Telescope>

for traces emitted from the website. In a case study across seven popular websites, Telescope helped identify less than 150 lines of front-end code out of tens of thousands that accurately described the desired interaction in six of the sites. In an exploratory user study, we observed users identifying difficult programming concepts by developing strategies to analyze relatively small amounts of unfamiliar website source code with Telescope.

## 4.1. Motivation and Contributions

### 4.1.1. Deriving Authentic Learning Material

Telescope aims to support authentic learning [66] by generating low-barrier learning materials to understand code from professional websites of personal interest. Professional websites offer rich details missing from training examples, content that relates to the real world, and opportunities to think in the models of the discipline. However, despite the abundant availability of front-end code, website source code is difficult to read and can contain superfluous details that distract from learning core concepts.

Deriving learning material from websites presents design and technical challenges due to the magnitude and complexity of the underlying source code. A simple UI interaction may require only ten lines of JavaScript, but modern web applications can have tens of thousands of lines of code [6, 64, 70]. Bindings between HTML and JavaScript support an interaction, but it is difficult to determine how such bindings are constructed. A simple calendar widget, for example, could be created entirely in JavaScript and appended to the DOM with listeners, or it could be built in HTML and CSS with inline calls to JavaScript hooks. Embedding the widget amidst all its library or utility code in a minification build process blurs the location and scope of code most relevant to enabling the widget’s

functionality. With prior tools [48, 59, 34, 14, 2, 25, 5], it is difficult to (1) capture the entire scope of JavaScript used, (2) identify the interplay between JavaScript and HTML, and (3) trim away inactive code and library code that get in the way of learning.

#### 4.1.2. Introducing Telescope

We thus introduce *Telescope*, a platform that supports the discovery of website feature implementation by allowing the user to fine-tune a composite view of responsible JavaScript and explore visual links between JavaScript, HTML, and rendered UI components (see Figure 4.1). Telescope helps users generate low-barrier learning materials — less than two hundred lines of code — from tens of thousands of lines of complex website code. For example, a curious user could discover how an interactive map component achieves its dragging effect in JavaScript and HTML by setting Telescope’s JavaScript detail level to minimum (dom-modifiers only) and time constraints before and after the click-and-drag. By clicking call and query markers in the interface, visual lines connect JavaScript methods to queried DOM elements, and corresponding DOM components are highlighted in the website. Telescope introduces three design principles to support the creation of learning materials from websites:

- (1) *Single Composite View*: As a user interacts with a website, Telescope brings together relevant JavaScript for an interaction into a single, composite JavaScript view to resolve the challenges in finding all code relevant to a behavior in unfamiliar code [29]. Users can easily hide sources they deem irrelevant or alter the display order of script sources relative to their dependency load order.

- (2) *Detail and Time Controls*: The user can scope relevant Javascript by call time and control the amount of detail they wish to see, ranging from showing DOM-modifying code excluding libraries to only showing all JavaScript present in the website. These controls address a critical need discovered through our human-centered design process, when we found users struggling to understand the code for an interaction when there is either too little or too much JavaScript to analyze.
- (3) *Visual Links*: Visual links connect active JavaScript to lines of HTML and website DOM components to expose end-to-end functionality.

The technical contributions of Telescope support its design principles and enable using Telescope to examine website UI interactions across the open web in real time. Specifically, we introduce (a) the *Wisat architecture*, which supports source code tracing and instrumentation on public websites, and (b) the *Sleight-of-Hand method* (SoH), which swaps a website’s client-side implementation during runtime with its instrumented counterpart. The SoH method transitions websites from a non-traceable state to a fully instrumented state, supporting live interaction traces as a user interacts with their website. The Wisat architecture then transmits runtime traces used to decide which JavaScript is displayed in Telescope’s composite view and provides the linking data necessary for drawing connections between JavaScript, HTML, and website components. In the rest of this chapter, we introduce Telescope and its main components for tuning UI discovery and linking JavaScript and HTML source code. We examine Telescope’s performance and study its effectiveness through a case study using Telescope on seven professional websites and an exploratory study with five users. We conclude with a discussion of design principles, limitations of our approach, and a brief look at the next chapter on Isopleth.

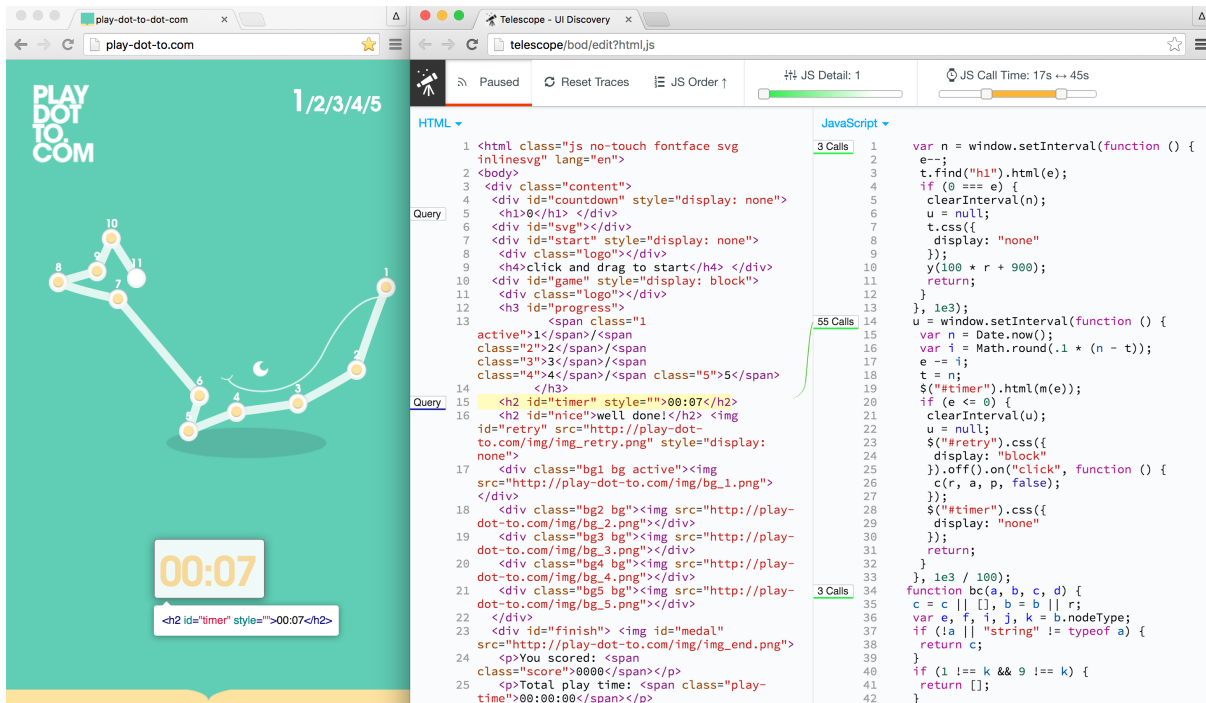


Figure 4.1. The Telescope interface is being used to discover how this HTML5 connect-the-dot game's timer works. The interface is paused to freeze the current view. The detail level is set at minimum, and the JavaScript call time is constrained between the 17th and 45th second of execution. The left Telescope panel (middle) shows a filtered HTML view, where an active element is highlighted and query markers denote that JavaScript queried those lines during the chosen time window. The right Telescope panel shows the website's JavaScript, filtered by time and detail. With the current settings, only the most relevant JavaScript is displayed: active non-library JavaScript which queried the DOM in the constrained time frame. A curved line is drawn to connect the JavaScript line to its DOM query.

## 4.2. Telescope

Telescope is a web-based platform for producing learning material to implement a UI interaction. By using the Wisat architecture discussed later, Telescope receives JavaScript runtime traces and DOM state changes from a website’s UI during use. The user views all JavaScript for a website in a single composite view, condensed by time constraints, filtered by detail level, and ordered by last-loaded script file first. User-activated visual links connect JavaScript, HTML, and rendered components in the browser (See Figure 4.1).

### 4.2.1. Receiving JavaScript, HTML, and Trace Activity

A user launches Telescope by initiating website instrumentation from a browser extension. Once connected, Telescope begins receiving traces and its interface updates in real time to reflect the latest DOM state and an accumulation of JavaScript traces. Queried DOM elements are marked with a *Query* gutter marker. Active JavaScript functions are marked with a *Call Count* gutter marker, a technique we adopted from Theseus [48]. Telescope continuously analyzes call graphs to determine which JavaScript calls were involved in querying the DOM. If an active function is identified as being involved in a DOM query, it is marked with a green call marker instead of a colorless marker to highlight its significance. Depending on the detail setting, a user will see a certain subset of JavaScript in view with the corresponding call counts for that subset. As a user continues their interactions with the observed website, their function invocation counts will increase.



### 4.2.2. Tuning Telescope: Order, Detail, and Time

A core design goal in Telescope is to avoid overwhelming the user with large amounts of trace information by presenting the most relevant JavaScript together in a single composite view. Most of the websites tested in our case study, such as The New York Times “Snow Fall” article, have tens of thousands of lines of unminified JavaScript and hundreds of lines of HTML. Even a simple photo-slideshow change effect could have thousands of function invocations if embedded in MVC logic from a large JavaScript framework like Angular or React.

The controls in the header of the Telescope interface allow the user to fine-tune the source code activity during a UI interaction (See Figure 4.1). From left to right, the user has the ability to (1) pause/resume activity, and to reset the interface to a cleared activity state; (2) flip the JavaScript presentation order; (3) adjust the detail of JavaScript sources displayed; and (4) constrain the time of active JavaScript sources. We discuss each of these affordances below.

**4.2.2.1. 1. Pause/Resume and Reset Traces.** The Telescope UI updates continuously as the website’s UI state changes to show live updates to source code execution. Users can see active JavaScript populate in view, as well as increasing call/query counts next to JavaScript/HTML lines. To freeze the capture state and ignore ongoing functionality, a Telescope user can pause the interface at its current DOM state and JavaScript trace collection. Users can browse and interact with other UI controls during this frozen state, but no new data will be displayed. Upon resuming, Telescope updates to the latest state of the website. Resetting Telescope empties its collection of JavaScript traces and synchronizes its HTML view with the latest DOM state.

**4.2.2.2. 2. JavaScript Order.** Early pilot studies revealed that relevant source is often found in scripts at the end of a website’s load order. The interpreted nature of JavaScript combined with the disorganized nature of website script-loading leads web developers to load scripts with more dependencies last and fewer dependencies first [4]. As a consequence of this dependency pattern, our earlier prototypes often placed the most important high-level JavaScript hidden at the bottom, leaving relevant code out of view. Based on this observation, Telescope by default inverts the load order to display last-loaded scripts first as a heuristic. The composite JavaScript panel in Telescope displays scripts sorted as a whole, so the inner contents of scripts will remain in their original form. The JavaScript order control allows a user to invert the presentation order, e.g. to support cases where our heuristic may not apply.

**4.2.2.3. 3. JavaScript Detail.** Early pilot studies also revealed that simply showing users all active JavaScript code provided little value. To support discovery, our test users requested variable control over the detail visible. With Telescope’s JS Detail slider, a user can control the amount of JavaScript visible. By default, Telescope slides detail to the left extreme (L1), which shows how higher-level JS achieves an effect using library APIs without showing library code. Low-level DOM API calls are often wrapped by libraries and would be hidden at this level, e.g. a jQuery call `$(div)` is displayed instead of the DOM API call. Sliding detail to the other extreme will reveal all of the JavaScript for a website. The detail levels include:

L1 (default): DOM API callers and parent callers, excluding library code. For example, call stacks to `document.getElementById` would be surfaced as well as calls to library API’s wrapping `document.getElementById`. In this detail level, a jQuery library call like

`$('#fooId')` would appear and be marked with a green hit marker, but the internal calls within jQuery would not appear.

L2: Active JavaScript, excluding library code. This includes any JavaScript that ran in addition to the above level without showing library code. For example, functions updating objects in memory or storing cookies would appear here.

L3: Active JavaScript. In this level, all of the JavaScript that run during a user's interaction with the page will appear here. In other words, only dormant code is hidden.

L4: All JavaScript excluding library code. This level will show all JavaScript in a website (both active and inactive) while hiding library code. In other words, this level shows users what code was written specific to the website while hiding third party library code.

L5: All JavaScript. This level will surface all of the JavaScript for the page to show users the most comprehensive view of libraries and professional code working together.

**4.2.2.4. 4. JavaScript Call Time.** Telescope users can use timeline constraints to set a start time and end time to see which functions were executed during the specified interval. While JavaScript can execute asynchronously at arbitrary times, users can still slide the time constraints as a way to omit code outside a time interval, such as initial setup code or continuous interval functions. Dragging markers on the timeline reshapes the scope of time in percentage of width dragged. Constraining the timeline in this way helps users who wish to inspect multiple interactions they made with the website by constraining the inspection view to different points in time.

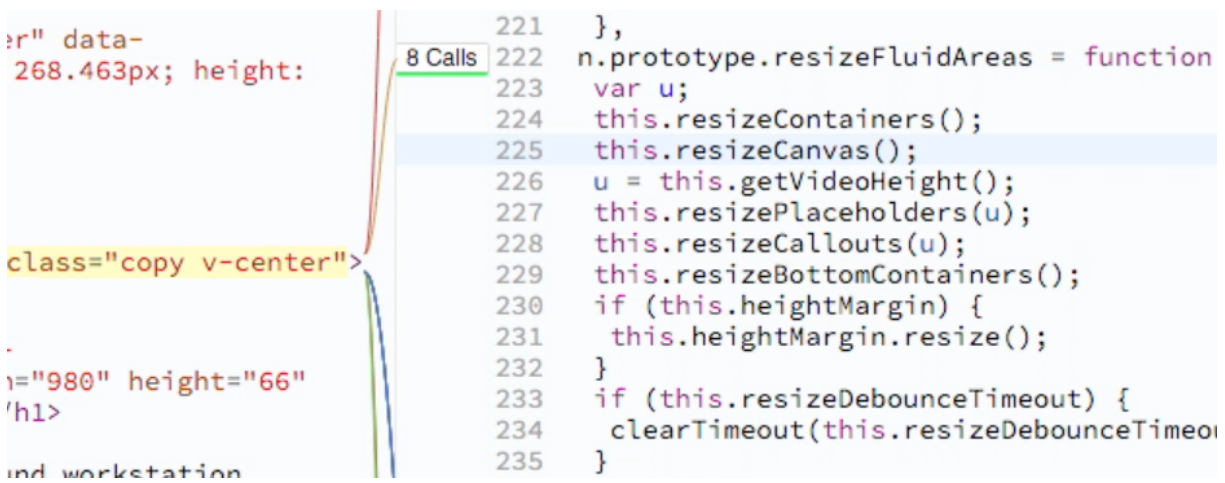


Figure 4.2. Clicking a Telescope HTML query marker from the Mac Pro website (left) shows lines to four JavaScript functions. In this view, a line leads to function `resizeFluidAreas`, which resizes elements on scroll.

#### 4.2.3. Linking HTML, JS, and the Rendered DOM

Telescope provides bidirectional visual links between the HTML, JavaScript, and website DOM to provide end-to-end connections from source code to its UI output. Inspired by *Glimpse* — which creates in-place visual transitions from code to UI and vice versa [20] — these links help form conceptual models of how JavaScript and HTML work together. But unlike *Glimpse*, Telescope shows both the source code state and rendered UI simultaneously. Users can visualize how high level functions change many elements (see Case Study: Mac Pro) or how a single element event can trigger many function handlers (see Case Study: Dot-to-Dot). During Telescope sessions, *Query* markers appear in the HTML pane, and *Call* markers appear in the JavaScript pane. Clicking an HTML query marker draws lines to JavaScript functions which query the HTML line (see Figure 4.2). Clicking a green call marker (signifies DOM-query) draws lines to HTML nodes which were queried by the JavaScript line.

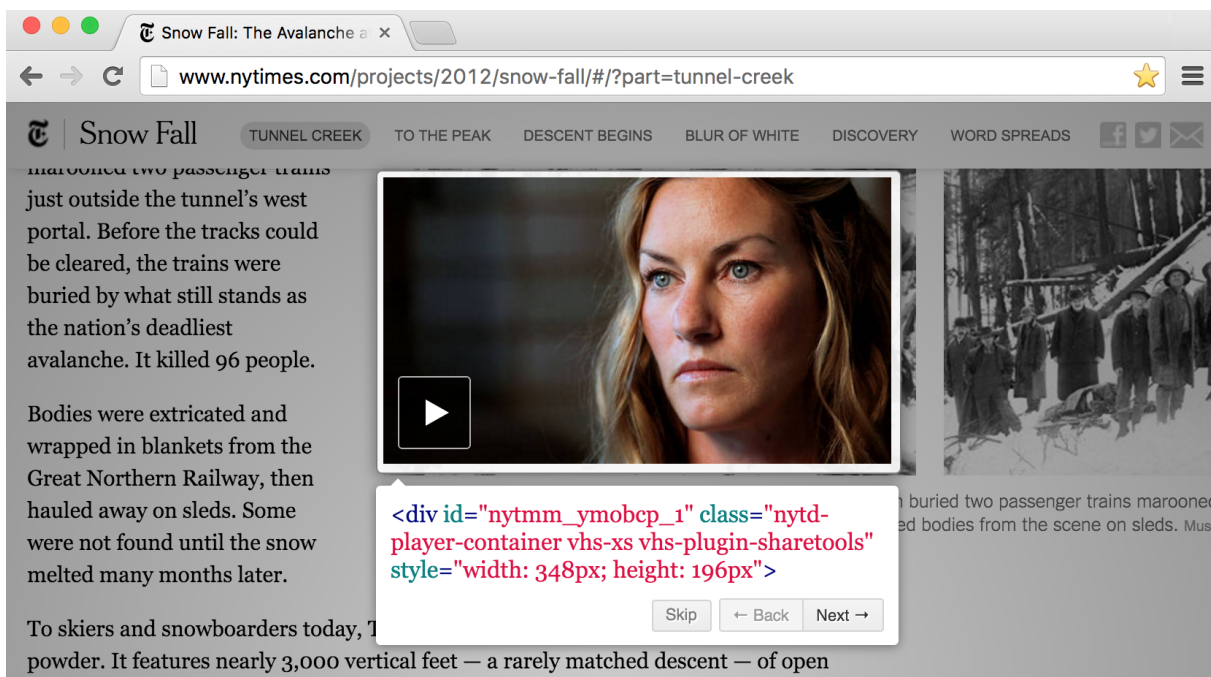


Figure 4.3. Clicking Telescope’s code markers for the New York Times “Snow Fall” website highlights related DOM elements in the website. The DOM element’s source is included in the highlight, connecting context to Telescope’s HTML view.

Exploring HTML-JS links in either direction invokes a response in the website, where the rendered DOM nodes are highlighted in the foreground (See Figure 4.3). If multiple DOM nodes are involved in a query, a walkthrough is constructed in the rendered website that highlights each involved element in sequence. Conversely, if elements were deleted, the user is notified that the element is no longer in the DOM.

In early pilot studies, traces from library, tracking, and ad-content scripts caused confusion in understanding UI feature implementation. Telescope now hides many libraries and irrelevant scripts and provides affordances for users to hide other scripts they deem

irrelevant. By default, library scripts such as jQuery and Angular are hidden, as are popular advertisement and usage-tracking scripts such as DoubleClick and ScoreCardResearch. Users can then hide or show scripts selectively in two ways. Through the JavaScript drop-down view at the top of the JavaScript panel, users can see a complete list of the sources in view and selectively toggle their visibility. Alternatively, users can slide the detail slider to the far right to bring all sources into view (more library and ads) or far left to show only sources relevant to DOM manipulation (less library and ads, see Figure 4.1 top right).

#### 4.2.4. Design Process and Design Insights

In the process of designing Telescope, we iterated through three software prototypes. Prototype 1 provided the ability to record an interaction and extract a subset of HTML, CSS, and JS into a web sandbox with visual output that can be shared with other users to explore on the web (e.g. for use in a group). Prototype 2 dropped sandboxed output and added affordances to selectively hide inactive code and sources. Clicking JS gutter markers exposed a function’s callstack. Prototype 3 gained the Wisat architecture for continuous distributed tracing. After prototype 3, we trimmed features users didn’t value and added controls for order, time, detail, and interactive links.

With each prototype we conducted a small pilot study to better understand how to help users overcome learning barriers tied to unfamiliar code. Each study recruited a convenience sample of three junior developers who used the prototype for 30 minutes each and were paid \$20. In this process we discovered four primary design insights:

- **Users need variable amounts of JavaScript to understand different programming concepts.** Each prototype provided affordances to selectively trim

down the JavaScript, but users were unsure what to trim and found it difficult to remember what they had trimmed from view. Users expressed desires to see both high-level code and low-level utility code at different times to establish a basic understanding of how the program works before looking into its details. We implemented the JS Detail control to adjust the composite JavaScript view to different detail levels such as more minimal for DOM-modifying code or more verbose for deeper discovery involving AJAX and MVC logic.

- **Users have varied processes for playing and inspecting.** Observed in all three studies, some users like to repeat their interaction several times before using Telescope, whereas others will create an interaction and jump to Telescope before it completes. Prototypes 1 and 2 had a static extraction technique that frustrated users who liked to alternate between playing and inspecting. Telescope now continuously updates both its HTML and composite JavaScript as user plays with a website, while also giving the ability to pause and constrain their historical runtime timeline.

- **Users benefit from visual links connecting code to observable output.** Similar to Gross et al’s recommendations to *connect code to observable output*, we found that linking the JS and HTML contexts to observable output helped users understand JavaScript’s relationship with HTML [29]. By the third prototype, our users were still having trouble understanding how the JavaScript and HTML related even though active-code highlights were provided in both panes. We added support to draw visual lines from either direction between HTML and

JavaScript. Upon drawing these lines, the DOM element is highlighted in the website to complete the connection between the code and its output.

- **Metadata and redundant filters overwhelm the user.** Throughout prototype iteration, we kept accumulating features which began distracting users from efficiently using Telescope. To promote simplicity, we cut away features that were distracting or provided little use to achieving the goal of promoting understanding. Features cut included call-stack inspection, the CSS pane, a DOM preview pane, code-hiding toggles, and other extraneous features.

### 4.3. Implementation

Telescope’s implementation goals include deployability across the open web, full-scope JavaScript instrumentation, and multi-user session support. Unravel [34] and Scry [14] provide JavaScript traces on public websites but limit their inspection scope to DOM-querying JavaScript. Theseus [48] provides full instrumentation but requires a debugging proxy for setup on public websites. To support future empirical field research and promote user adoption, we seek implementations that are easy for users to install with minimal setup. Existing architectures from related systems are designed to only support single-user sessions.

In the rest of this section, we describe the *Wisat architecture* and *Sleight-of-Hand methodology* that together enable Telescope to bring source instrumentation and JavaScript trace analysis to public websites with minimal user setup. Building upon related systems, Telescope brings Fondue’s source instrumentation to the open web, augments Theseus’



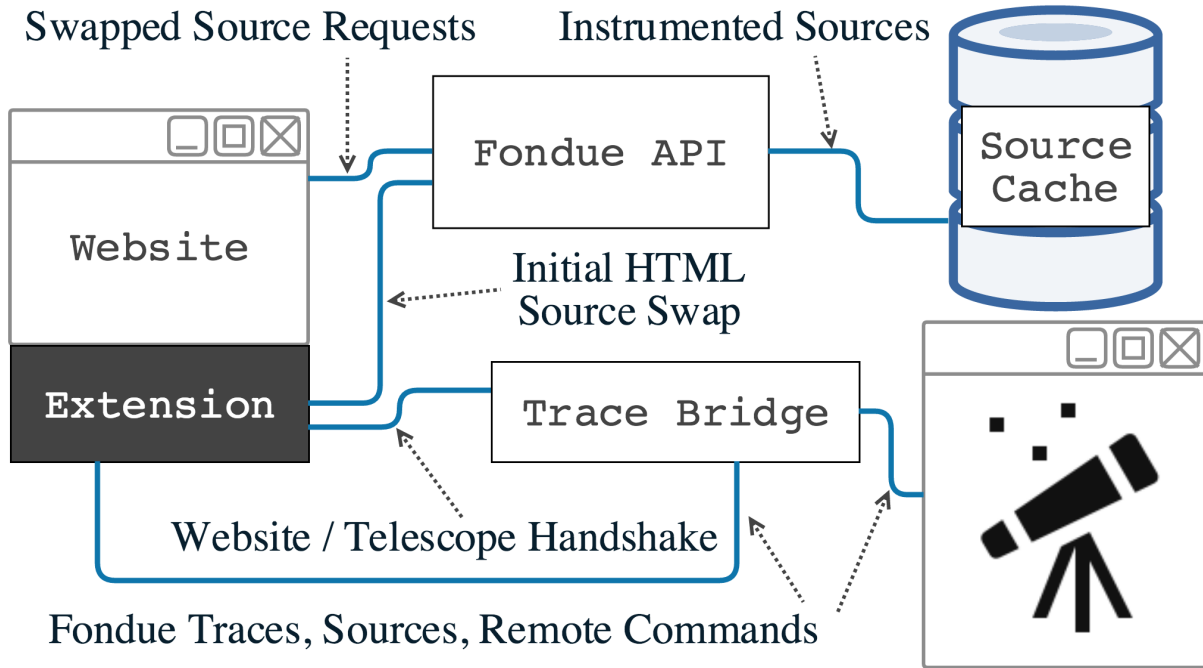


Figure 4.4. The Wisat architecture supports Telescope’s ability to remotely process website interaction traces. A website receives its initial source swap via the Chrome extension. The website fetches instrumented scripts from the Fondue API (top), and the Chrome extension negotiates a two-way handshake via the Trace Bridge to connect it with its Telescope session (bottom). Upon successful connection, JavaScript traces and source data propagate continuously over the trace bridge.

active code markers with interactive links, and uses JSBin’s collaborative online editor environment as a foundation [48, 67]. Telescope consists of a component-based architecture where new technologies can be swapped in or integrated later on.

#### 4.3.1. Wisat Architecture

The Wisat (Web interface swap and trace) architecture supports Telescope’s JavaScript instrumentation, trace propagation, source transmission, remote control, and sleight-of-hand source swapping. After a website is instrumented via the browser extension, Fondue

API, and source cache (see Sleight-of-Hand Method), the browser extension negotiates a two-way handshake between the website and Telescope interface via the *trace bridge*. Once connected, traces, sources, and remote commands can flow freely between the two, populating Telescope’s code views and enabling remote DOM component highlighting (see Figure 4.4). Designed for web scalability, this architecture separates functional components so that each may be distributed across multiple load-balanced instances. The components of this architecture are defined as:

- Telescope UI: A website for receiving source trace activity from an instrumented website, fine-tuning source findings, and sharing with others.
- Fondue API: REST web service for JavaScript & HTML instrumentation and deobfuscation with caching, served over HTTPS to comply with mixed-content policies.
- Trace Bridge: WebSocket server for live cross-origin-compliant transmission of JavaScript traces, DOM changes, and commands between the website and Telescope interface.
- Chrome Extension: Agent injected into website to deploy the Sleight-of-Hand source swap, broker handshake with Telescope interface, and broadcast source activity.

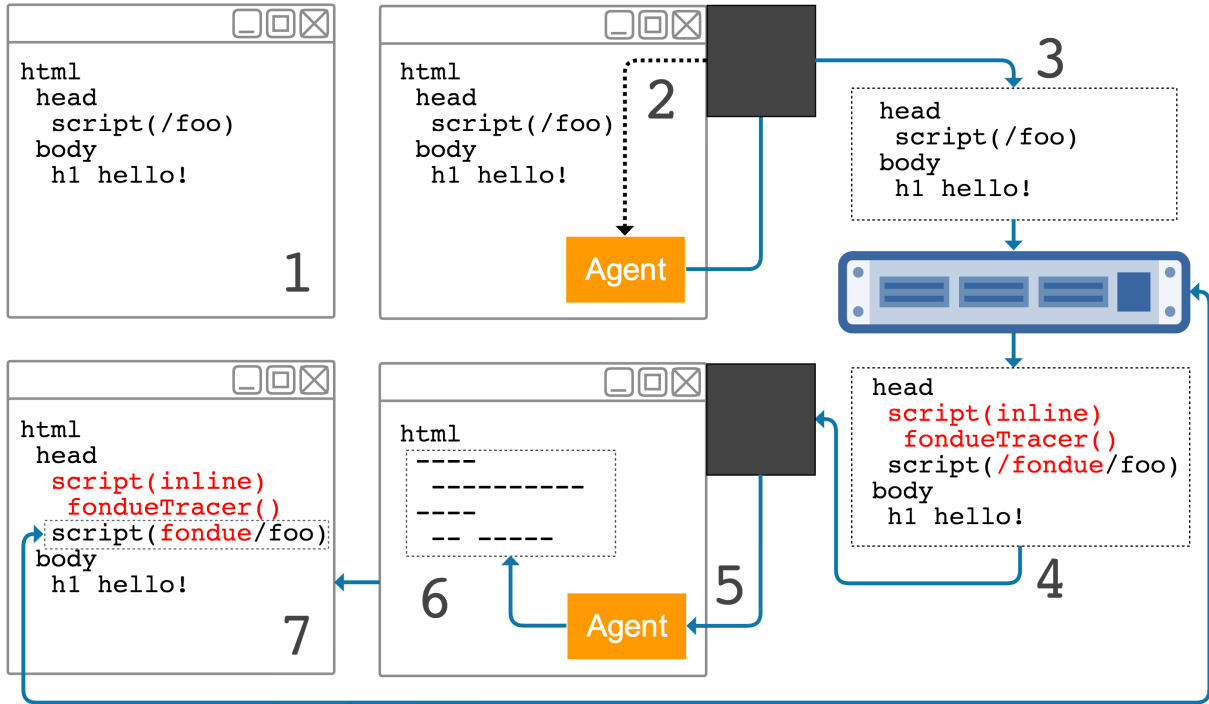


Figure 4.5. The Sleight-of-Hand technique pictured above is a 7-step process for instrumenting a website’s source code via browser extension (black squares) and external instrumentation server (blue, middle right). After website load (1), the extension deploys an agent (2). The agent sends the sources for instrumentation via AJAX (3), which are returned (4), passed to the agent (5), and swapped for the originals, deleting references (6). The browser makes requests for the newly instrumented sources (7).

#### 4.3.2. Sleight-of-Hand Method

The Sleight-of-Hand Method (SoH) expands upon techniques from Fondue [48] to bring source instrumentation to public websites. Current methods for JavaScript source tracing either trace only DOM-querying JavaScript [34, 14, 13] or require a man-in-the-middle debugging proxy [48]. Neither of these approaches fits with our goal to fully trace JavaScript execution and make setup simple. The SoH method — deployed from a one-click-install browser extension — implements full JavaScript traceability by swapping the

scripts of a website with their instrumented versions. The SoH process is outlined below (see Figure 4.5):

- (1) Load a website and initiate SoH.
- (2) Deploy a JavaScript agent into the website from a browser extension with bidirectional communication.
- (3) Agent transmits the OuterHTML property of the root DOM element to the instrumentation API via extension, circumventing cross-origin policy.
- (4) Instrumentation API returns the HTML with inline scripts instrumented and `<script>` tags with altered “src” attributes pointing to an instrumentation API URL.
- (5) Browser extension passes the response to the agent.
- (6) Agent clears the DOM and JavaScript state to ready the page for an artificial load process (without refreshing). It does so by overwriting the existing DOM with an empty root, iterating through non-native window object attributes while deleting them, and calling `clearInterval` on global interval indices 1 to 999.
- (7) Agent inserts instrumented pieces of the DOM in a strict order to control script loading to simulate the script load order of the original site.

SoH leverages vulnerabilities enabled by browser extensions, circumventing source alteration protection by overwriting original sources [15]. An SoH is deployed from a browser extension with liberal permissions to modify the page and communicate with third party servers. It does so regardless of logged-in state or HTTPS encryption.

The SoH method works for many websites, but synchronized HTML/JavaScript workflows and Content Security Policies (CSP) can cause problems. For example, if a user

kept scrolling for more news to load in a Facebook news feed, the in-memory JavaScript would reflect news list additions and the HTML would reflect the same. If the SoH was initiated after scrolling for more news, the news list HTML would be correct, but the in-memory JavaScript would not have the news list additions. The result would be an odd-UI experience where interactions hit sync-error handling, such as moving the user back to the top of their news feed. Further, any scripts lazy-loaded after the SoH starts and before SoH ends would cause more UI oddities or potentially break the process. If breakpoints were injected into the page during the SoH process, it would simply pause the process. Implementing a whitelist CSP successfully blocks the SoH method, because it asks the browser to enforce a strict list of source domains [77]. However in Chapter 5, a workaround is provided to remove CSP headers from obstructing the SoH process.

#### 4.4. Case Study

To better understand Telescope’s capabilities and performance, we used it to identify relevant lines of code, key interaction methods, and implementation patterns across UI features on seven popular websites. This study aims to address the following research question:

**RQ1** To what extent can Telescope reduce and scope lines of code for understanding complex feature implementations?

We chose websites with interesting and complex UI features that are not straightforward to understand, that have over ten thousand lines of code. Interactions of interest include a map-drag (XKCD), a scroll animation (Tumblr), a dot-drag (DotToDot), scroll-driven video sizing (NYT), a load-and-scroll-driven float (iPhone), a scroll-driven product

	Class	Initial Stats		Website On-Load Activity				Website Interaction Lines of Code			
		HTML LOC Total	JS LOC Total	HTML Queried	Active JS	Telescope Default JS	LOC Reduced	HTML Queried	Active JS	Telescope Default JS	LOC Reduced
XKCD 1110	L	77	11,023	31	9,378	4,730	57.09%	1	1,079	49	99.56%
DotToDot	M	34	12,910	3	9,697	5,534	57.13%	23	1,687	115	99.11%
iPhone SE	M	788	53,810	95	8,648	2,341	95.65%	20	907	84	99.84%
Tumblr	H	182	92,070	34	10,504	4,970	94.60%	1	1,839	52	99.94%
Mac Pro	H	794	33,631	248	10,095	1,877	94.42%	68	1,650	934	97.22%
Southwest Air	H	4,140	35,011	143	8,342	4,577	86.93%	1	1,825	53	99.85%
NYT Snow Fall	H	1,458	41,526	2	2,546	521	98.75%	30	522	150	99.64%
<b>Average</b>		<b>1,068</b>	<b>39,997</b>	<b>79</b>	<b>8,459</b>	<b>3,507</b>	<b>83.51%</b>	<b>21</b>	<b>1,358</b>	<b>205</b>	<b>99.31%</b>

Figure 4.6. Results from our case study show the amounts of code Telescope reduces, using time and detail filters to draw distinction between on-load setup code and interaction code. Each website’s complexity class is provided (Small, Medium, High). The JS total lines of code (LOC), calculated after normalized unminification, are listed per each website (left) and categorized by all active JS LOC and the default DOM-modifying JS LOC with library code removed. In blue (middle, right) the LOC in Telescope’s default view for on-load and interaction show the amount of reduction Telescope performs for the user while maintaining relevance. HTML LOC queried are listed, showing the small portion of DOM elements involved in each UI interaction. Interactions include a map-drag (XKCD), a scroll animation (Tumblr), a dot-drag (DotToDot), scroll-driven video sizing (NYT), a load-and-scroll-driven float (iPhone), a scroll-driven product show (Mac Pro), and a date-picker render and select (Southwest).

show (Mac Pro), and a date-picker render and select (Southwest). We classified websites as light (L), medium (M), or heavy (H) in proportion to their UI complexity and average number of function invocations. For each example, we tracked the minimum usage necessary to discover UI features on the website, while comparing against Unravel as a control.

#### 4.4.1. Fine-Tuning Lines of Code

Telescope supported discovery on the seven websites with minimal tuning regardless of source code size (see Figure 4.6). We measured the lines of code visible in Telescope

during on-load and interaction, normalizing JavaScript and HTML with unminifying pre-processors. Telescope identified each site's large on-load setup processes (521 to 5,534, mean 3,507 LOC), allowing us to easily scope timeline constraints beyond the setup code to yield each interaction's code (49 to 934, mean 205 LOC). Besides the Mac Pro example, **running Telescope on all other websites with the default detail setting yielded 150 lines or less of code that sufficiently explained how the interaction was created in each site.** With 1 to 68 (mean 21) LOC of HTML queried during interactions, the HTML query markers offer a simple starting point for exploration.

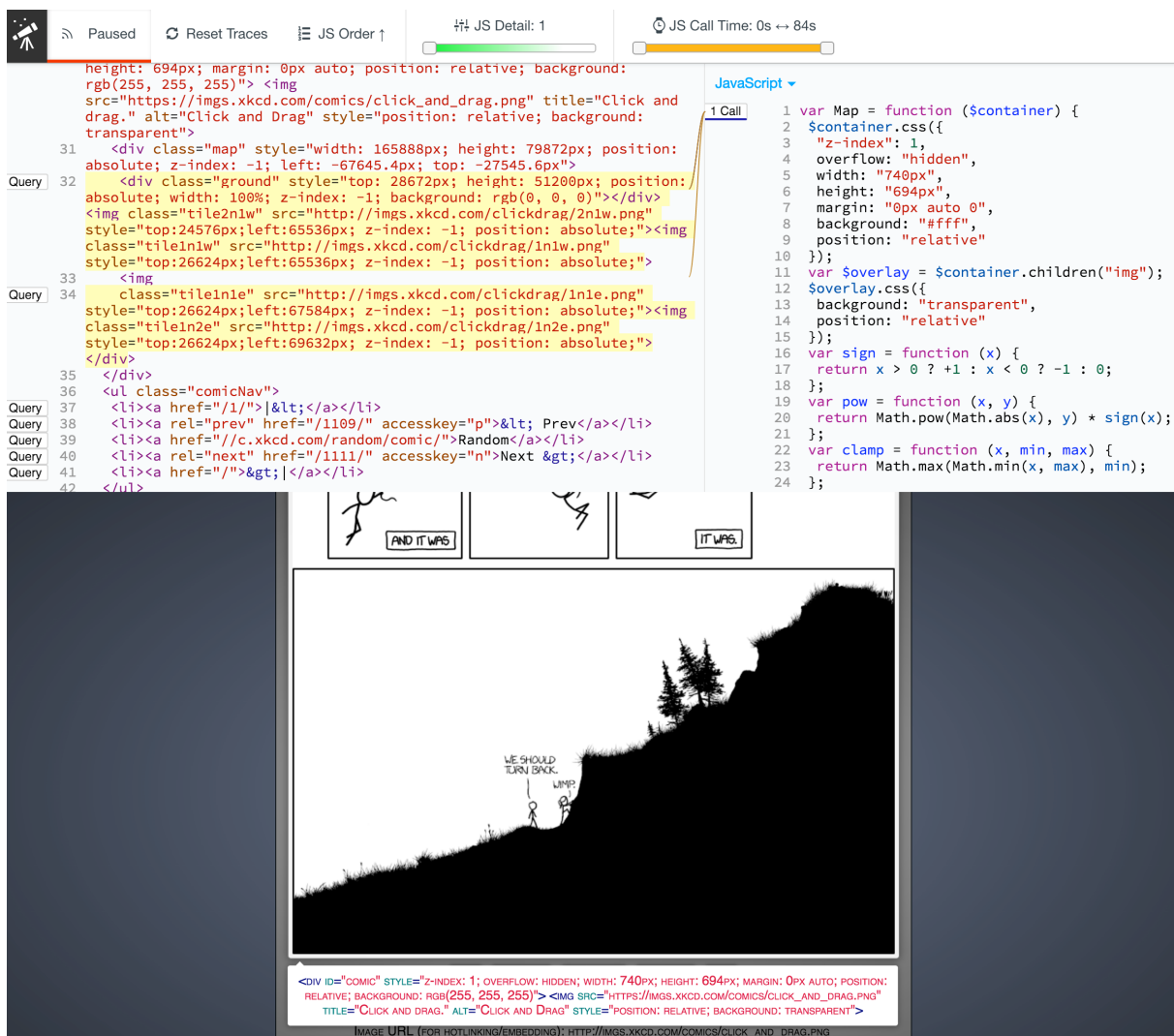


Figure 4.7. Telescope is being used to discover XKCD's map-drag implementation. A JavaScript call marker has been clicked next to the `Map` function, resulting in HTML line highlights and a DOM element highlight in the website.



#### 4.4.2. Low Complexity Example: *XKCD 1110*

XKCD’s interactive comic #1110 website presents a simple test scenario for Telescope with its relatively small codebase and direct UI interaction (see Figure 4.7). Telescope revealed a composite 49-line draggable map implementation (excluding library code). We quickly discovered functions `map`, `update`, and `drag` with Telescope’s default settings. We examined the startup code and moved the timeline past startup to see the interaction. The map-drag effect is achieved by events bound on `mousedown` that track mouse position relative to a center start position. The map is a grid of image tiles with names representing their position, where images  $\pm 1$  away from the centered tile are loaded and set to visible, while others are hidden.

Using Unravel on the same interaction, we were able to easily find the same functions behind XKCD’s map load, however we needed to look through 420 lines of JavaScript to find how relevant calls in separate files fit together. Unravel showed changes to the DOM caused by dragging the map, but it was difficult to determine the scope of JavaScript operating on the map. Setting DOM breakpoints through Chrome Developer Tools, we were able to step through function calls responsible for modifying the map.

#### 4.4.3. Moderate Complexity Example: *Dot-to-Dot*

In analyzing the design award-winning Dot-to-Dot game, Telescope helped us to understand how the game connects the dots (see Figure 4.1). We sought to understand the code behind connecting a dot to another: dots appear, a line is drawn, and audio plays a dot sound. We didn’t need to look far to find a `dot` class in the setup code, which was referenced later in the JS time 23s to 42s. The JavaScript code was heavily minified, but

Telescope expanded it in a way we could infer how functions operated even without their names. Function `c` activates a game round, function `y` starts the timer interval, function `o` draws a line invoking RaphaelJS, and function `v` handles dot clicks and dot animation. Sliding JS detail towards the middle we found a `pop.mp3` xhr request, where the response is stored in a variable and played via `SFX.pop()`.

In this scenario, Unravel provided hundreds of JavaScript inspection points and DOM changes. We inspected the top two most-called functions and quickly found the game’s timer and dot-insertion logic by clicking through Unravel’s inspection points. Using Chrome’s search feature was more convenient than manually looking through the remaining Unravel results, so we ran find-all queries for RaphaelJS calls and set breakpoints to determine how game rounds began. Separating the game’s setup code from runtime code was difficult with Unravel, because all of the JavaScript functions accumulate in one list that is only sortable by call count or function name.

#### 4.4.4. High Website Complexity Example: “*Snow Fall*”

The Pulitzer Prize winning New York Times article “Snow Fall” stretched Telescope’s technical ability with 41,526 lines of JavaScript and 1,458 lines of HTML along with a high volume of recurring background JavaScript execution. In this test, we sought to discover how the Steven’s Pass flyover interaction was activated. We scanned through 300 lines of irrelevant ad and tracking code before finding the right Telescope settings. We set the JS Call Time to 41s to 73s and set the JS Detail to the middle, where we found relevant functions `videoBG.setFullscreen`, `checkArticleProgress`, and `percentTillNext` related to an HTML5 video player (see Figure 4.3). The latter two run on every scroll

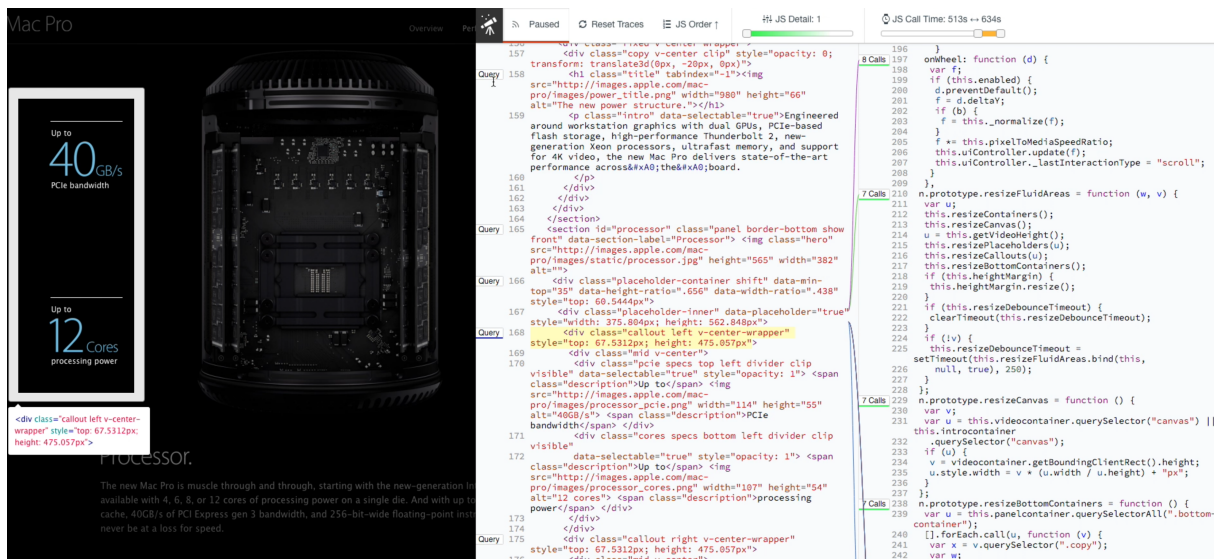


Figure 4.8. We evaluated Telescope’s performance and source discovery on Apple’s Mac Pro product demo website. While performance lagged during UI animation, Telescope accurately captured and reduced the source code view to show how the scroll-driven effect works. Above, an HTML line marker has been selected in the Telescope interface that draws lines to linked functions and highlights the DOM component.

event and the former is activated when the article progress reaches the “Tunnel Creek” narrative. We found related HTML elements `div.nyttmm_video_player`.

In comparison, Unravel quickly revealed results pointing to functions responsible for setting full screen and initiating video playback, but like in the previous case, the magnitude of function traces occluded the search for other meaningful functionality. We were unable to quickly find the remaining functional pieces for checking the article progress and activating new sections.

#### 4.4.5. High Complexity Example #2: *Mac Pro*

The interactive product page, which disassembles an Apple Mac Pro on user scroll, tested Telescope’s performance limitations but revealed insight into the website’s design (see Figure 4.8). The initial product-rising animation was captured in Telescope, logging 30k+ function invocations. We scrolled down to activate the Mac Pro’s disassembly animation and tuned Telescope’s JavaScript time to exclude on-load code and any code after our interaction. We disregarded 400 lines of code before finding the appropriate settings. We found an MVC architecture with event-driven-design, where a `sectionController` and a `clipController` listens for events relative to a `timeline` with functions like `pauseTimeline`, `getVideoHeight`, `resizeFluidAreas`, and `resizeCanvas`. While the clever video playback and container resizing became more evident, we found misleading code that queries and resizes canvas elements when there are none.

Similar to the previous two cases, Unravel found hundreds of changes and traces, with the topmost being calls to trigger, enable, and update sections via an `onWheel` handler. Discovering components of the MVC architecture through Unravel was extremely difficult in this case. In sorting by JavaScript invocation count and DOM query count, Unravel highlighted portions of the MVC most active in DOM modification. This resulted in pointers to view logic, but model/controller logic was difficult to surface.

#### 4.4.6. Runtime Performance

Telescope performed without significant delay on four sites but experienced intermittent UI blocks on three dynamic sites with hundreds of UI transformations per second. While Telescope is primarily a retroactive inspector, it continuously receives trace information

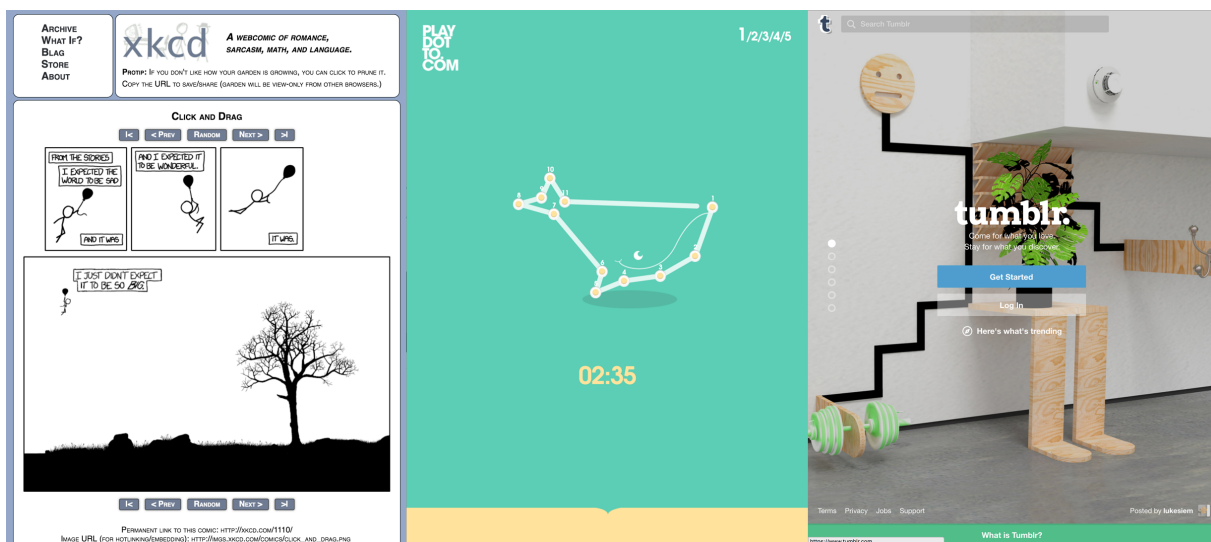


Figure 4.9. We observed Telescope’s use while discovering a map-drag interaction on XKCD (left), a dot-connect interaction on Play-Dot-To.com (middle), and a scroll animation on Tumblr (right).

from websites. With each new trace, Telescope recalculates hit counts and surfaces DOM-querying calls out of library call stacks. This computation happens in Telescope JavaScript UI, thus slowing down its UI updates. With a relatively small codebase and heavy JS use for SVG modification, the Dot game caused UI blocking in Telescope for 2-3 seconds during some SVG transformations and line renderings. We noticed UI blocking for 3-4 second intervals for “Snow Fall” as well as some UI delay as all of the startup code traces were transmitted. The Mac Pro website incurred the most significant UI performance delays for up to 20 seconds while traces were being processed. In the future, Telescope’s performance can be optimized by collating and garbage-collecting repeat invocations (see Chapter 5).

## 4.5. Exploratory User Study

Having demonstrated Telescope’s capabilities, we evaluate Telescope’s use to answer the following research questions:

**RQ2** What web programming design patterns are users able to elicit using Telescope?

**RQ3** What usage strategies do users employ while discovering a web interaction with Telescope?

### 4.5.1. Method

We conducted an exploratory study with five student software developers at Northwestern University to understand how they can use Telescope to learn from professional websites. Three of the developers stated they had at least 3 months of professional web development experience through internships. The other 2 stated they knew enough to create website and setup simple JavaScript interactions with libraries like jQuery or Bootstrap. Each user was interviewed about their technical experience and trained to use Telescope for 5 minutes on toy examples. They were then asked to explore 1–3 websites on their own in the time remaining. Sessions lasted 45 minutes each, and each participant was compensated \$20. Each participant provided a screen recording with audio for the entire test.

We chose three websites and interactions from the seven in the case study (see Figure 4.9) that had fun or clever dynamic UI’s whose implementation involved at least two functional UI transformations. For each website we observed how users reacted to aspects of code we identified as highly relevant to the UI interaction through prior review. We prompted users to think aloud during their interaction and periodically asked them open ended questions such as, “What can you tell me about the way the feature is constructed?”,

“What coding lessons or decisions can you identify?”, and “How does Telescope help in understanding this feature’s source?”

### 4.5.2. Results

In our exploratory study, Telescope helped junior developers quickly identify coding design techniques and programming concepts in the unfamiliar code underlying professional websites, while also inspiring additional discovery. This section addresses our research questions with results from user observations and think-alouds during user testing.

**4.5.2.1. RQ2: Web Design Patterns Recognized.** All five users identified front-end web design patterns including lazy media loading, mouse position tracking, class-toggled effects, library usage, and animation. A user said, “Seeing what this is helps me know how to approach this problem design-wise (code design).” Four users found an example of lazy-loading and mouse position tracking in XKCD’s map viewport by moving the JS timeline constraints past the startup code activity and watching the JavaScript call counts while repeating the map-drag interaction. Two users discovered class-toggled effects by watching the HTML view change during Tumblr’s scroll effect, then clicking the HTML query markers to see what JavaScript queried the section element; however, these users did not look into the CSS properties related to the effect. All users identified instances of library usage in the Dot game’s RaphaelJS line-drawing or each site’s jQuery references. Two users found how to construct simple animation through Tumblr’s use of jQuery animate.

Seeing in-context front-end architectural patterns working together helped users learn from examples. Users identified patterns for interactive UI including event-driven design,

function closures, and state maintenance. Before using Telescope on the XKCD map, a user said, “I know how to make event handlers, queries, and I know the syntax of JavaScript, but I’m missing the *how* of making them work together for a feature like this draggable map.” Telescope enabled this user to find multiple patterns in XKCD’s comic. Users intuitively found the nature of function closures in JavaScript in scenarios like XKCD’s `update` function callback, which contains a `map` variable declared outside the function scope but is referenced without declaration inside the function scope. Users found alternate implementations of state maintenance: storing active state in HTML attributes on Tumblr, or storing the game state in an in-memory JavaScript object via references to `this` in Dot-To-Dot’s `Dot` object.

**4.5.2.2. RQ3: Telescope Strategies.** We discovered a mix of strategies for interacting with Telescope that our users employed while learning from a UI with Telescope: *constrain-expand*, *copy-paste*, *watch-and-wait*, and *step-constrain-step*.

The *constrain-expand* strategy helped users focus on relevant code and other users curious about library code, external dependencies, or background code. One user said, “The detail control is crazy, because it lets me see just what modified the DOM or I can bring in background code too.” *Constrain-expand* was typically used after the user gained a significant understanding of the interaction and wanted to validate their assumptions of hidden variable references or function declarations.

The *copy-paste* strategy emerged when users either tried to play with a portion of code themselves or wanted to see the external media referenced by JavaScript and HTML. The XKCD and Dot-to-Dot websites load external images and audio, which are referenced in Telescope’s HTML view. Users copied links to the media to view them as whole files



outside the interface. Users copied portions of JavaScript code to an external IDE to see which variables were declared in scope and which ones were not.

We also observed users adopting two other strategies that were less successful in our test. With *watch-and-wait*, users watch the Telescope interface update without adjusting any controls. This made it difficult for users in our test to find interaction code amidst setup code, but could be effective when used on websites with little setup code. Another strategy is *step-constrain-step*, where users narrow the timeline min and max to examine one second of execution at a time. This made it difficult to see calls from high order functions which span multiple seconds, but it was effective in reducing noise from background functions.

Users were able to quickly and easily locate relevant source code for complex interactions. Averaging less than four control toggle changes to find code pertinent to their interaction, users excelled in parsing through fine-tuned views of JavaScript. Three of the users continued exploration past their goal to discover additional coding concepts. One user said, “Once I found that Raphael was being used, I wanted to dig deeper to see how it was configured to make a line wobble.”

Developers with less JavaScript experience chose Telescope’s HTML pane as a reference point, whereas developers with more experience spent time carefully gaining insights from JavaScript implementation decisions. Telescope’s line drawing features helped less experienced developers explore JavaScript from an HTML reference point they felt familiar with. A user said, “This would become my starting point over forums/tutorials — I might even use it on a tutorial’s solution instead of reading the tutorial’s example code.”

Telescope’s detail expansion feature helped developers with more experience learn architectural decisions about the code. Less experienced developers focused on understanding how to recreate the effects in the default, least detailed view.

## **4.6. Limitations**

### **4.6.1. Instrumentation Scope and Applicability**

While Telescope currently supports UI discovery on many popular websites, some limitations prevent it from working on all websites. Scripts that are loaded via lazy-loaders can escape Telescope’s instrumentation if they are not present on the page when the Sleight-of-Hand method takes place. Lazy script loaders use URLs in strings to append to scripts to the DOM asynchronously. Telescope will capture and rewrite sources at the time of its invocation, but scripts loaded later are beyond the rewrite scope. However, Telescope does capture calls to load the scripts. Lazy intercepts can be added to Telescope in the future through request blocking and source redirection.

Telescope only instruments and monitors the top-level website frame. Subsequent or nested iFrames were omitted in this project, as iFrames are typically used to embed external content. Future versions of Telescope can recursively traverse the DOM to instrument and listen to traces from iFrames.

While calls to their API’s are captured in Telescope, the rendering logic underlying HTML5 Canvas, OpenGL, Flash, Silverlight, and Java Applets are not visible to Telescope. Instrumenting these technologies through website source rewriting is currently not possible.

#### 4.6.2. Performance

Unlike Unravel, Scry, and FireCrystal, Telescope depends on third party servers and lengthy instrumentation processes for large files. The performance overhead required for source instrumentation is considerable on modern hardware and exceeds the capabilities of web browsers. A rich UI might contain fifty thousand lines of code, which can require up to three minutes to instrument. While instrumented files are cached to speed up repeat-loads, future versions of Telescope could optimize the instrumentation process for larger script transformations by indexing and caching common file subsets like modules and libraries.

Telescope was unable to capture UI interactions on several test sites due to memory limits and website implementation techniques. Telescope sessions for the Netflix and Spotify web players exceeded the browser's memory limitations, resulting in truncated trace data. Amazon's use of iFrames, Airbnb's content security policy, and Forecast.io's app cache script loading prevented Telescope from collecting meaningful trace data. Telescope successfully displays interactions from Google web products, but we found their minification techniques especially difficult to read due to the minification of HTML attributes in addition to JavaScript. In future work, memory problems can be overcome by disabling source tracing and logging for portions of a website until needed, CSP's can be filtered out by debugging proxies, and given enough interest, a crowd of experts could help identify minified HTML attributes.

### 4.6.3. Code Explanations

Telescope instruments and examines only client-side code and does not curate or explain the code. Further, Telescope does not process or interpret CSS. Existing tools like Theus and Scry help users discover how server-side code is executed and client side CSS transformations alter the DOM rendering [48, 14]. Future versions of Telescope could incorporate technologies like Tutorons in order to explain the code in the context of active traces [33].

## 4.7. Conclusion

Having demonstrated the effectiveness of Telescope for helping web developers discover implementations underlying UI interactions, we revisit techniques that contribute to Telescope’s effectiveness.

### 4.7.1. Design Principles for Understanding Unfamiliar Code

The design of the Telescope platform evolved from three prototypes, each shaped by user feedback. Initially we aimed to deliver a code-extracting tool for delivering all code behind an interaction to the users, but providing code by itself was of little value. A participant said, “I can finally see everything that happened, but I don’t know what it means.” Each subsequent iteration incorporated techniques to present JavaScript and HTML to the user in a way the didn’t overwhelm them, which shaped Telescope’s three design principles: (1) Bring together relevant JavaScript for an interaction into a single composite JavaScript view. (2) Give the user control over the amount of JavaScript detail they wish to see for any given time frame. (3) Provide affordances to visually link functionality end-to-end,

connecting active JavaScript to queried HTML and components in the rendered website. Evaluating the current prototype showed success in helping junior developers understand UI's. All users were able to identify UI engineering concepts in unfamiliar code, and seeing architectural patterns in-context helped users identify how programming techniques can be used to construct a system.

#### **4.7.2. Enabling UI Discovery**

Advancing related work [48, 59, 34, 14, 2, 5, 25, 26], Telescope's live tracing and source view constraints helped users identify and understand code supporting an interaction. As a user interacts with a website's UI, Telescope receives trace information and processes it into HTML and JavaScript views for the user. The display of these views are controlled by JavaScript load order, detail, and time constraints. Default settings show the user a focused view of JavaScript responsible for modifying the DOM. Clicking code markers draws lines connecting JavaScript to HTML, helping the user see how JavaScript manipulates the DOM for a desired outcome. Evaluating the UI discovery in our case study, we found that the source code needed to understand a complex UI behavior is often 150 lines or less.

#### **4.7.3. Toward Sensemaking Scaffolds**

This chapter provides a contribution in creating interactive learning materials from professional websites for users wishing to become professional contributors in web development. But in creating the low-barrier learning materials, relationships between logical components in the code are either hidden or lost during source filtering. Using telescope,

learners were able to find and recognize design patterns and developed strategies in finding new patterns with Telescope, but were not provided with scaffolds to make sense of components or relationships in the code. The next chapter introduces Isopleth and describes a new contribution for scaffolding users into a sensemaking process where they opportunistically compose understand of complex JavaScript artifacts and their relationships.

## CHAPTER 5

**Isopleth: Mixed-Initiative Sensemaking in Web Application Code**

This chapter presents the third application towards RALE, Isopleth, which is a web-based platform that enables a mixed-initiative sensemaking process by combining system and user-generated content to support learners as they make sense of complex JavaScript features in professional websites. This chapter contributes a technique to overcome Unravel and Telescope’s limitations in making sense of complex JavaScript artifacts whose relational structures are hidden or obfuscated. The source code for Isopleth is openly available <sup>1</sup>. All uses of “we”, “our”, and “us” in this chapter refer to coauthors of the aforementioned paper.

Unravel (Chapter 3), Telescope (Chapter 4) and prior approaches including Scry [14] and Theseus [48] reduce the complexity of professional code by surfacing relevant information and provide methods for walking through code in execution order. But in doing so, they lose the structure of how code constructs work together to implement a feature. Since JavaScript functions are often executed asynchronously, visualizations of execution order like those provided in Scry provide little information about the conceptual structure of web programs. One could understand the structure by walking through the entire execution path as they might when debugging, but this can contain thousands of steps for professional examples. Surfacing relevant information (e.g. top-level invocations, functions with high call counts) is a reasonable approach for identifying important

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<sup>1</sup>Isopleth Github <https://github.com/NUDelta/Isopleth>

functional components, but hides lower-level functions that are the necessary bridges for understanding how components work together to produce a feature. In order to bridge the knowledge gap for inexperienced developers, scaffolds must provide rich representations of the underlying code structure [61] and support multiple ways of visualizing code to help learners develop expert models [10, 65, 3].

*Isopleth* is a platform that enables learners to explore complex JavaScript features in professional websites through a mixed-initiative sensemaking process. *Isopleth* supports learners by (1) automatically identifying common JavaScript *facets*, or code constructs defined by their inputs and outputs, (2) automatically finding functional and event-driven relationships between facets to visualize in a graph interface, and (3) providing affordances for users to create their own facets, labels, and code comments. To expose event-driven relationships, we introduce a Serialized Deanonimization technique that determines how functions are passed through other functions to bind asynchronous behavior. In a case study across 12 popular websites with interesting user experiences, *Isopleth* supported the discovery and sensemaking of 20 different design patterns, and identified common and distinct implementation approaches used across these websites.

### 5.1. Motivations and Contribution

Beyond Unravel and Telescope (Chapters 3 and 4), additional challenges remain in helping inexperienced developers make sense of complex JavaScript relationships, design patterns, and code constructs. Unravel supports identifying features in the source code of professional websites, and CDT allows users to inspect features with a profiler [27]. Telescope can extract web features into reduced examples that remove complexity. However,



beginners lack the conceptual knowledge required to make sense of the undocumented code and JavaScript call graphs provided by these tools. Learning to implement web features is particularly challenging because they are composed of many small components working together, and each tool provides a limited view of how these components work together. Existing tools are not designed to extract programming concepts for learners or highlight how solutions are structured to support the development of expert models of programming constructs and strategies.

To address these challenges, *Isopleth* is a web-based platform that enables a mixed-initiative sensemaking process by combining system and user-generated facets and source code alterations to support learners as they make sense of complex JavaScript features in professional websites. In the learning sciences, sensemaking refers to the process of understanding a new example or artifact by generating representations that explain what is known or understood [75, 62]. This includes providing conceptual organizers, embedding expert guidance, giving multiple representations that can be inspected to reveal underlying data, providing malleable representations of the data, and restricting complexity by setting boundaries [62]. Mixed-initiative in this case refers to systems and users collaborating efficiently to achieve the user’s goals [37]. *Isopleth* automatically identifies programming *facets*, or code constructs that are defined by their inputs and outputs. *Isopleth* exposes functional relationships and hidden asynchronous relationships in its call graph. In contrast to existing systems, our goal is to help users identify meaningful entry points into complex code and then interactively explore, label, and filter facets to produce their own understanding of its functionality. *Isopleth* supports mixed-initiative interaction by integrating newly created facets and labels into recalculated views. For example,

a user could explore how autocomplete works by (1) selecting the “Keyboard” facet (2) creating a new facet filter for the text of their autocomplete query, and (3) following asynchronous links between keyboard-related invocations and query-related invocations.

The conceptual contribution of Isopleth is the idea of *scaffolding sensemaking of complex professional code by surfacing hidden relationships between code constructs and providing a mixed-initiative process to interactively explore, label, and identify system components and how they relate*. Distinct from function call count filters, code detail levels, or web feature-location, Isopleth leverages automated techniques to surface facets (code construct defined by inputs and outputs) and expose hidden asynchronous relationships among function invocations. Users can engage in sensemaking by editing code, rearranging invocations, and composing their own invocation labels. As users explore connections between facets and code constructs, they can define new facets in a mixed-initiative for the system to respond with newly surfaced facets and hidden relationships.

The technical contribution of Isopleth is *a Serialized Deanonimization (SD) technique that places unique identifiers in all functions in a web application’s JavaScript source to trace how functions are bound, passed, returned, and invoked asynchronously*. This technique gives Isopleth the ability to take users beyond a UI feature’s binding to show them how the feature’s bindings was created. Related toolkits [48, 28] are limited to linking to a function invocation to its declaration context, and therefore cannot expose where the function was bound, passed, or set as a callback. For example, imagine a web application that creates an anonymous function at line 13 of a source file, and binds it as a click handler at line 93. When a user clicks, existing tools would point to line 13 and neglect line 93, thereby making it difficult for the learner to see how the function was used.

SD provides missing links such as these by adding them to the call graph; this allows us to see a complete picture of code activity between declaration and invocation, and thus surfaces crucial information for understanding how web features are implemented.

In the rest of this chapter, we introduce Isopleth and its affordances for supporting sensemaking through source code frame views, facet-filtered call graph, and extensible filters. We detail the serialized deanonymization technique; evaluate the extent Isopleth identifies and relates facets in professional websites through an in-depth case study; and conclude with a discussion of design principles and limitations of our approach. Isopleth takes an important first step towards the development of Readily Available Learning Experiences (RALE), a conceptual approach for transforming all professional web applications into opportunities for authentic learning.

## 5.2. Isopleth

Isopleth is a web-based platform that enables a mixed-initiative sensemaking process to scaffold learners as they make sense of complex JavaScript artifacts in professional websites. At Isopleth’s heart is the JavaScript call graph that results from the user’s interaction with a feature on a professional website. In this graph, nodes represent collated function invocations, and edges represent parent-child calls or asynchronous bindings. Isopleth provides a variety of views into this call graph to support sensemaking, enabled by *facets*. Facets define filters on functions with particular arguments or return values to identify conceptually related functions. The Isopleth interface, shown in Figure 5.1, supports three central activities: exploring program flow, exploring programming facets, and generating custom facets and labels.

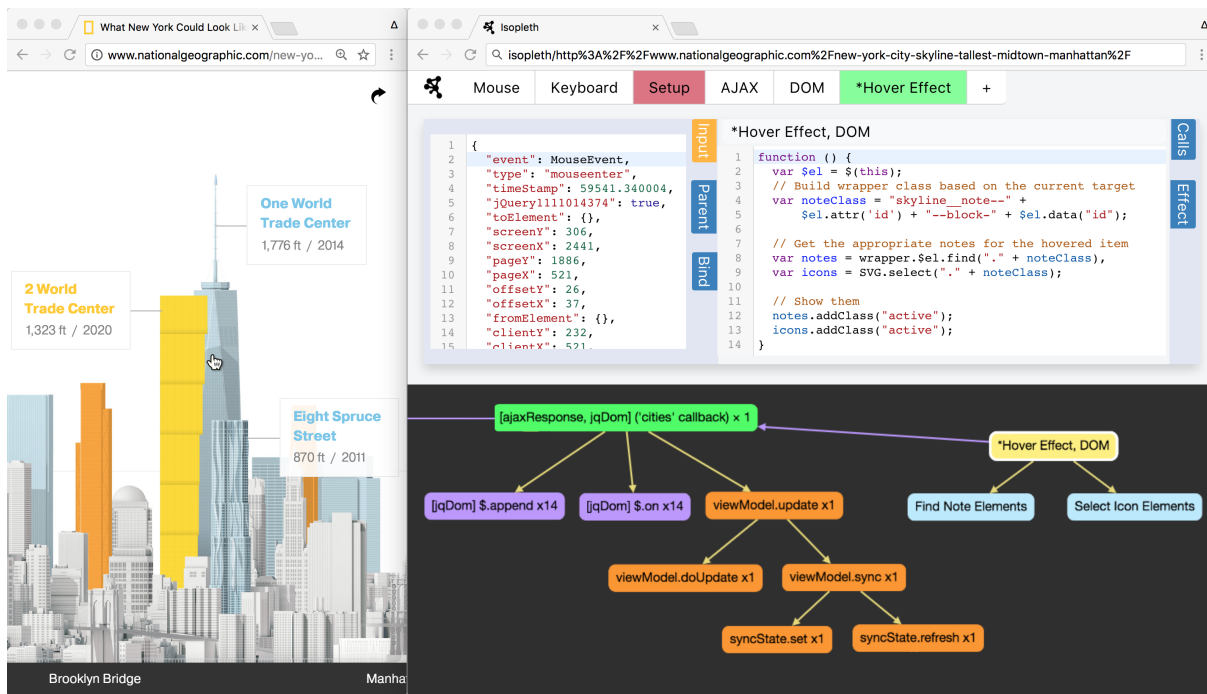


Figure 5.1. A learner is using Isopleth to understand JavaScript code constructs related to moving and scrolling their mouse on National Geographic’s *New New York Skyline* article. Isopleth opened in a new window after the user activated it on the website; it continuously updates with JavaScript activity. Facet filters (top) are used to filter display based on facet, or code constructs defined by their inputs and outputs. Source frame views (middle) display specific function invocation states in the runtime with their inputs and outputs, parent and child calls, asynchronous declaration context, asynchronous binding, and asynchronous effect if present. The condensed call graph (bottom) displays a collated, filtered, labeled, and color-coded JavaScript runtime call graph (See Figure 5.2). Users can apply **or** and **not** operators on the filters by left and right clicking, respectively. To support mixed-initiative sensemaking, users can add custom filters (See Figure 5.3), modify code in the source frame views and graph node labels, and add commentary in source code — the system reacts by integrating learner input into its views. Pictured here, a user has added a custom “Hover Effect”, altered source code, and updated node labels to make sense of smaller call trees.

### 5.2.1. Exploring Program Flow

Isopleth’s condensed call graph view and detailed source frame views, shown in the bottom and middle panels of the interface in Figure 5.1, provide affordances to help users explore and make sense of complex relationships in JavaScript program flow. Program flow is particularly challenging for learners to understand because JavaScript functions can execute asynchronously and often appear in a different runtime order than their initial source order [2, 48]. Further, JavaScript’s functional nature means that functions can be passed by reference in arguments, return values, and closures. No previous system is able to draw connections that outline a JavaScript function’s journey from declaration to binding during runtime, but this information is crucial for making sense of the conceptual design of web applications. Isopleth provides the first interface for exploring these conceptual relationships.

In Isopleth’s condensed call graph, shown in detail in Figure 5.2, Isopleth orders call trees by time and draws colorful edges between nodes to denote their relationships. Call trees are ordered from left to right by root-level invocation over time, and nodes in the call trees can be rearranged by dragging them. Users can zoom and pan the call graph, and can also control the level of detail of the view using a flyout control panel (not pictured), showing and hiding library nodes, unidentified facet nodes, repeat nodes, or heat-maps of nodes. Clicking relationship edges highlights both nodes touching an edge. Repeat invocations are collated by unique call chain into their first occurrence in a tree. Yellow edges represent parent-child (or caller-callee) relationships. Orange edges represent asynchronous parent-child (or declaration context, invocation) relationships. Finally, purple

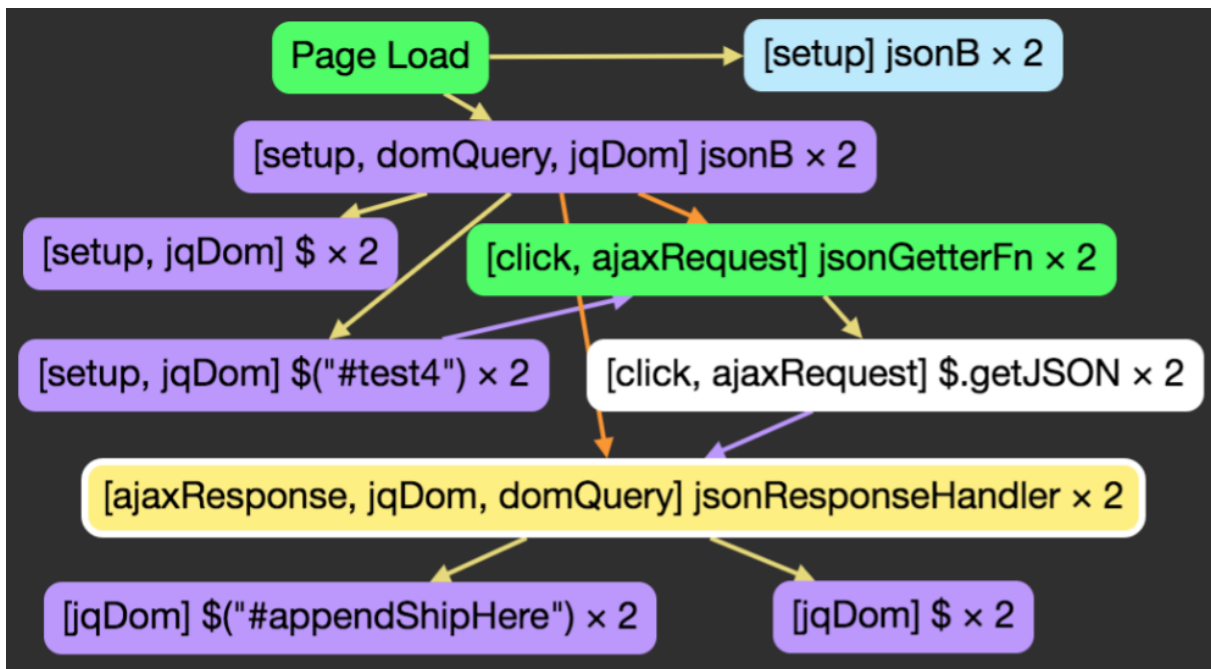


Figure 5.2. A cluster of related collated function invocations (with their invoke-counts), manually organized here for display. Nodes are colored green for top level calls, yellow for currently-selected, purple for DOM facets, white for AJAX, blue for Setup. Edges in the graph are color-coded yellow for a call, orange for asynchronous declaration, and purple for asynchronous bind location (via Serialized Deanonymization). In this toy-example of a lazy-loaded image, we bound a click handler on `#test4`. On clicking `#test4`, the handler made an AJAX JSON request and bound `jsonResponseHandler` as the callback. The `jsonResponseHandler` queried the DOM for `#appendShipHere` and added the image.

edges represent asynchronous binding sites, denoting how functions are passed through call chains to produce an asynchronous effect.

When the learner clicks on a node in the condensed call graph, Isopleth displays the function body in the source frame view. The interface also displays navigational buttons on the perimeter of the source frame views, which provide snapshots of related functions, arguments, and return values. Users can access a function's parent caller, child

calls, asynchronous declaration context, asynchronous binding locations, as well as other functions the frame binds as effects. These affordances allow users to quickly access more information about each node in the call graph to make sense of their functionality and relationships.

As an example scenario, consider learner Cindy who wants to understand the end-to-end logic involved in the infini-scroll feature of a blog website, where photos are continually added to the bottom of a blog after scrolling to the end of the page. Using Isopleth, Cindy activates the mouse and DOM-query facets, and the call graph is filtered by invocations with those facets, displaying 20 remaining nodes. Cindy sees nodes on the right side of the graph with DOM facets showing how JavaScript queried and appended some elements. Following purple lines to nodes on the left (an asynchronous link to an invocation earlier in time), Cindy discovers the exact function that binds DOM modification as an asynchronous response to mouse scrolling.

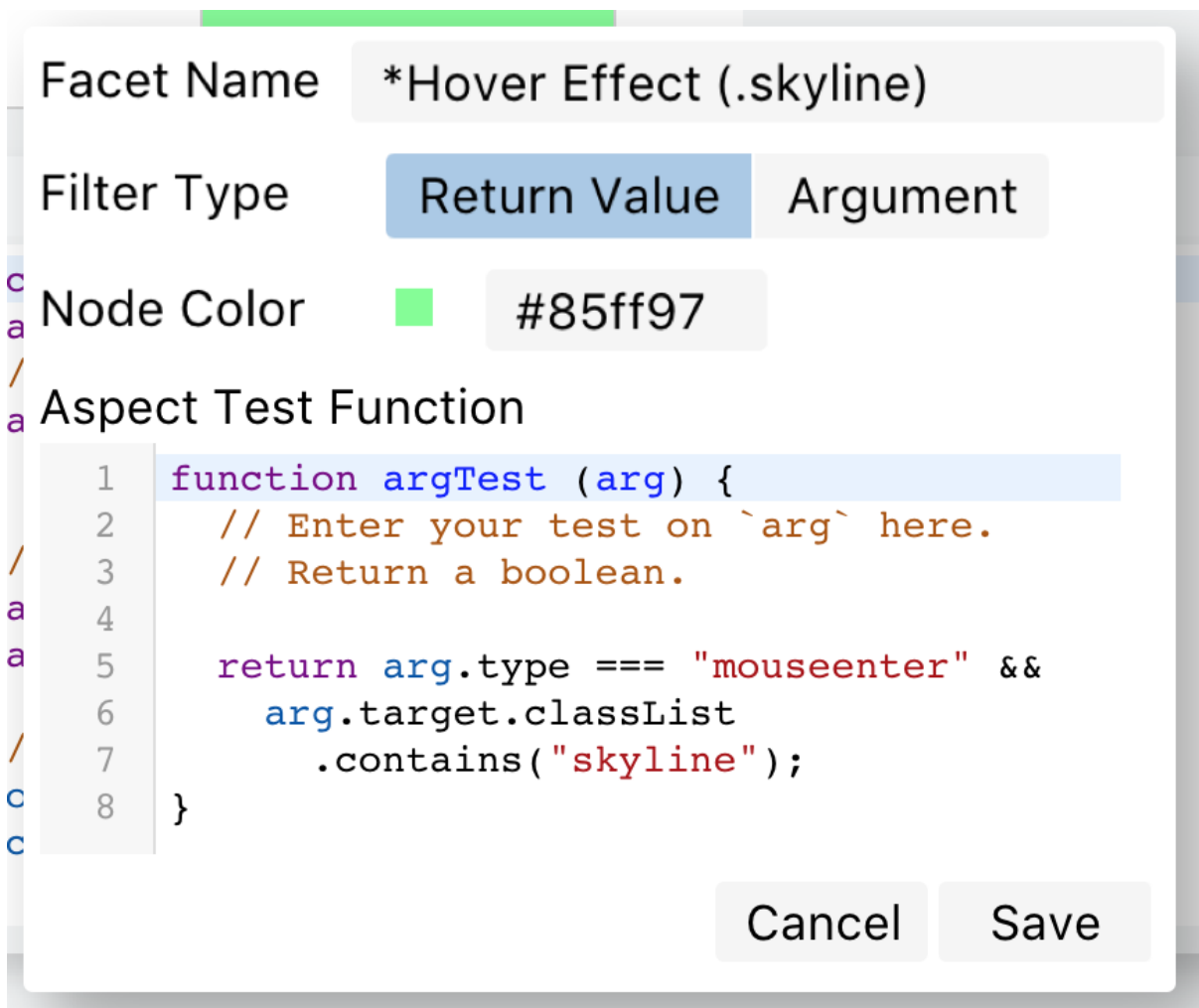
### 5.2.2. Exploring Programming Facets

While the condensed call graph is designed to support exploration and expose relationships, the full call graph is very large, and therefore still challenging to understand. Facets provide a method for filtering the condensed call graph to expose conceptual relationships between JavaScript functions. Isopleth includes a set of predefined facet filters that are shown by default including Mouse, Keyboard, Setup, AJAX, and DOM. These facet filters are predefined tests for arguments or return values in function invocations, such as `EventTarget` arguments for Mouse, `onload` arguments for Setup, or `XHR` objects in return values for AJAX. Facets detected in library code are bubbled up their invocation chain, as

DOM and AJAX are often abstracted. See the facets at the top of the Isopleth interface in Figure 5.1.

When an facet filter is selected, the condensed call graph at the bottom of the interface is filtered to display a subgraph that includes functions related to the selected facet, along with their parent and child relationships. These default facets allow learners to view all functions related to mouse and keyboard events, all setup code and AJAX calls, and all functions that modify the DOM. Filters can also be joined by by left-clicking for an **or** operator and right-clicking for a **not** operator, which recalculates the display of color-coded nodes appearing the call graph. Through these affordances, facets highlight conceptual relationships between functions that are not apparent in tools that visualize execution order exclusively.



A dialog box titled "Facet Creator" with a light gray background. It contains several input fields and a code editor. The "Facet Name" field is labeled "Facet Name" and contains the text "\*Hover Effect (.skyline)". The "Filter Type" section has two buttons: "Return Value" (highlighted in blue) and "Argument". The "Node Color" section has a small green square icon and a text field containing "#85ff97". The "Aspect Test Function" section contains a code editor with a line number list on the left (1-8) and a JavaScript function definition. The function is named "argTest" and takes "arg" as a parameter. It includes two comments: "// Enter your test on `arg` here." and "// Return a boolean.". The function body returns a boolean expression: "arg.type === 'mouseenter' && arg.target.classList.contains('skyline');". At the bottom right of the dialog are two buttons: "Cancel" and "Save".

Facet Name \*Hover Effect (.skyline)

Filter Type Return Value Argument

Node Color ■ #85ff97

Aspect Test Function

```
1 function argTest (arg) {  
2   // Enter your test on `arg` here.  
3   // Return a boolean.  
4  
5   return arg.type === "mouseenter" &&  
6     arg.target.classList  
7     .contains("skyline");  
8 }
```

Cancel Save

Figure 5.3. A learner is creating a custom facet filter. Facets are functional input-output schemas, and in this facet creator view, user input is structured in terms of testing arguments and return values to identify function invocation nodes containing the argument or return value. Users assign a node color for display in the condensed graph, where the last filter applied colors the node. The learner is defining a skyline hover facet, visible in Figure 5.1.

As an example scenario, consider a learner Alice who wants to quickly discover which code constructs are used to react to her keyboard strokes on a search bar, and see if any code is reused when she clicks the search button. Using the facet filters, Alice left-clicks the mouse and keyboard facet filters to activate an **or** condition and right-clicks the DOM filter to activate a **not** condition on DOM-querying nodes. Results in the condensed call graph show Alice keyup and click handlers in top level nodes. In examining the nodes, Alice quickly sees two different programming constructs that support her feature of interest.

### 5.2.3. Creating Custom Facets and Labels

Dynamic interactions with websites are comprised of either user inputs or scheduled inputs with corresponding changes to the DOM as outputs. The set of possible inputs and outputs is unbounded thus infeasible to automatically identify all that might be relevant to a learner’s sensemaking process. As a result, learners need the flexibility to filter on inputs and outputs not represented by pre-defined facets to see patterns that arise in specific use cases. For example, a learner may type the text “dog” into an autocomplete field, and want to trace how the string “dog” is passed from an input to an AJAX request and finally into a result list. To address this challenge, we use a mixed-initiative approach, allowing learners to define their own custom facets to query the call graph regarding context-specific functionality.

A learner adds a custom facet filter by clicking the + in the facet filter bar, which opens a dialog as shown in Figure 5.3. This dialog embeds an expert guidance technique to help the learner prime their mental model about the role(s) of a function based on its inputs and

outputs *before* looking at the function body. This helps learners to overcome the initial information barrier of not knowing the purpose of a code body. After defining a custom filter, the condensed call graph is recalculated to include the new filter in combination with existing filters to produce node labels and coloring in the displayed graph.

Isopleth also provides affordances to support learners' self-explanations during the sensemaking process as they work to understand individual functions and relationships. Isopleth's graph node labels and source frame view are editable and update referentially. When examining the source frames for nodes in an facet graph, learners can add their own labels for each node, add comments to the code, name anonymous functions, and even refactor code. Learner-inputted changes appear whenever the source is referenced by other nodes, propagating through the graph to help support understanding. The Isopleth interface provides edit cues, such as placeholder boxes and blinking code cursors, as affordances that invite learners to participate in compositional sensemaking tasks. These mixed-initiative interactions are designed to help bridge from learners' understandings.

As an example scenario, consider learner Mark who wants to understand how the game timer causes a game-over action in an HTML Tetris game. He first defines a custom facet for timer events. He then finds the final timer event on the right of the call graph and notices 15 nodes underneath. He doesn't easily recognize functionality in the top level node, so he clicks a few other nodes in the tree to find familiar code. Mark finds a node three nodes down and works through the source, adding comments about a Model state being updated and labels the node "Game State Update." He explores two other related nodes and identifies a link between the game state and the timer methods. This helps

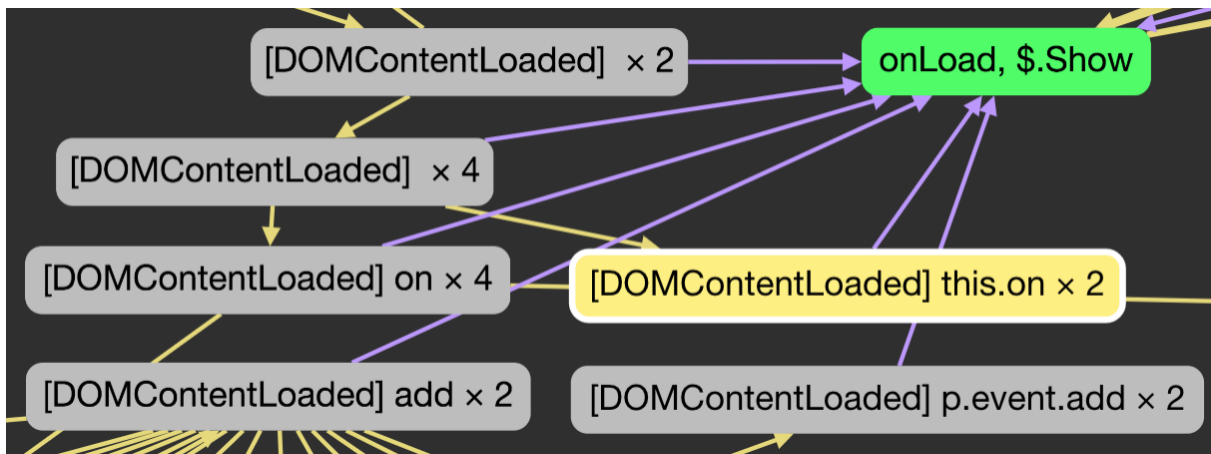


Figure 5.4. Functions existing inside known libraries are colored grey, currently-selected nodes are colored yellow, green nodes have initiated DOM changes, and purple lines denote an asynchronous relationship. After removing library code filtering from the condensed call graph, this figure shows how Serialized Deanonimization allows for a DOM-modifying facet to be bubbled up out of a library call. Only the green node is present outside of jQuery.

him understand the higher-order design pattern of separating concerns, such as game view updates and game timing.

### 5.3. Techniques for Discovering Hidden Links and Surfacing Facets

Without Isopleth, current methods for detecting facets, or code constructs defined by their inputs and outputs, in JavaScript are limited in scope to identifying DOM invocations [34, 14, 35] or manual inspecting inputs and outputs through debuggers [5, 25, 26]. Further, JavaScript function names, function bodies, and variable names are an unreliable means of determining facets, because programmers struggle to create well-named variables [24] and minifiers swap variable names with short system-generated names [6, 64, 70].

Javascript’s functional nature and library ecosystem make it difficult to draw direct links between cause and effect relationships and identify facets, which is a key component of Isopleth — helping users see relationships between code constructs of interest. Current tools identify the declaration scope of the function and calling scope of the function [48, 28], but the function’s journey from creation to invocation is missing.

Facets don’t surface themselves: By supporting opportunistic learning, we hide and collate certain parts of the call graph to highlight entry points for the learner, but learners needs to see facets detected from hidden portions of the tree to continue their sensemaking process. For example, AJAX facets are often hidden in library wrappers around the JS XHR API, but learners need to know calls to \$.ajax are AJAX facets. In detecting facets, Isopleth is designed to bubble facets up call-chains or down through descendants to surface them out of libraries for the user (See Figure 5.4).

### 5.3.1. Serialized Deanonymization

The goal of Serialized Deanonymization (SD) is to trace the lifecycle of anonymous functions, especially those that are used in the popular event-binding callback style, such as `object.on(“some event”, anonymousCallback)`. But JavaScript allows for functions to be declared, passed, invoked, and manipulated during runtime in synchronous or asynchronous fashion. Tracking the lifecycle of a function from creation to invocation is especially difficult, because a function could be created and passed by reference through a complex library event system before being bound to a UI event.

Our strategy is to add unique ID's to each function at instrumentation time, then record all instances of the function that appear in serialized arguments and return values at run time (i.e. from the `Function.toString` prototype, which provides the string representation of the function — including our injected ID).

We detail SD in the steps below (See Figure 5.5):

- (1) Initiate public website instrumentation using the Sleight of Hand (SoH) technique (Chapter 4) to instrument a website’s source code.
- (2) Extract the source for instrumentation via website-instrument-swap-and-trace (Wisat) architecture (Chapter 4).
- (3) While applying Fondue tracer code [48] to the JavaScript source, for each function body in the JavaScript abstract syntax tree:
  - (a) Prepend a unique ID as a terminated string expression to the function body.
- (4) Reinsert the source via Wisat architecture and complete the SoH technique, rendering the instrumented source.
- (5) Collect function trace activity, including logs of our newly added serials if present in arguments or return values.
- (6) Load trace activity for call graph calculation
- (7) Make purple SD graph edges (See Figure 5.2) by backtracing function invocations through the logs of arguments and return values from other function traces.

### 5.3.2. Facet Tree Decoration and Node Collation

JavaScript libraries typically wrap API concepts deep within legacy-support constructs [40] that are important to facet inspection, such as XHR formation and MouseEvent binding. Thus it is challenging to surface facets without showing library internals for opportunistic learning (See Figure 5.6).

In order to support exploring a call graph based on identified facets (such as DOM, Setup, AJAX), we must reliably determine a function’s facet. Function names and function bodies are often unreliable or misleading determinants of facets because they either

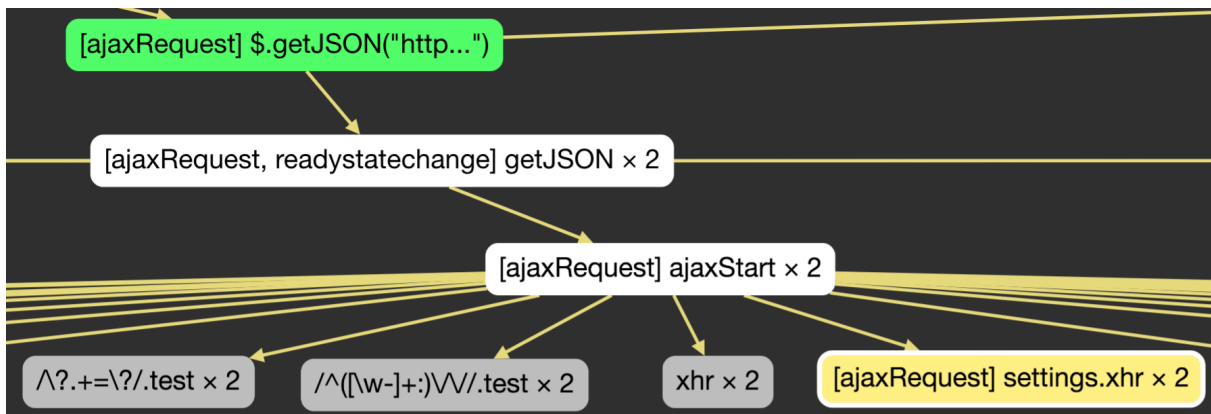


Figure 5.6. After removing library code filters, we demonstrate how facets are bubbled out of library code. The green node is the only node in the graph not present in a library. AJAX facets were detected at a low-level in the library (yellow node), but the jQuery library API only surfaces a `getJSON` wrapper-method. During call graph calculation, if we detect an facet in a library, we bubble the facet up to the first occurrence of non-library code to help learners identify the facet roles of library API calls (i.e. `getJSON` actually delegates to the XHR AJAX API).

lack appropriate names (from minification) or they reference other functions. With the current tools [48, 14, 59], we see source code, individual variable states, and active lines at certain points of time, but this tells us less about what specific function chains and code constructs are doing. To identify facets, we must look at a function’s inputs and outputs as well as its source code (such as detecting an XHR response in an argument as an AJAX facet).

When Isopleth detects an facet in a return value or argument, it traverses the call graph to label nodes in a call-chain. But Isopleth hides library code by default, which introduces an unforeseen facet decoration challenge. For argument values, it begins the search at the node with the argument, and if the node is library code, it traverses descendents until finding non-library root nodes to mark with the facet. Similarly with return value facet



identification, if Isopleth detects the return value within library code, it bubbles the facet up the tree until finding non-library code to label with the facet.

## 5.4. Implementation

Activating Isopleth and source instrumentation for a website follows the same workflow as Telescope (Chapter 4). A user navigates to a website in a browser (i.e. currently supported in Google Chrome), activates source instrumentation via a browser extension, and explores Isopleth at a newly launched URL. Isopleth then communicates with the instrumented website to gather traces and generate a call-graph using Fondue with the added SD technique.

In order to provide Isopleth users with RALE on the open web, Isopleth uses the Wisat architecture (Chapter 4) to instrument websites and extends Fondue [48] for adding unique identifiers in its Serialized Deanonimization technique. Unlike static graph analysis techniques [31, 23, 39], Isopleth determines a runtime call graph based on invoked nodes, which provides users with reliable opportunistic learning. We extended the Wisat architecture to block CSP headers via Chrome network intercept requests to streamline source instrumentation on more public websites.

To support opportunistic learning, we added graph collation to avoid repeat call trees in the call graph. Traversing through the graph, nodes are collated based on identical source, identical parent source, and identical children source. Referential links are appended to the remaining singleton. In some feature-rich applications, we employed the same parent-node-child technique as a throttling mechanism in Fondue to free up the UI to update as needed.

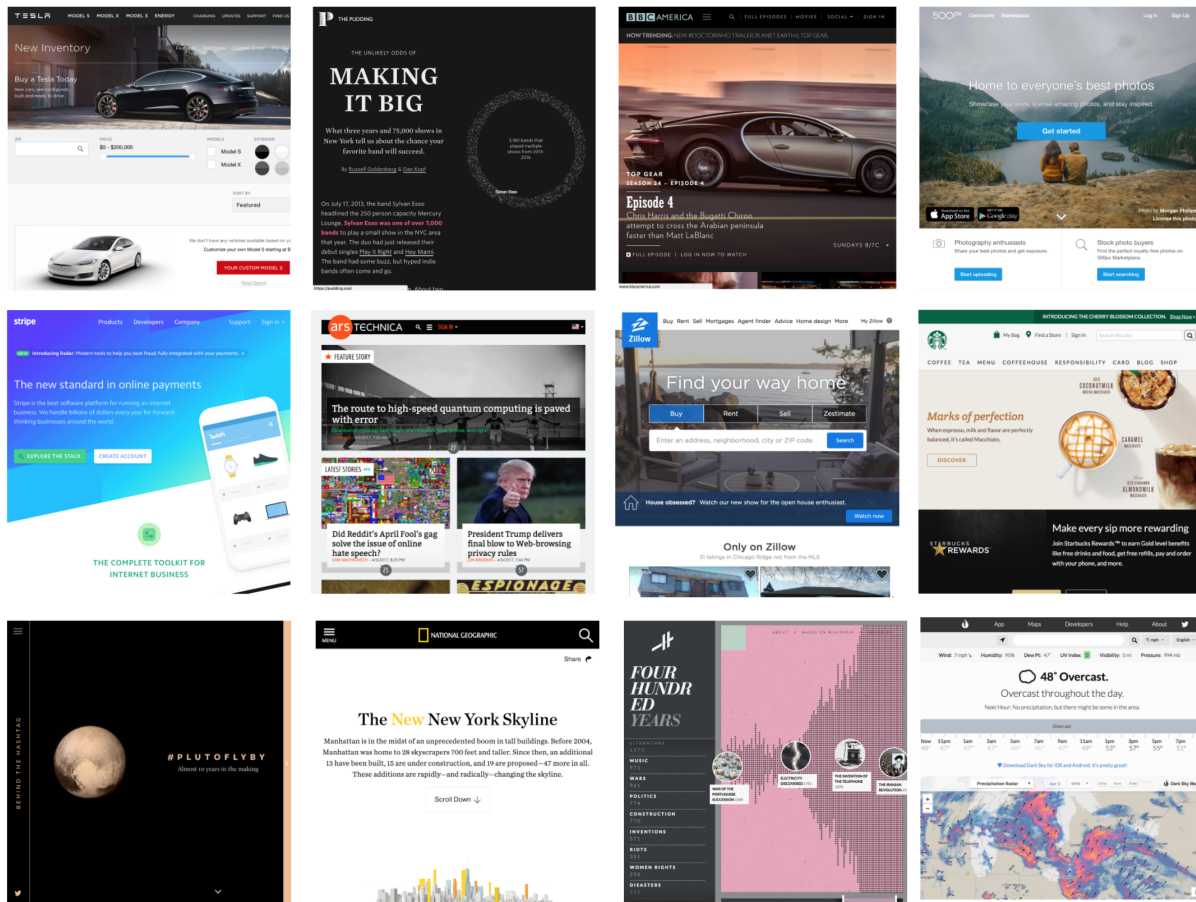


Figure 5.7. We studied Isopleth’s ability to support sensemaking and elicit design patterns across 12 websites selected from a diversity of industries based on Alexa popularity rankings, the Webby awards, and personal interest. From top left to bottom right: Tesla, The Pudding’s “Making it Big”, BBC America, 500px, Stripe, ArsTechnica, Zillow, Starbucks, HashTagsUnplugged’s “#PlutoFlyBy” article, National Geographic’s “New New York Skyline” article, Histogram.io, and DarkSky.net.

We wrote custom serializers for non-serializable JavaScript types such as Events, Dom Elements, and Abstract types like Object and Array for display in Isopleth’s source frame views as inputs and outputs.

## 5.5. Case Study

To better understand Isopleth’s capabilities in making sense of concepts in a website, we used it to surface programming patterns and implementation techniques across 12 websites that were selected from a diversity of industries based on Alexa popularity rankings, the Webby awards, and personal interest (See Figure 5.7). As this study was conducted with expert users, the goal was to assess Isopleth’s capabilities across sites of varying complexity rather than its effect on learners. This study aims to address the following research questions:

**RQ1** How does Isopleth support the process of making sense of complex code artifacts?

**RQ2** What programming patterns/concepts can users surface through Isopleth across professional examples sharing similar and different features?

### 5.5.1. Supporting Sensemaking

In evaluating how Isopleth supports sensemaking, we tested its use in terms of the formal components of scaffolding sensemaking such as providing conceptual organizers, embedding expert guidance, giving multiple representations that can be inspected to reveal underlying data, providing malleable representations of the data, and restricting complexity by setting boundaries [62].

**5.5.1.1. Conceptual Organization and Guidance.** For websites that coordinated multiple components to achieve an effect, such as BBC America’s header-open and image-load, Isopleth helped us organize related concepts with its labeled call graph, relational links, and facet filters. In activating Isopleth for a load-on-scroll feature on the BBC

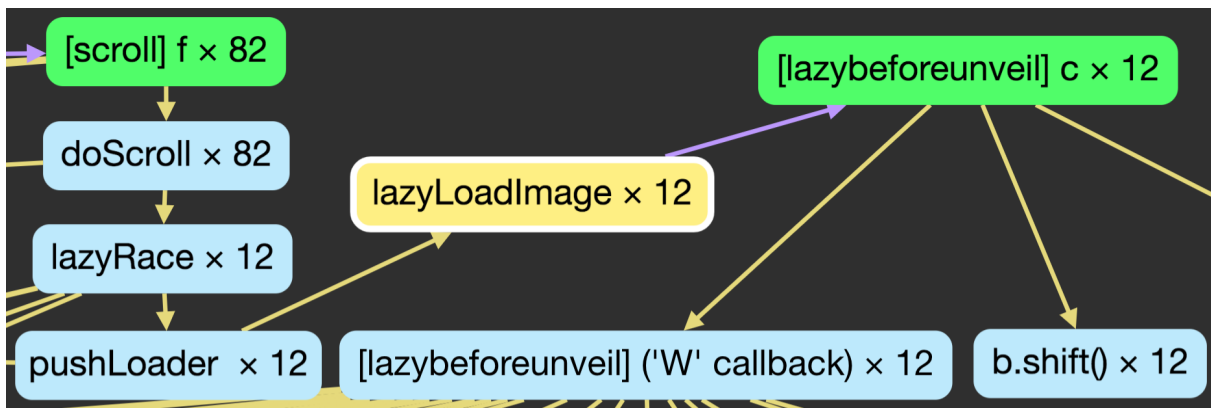


Figure 5.8. The condensed call graph representation of BBC America's lazy-image-loading strategy. By following SD asynchronous bindings, and completing small sensemaking tasks of examining source frames and updating labels, we elicit the design pattern of appending images only when the user scrolls below the fold.

America website, we observed how Isopleth organized and guided our conceptual formation of its design. With an initial view of the call graph organized by time and facets, we looked to the DOM-modifying and Mouse facets first. We scrolled a few times to load more images and looked to the right, most recent portion of the graph. We found a `lazybeforeunveil` event directly linked to AJAX-faceted nodes underneath it. Curious how the AJAX activity worked together with mouse scrolling, we followed purple lines from AJAX to nodes in a different call tree, then yellow lines to see where the AJAX response callback was created. Some functions were anonymous, so we renamed nodes according to their inputs, outputs, and function bodies, like `lazyLoadImage` (See Figure 5.8). In this case, Isopleth's facets provided an organized space for us to explore. Isopleth's links and source frames embedded expert guidance. Without this organization and guidance we would have had to spend extra time looking for distinctions between separate call trees.



Figure 5.9. A source frame view found while learning about Zillow’s recent search results feature in its autocomplete. The construct for loading previous searches is on the left and the captured return value is on the right. We were surprised to find recent searches stored in the browser’s local store rather than the user’s profile, or synced with the server.

**5.5.1.2. Multiple Representations and Inspection.** For websites with distinctly complex feature implementations, such as Zillow’s search query local store, Isopleth helped us walk through complexity by decomposing features into call trees, collating them together, and providing us with multiple ways to see code constructs and relations in its source frame view. In the AJAX autocomplete on Zillow’s logged-in homepage, we studied how Zillow supports populating the user’s previous home searches into its autocomplete search bar. Initially seeing keyboard and AJAX facets, our first assumption was that Zillow saved recent searches on a user’s profile or session, but neither was true after looking at the underlying return values in the AJAX invocation source frames. Using a different representation of the data, we ignored the DOM, AJAX, and Setup facets to focus closely on calls directly related to key events. We found a branch invoked from a keyup handler that checks for and uses the browser’s `localStorage` if available. Otherwise, the feature

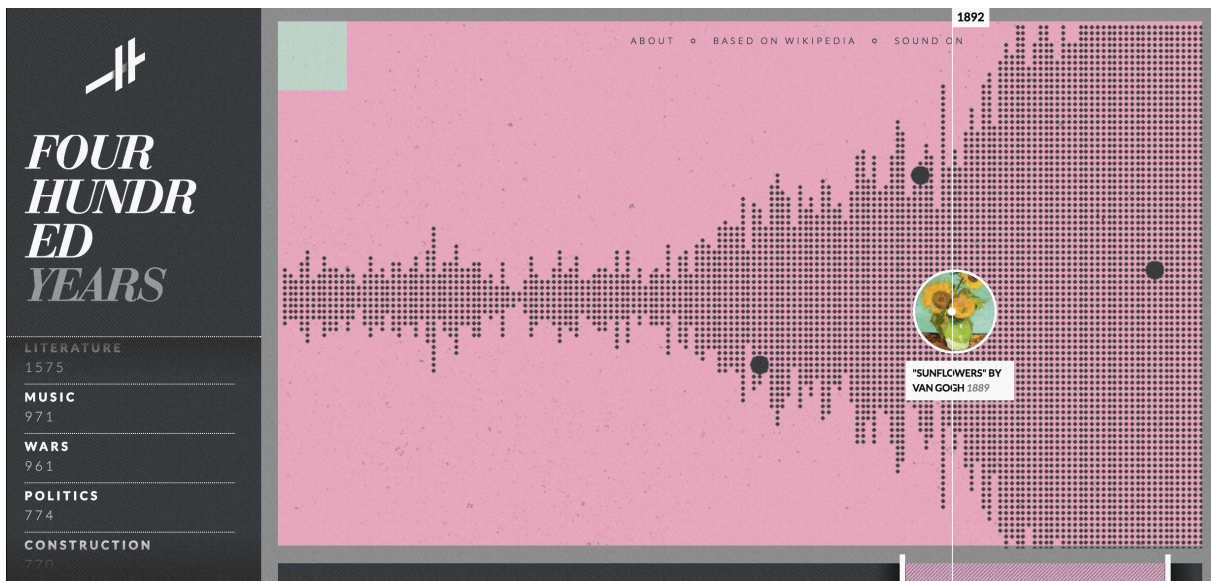


Figure 5.10. The most complex UI we tested was [histography.io](#), and Iso-pleth performed well in collating thousands of loop calls. On hover, different history events in time bubble up with randomly decaying dots.

is simply ignored (See Figure 5.9). Without simple affordances to reshape the display of data, we would be left with the more daunting task of manually stepping through large sets of invocations.

**5.5.1.3. Complex Task Boundaries and Malleable Representation.** For websites with overwhelming amounts of function activity or distinctly complex features, Iso-pleth helped us narrow in on the activity we wanted to see and it helped us organize our understanding of logic as we worked through understanding the feature. In our most complex test website [Histography.io](#), we found ourselves relying heavily on boundaries provided by Iso-pleth’s graph and the ability to edit labels and code. With such a lively interface, we focused on discovering how the hover-based interactions worked. (See Figure 5.10). Using Iso-pleth’s *setup* facet and *mouse* facet, we created an initial filtering of the call



graph, but many poorly named function nodes remained. As a basic search, we quickly scanned nodes depth-first to discover the boundaries of functionality in each call tree remaining in the graph. Upon finding numeric calculations in invocations with a mouse facet, we created a new facet to detect numeric types in return values. This new numeric facet reshaped the graph into a much smaller search space when coupled with the mouse facet. A few unknown nodes remained, so we began to directly manipulate the source representations by changing labels, variable names, and adding comments while working our way up the tree (i.e. bottom-up composition). By studying and labelling each of the smaller pieces, we discovered how the year values were updated upon hovering over certain elements. We saw how dots were scaled relative to cursor location and randomized via decay values between 0 and 1. Isopleth helped us iteratively scope down our search space and compose meaning from decomposed code constructs.

### 5.5.2. Surfacing Design Patterns

With Isopleth we were able to find (1) common patterns across similar features, (2) common patterns across different features, and (3) different patterns across common features. The principal design characteristics of Isopleth are to promote opportunistic learning, support sensemaking processes, and allow users to understand patterns and strategies across software components.

**5.5.2.1. Common Patterns across Similar Features.** Isopleth's relational links, facet filtering, and argument inspection helped us discover consistent design patterns across similar features. Starbucks, ArsTechnica, Zillow, and 500px showed a content swapping technique based on logged-in state when examining Isopleth relations among

Dom Query facets and with Setup facets. After filtering Isopleth on the DOM Query facet, we inspected the arguments in Isopleth’s source frame views that showed ArsTechnica, DarkSky, NatGeo, and Stripe add and remove a class “hidden” to DOM elements to toggle their visibility. We found 500px and PlutoFlyBy’s animated scrolling technique when simply looking into the latest occurring invocation with a Mouse facet.

**5.5.2.2. Common Patterns across Different Features.** Isopleth’s sensemaking process, argument, and return value inspection helped us elicit consistent design patterns across websites with different features. Tesla’s car picker and BBC’s landing page each listen for a UI event that triggers an AJAX call, which loads JSON containing image URL’s, which are appended to a template and rendered to the DOM. This lazy-load pattern emerged through an iterative sensemaking process between DOM, AJAX, and Mouse facets for both pages. 500px, MakingItBig, and NatGeo’s scroll-based CSS transform animations were surfaced by using Isopleth’s Mouse facets, then inspecting arguments and return values in source frame views. We identified loops operating on values modifying CSS `translate3d` positions to achieve a smooth GPU-enabled transition.

**5.5.2.3. Different Patterns across Common Features.** We also used Isopleth to discover contrasting implementations for the same feature. Different patterns may be equally valid, but often the pattern highlighted the needs of the application domain, such as a socially integrated login on the BBC America site compared to a simple form-post login on Stripe. DarkSky, BBC, and Zillow’s autocomplete search techniques were surfaced through Isopleth’s Keyboard, AJAX, and DOM facet filters, and each of their implementations fits their domain. DarkSky’s autocomplete searches local storage for previous searches and builds a URL query otherwise, fitting the site’s simple design.



BBC issues AJAX calls and populates templated results, fitting the site's reactive design. Zillow's search populates a result list, but builds a URL redirect to their map interface, fitting their real estate shopping design. Each website's login technique varied, and while Isopleth helped reveal insights, some sites did not use JavaScript to support user login. 500px, Stripe, Tesla, Starbucks, and ArsTechnica simply redirected login actions without JavaScript. Isopleth revealed BBC's use of the social Janrain platform for an AJAX social login through its DOM and AJAX filters, however on successful AJAX login, BBC oddly refreshes their page. Isopleth's DOM, Keyboard, and AJAX facets along with a customized facet filter for login arguments showed that Zillow uses a refreshless login strategy via secure AJAX post and view update.

**5.5.2.4. Surfacing Architectural Decisions.** Using unfiltered views in Isopleth, we surfaced unexpected lower-level characteristics of websites such as identifying their JSON API, or revealing large amounts of dormant code from framework-bloat or analytics packages. 8 of the 12 websites have mouse-tracking analytic packages, which we noticed through high call counts in collated superfluous invocations related to mouse events. 3 of the sites use large frameworks including Angular, YUI, and React, with thousands of invocations in Isopleth's unfiltered call graph views during simple UI changes. Isopleth revealed excessive polling activity in un-collating its call graph, where 4 websites contain library code that polls `window.location` every 20ms for hash changes. Finally, by showing library code and filtering for AJAX facets, Isopleth streamlines the ability to surface how applications structure their interaction with a remote API.

## 5.6. Isopleth User Study Design

### 5.6.1. Method

In evaluating Isopleth, we aim to understand four main research questions:

- **RQ1** How does using Isopleth affect a user’s prior conceptual model of a complex JavaScript artifact?
- **RQ2** Which features in Isopleth are most effective in supporting its sensemaking process?
- **RQ3** Which features in Isopleth are most effective in scaffolding opportunities to learn coding design patterns from the complex websites?
- **RQ4** How do junior developers’ Isopleth sensemaking strategies differ from senior developers?

The participants of the Isopleth study were ten junior web developers with less than one year of professional experience and four senior web developers with greater than five years of professional experience. The study is a between-subjects design, where each user was asked to use Isopleth to make sense of the source code underlying a UI interaction of their choice from a pool of four websites. In the study results we detail the following findings:

- (1) Isopleth altered the conceptual models of users in three different classifications: prior model verification, prior model nullification, and prior model augmentation.
- (2) The features most supportive of sensemaking include the ability to change labels, rearrange the call graph, and modify code; these features implement properties of theoretical sensemaking such as retrospect or enactment.

- (3) The features most supportive of scaffolding sensemaking in web programming are the facet filters, the simultaneous display of call graph and source frames, and the relational links in Isopleth’s call graph; these features implement properties of theoretical scaffolding such as providing malleable representations or providing navigation.
- (4) There was a distinct difference in usage patterns and sensemaking strategies when comparing junior and senior developers. Junior developers found the most relevant Isopleth affordances to be the ability of renaming and rearranging nodes in the condensed call-graph and viewing relational links among nodes, depending less on adding custom facets or following asynchronous lines. Senior developers used Isopleth to search for and verify their prior assumptions, spending more time tuning the interface through adding facets and filtering the graph view.

### 5.6.2. Study Design

We chose UI features from four popular websites present in the case studies from Isopleth and Telescope (Chapter 4): National Geographic NY Skyline Article, Histogramy.io, BBC, and XKCD’s big map. While widely used, each contains a simple surface-level concept but clever underlying implementation. When clicking the header on BBC America’s landing page, it expands and reveals images not present before. In the National Geographic NY Skyline article, scrolling horizontally causes a zoom effect on the skyline, and hovering over new buildings yields information about them. On hover in the Histogramy.io site, little dots follow the cursor in a decay pattern and dates change for which year the user is navigating over. XKCD’s big map strings images together to form a draggable

map, with an extremely large comic to explore through a normal browser-sized viewport. As an added depth to our test, each website has a seemingly obvious conceptual implementation, but in looking deeper through the implementation a more clever and scalable design pattern exists.

As a prerequisite 15-minute task, we taught users how to use Isopleth, and verified their background through a series of basic web development questions such as, “What is one way you can hide a DOM element?” Before the test, participants were asked to observe and interact with a toy example to demonstrate advanced features in Isopleth such as exploring asynchronous bindings or creating custom facet filters. Participants were recruited based on experience they described in their CV. Each participant agreed to a screen recording with audio and click history for their entire task.

We elicited each user’s prior understanding of their test concept through a 5-minute diagramming activity. Users were given a feature to explore on their own for less than a minute, then asked to describe in their own words how they thought it worked. We then asked them to draw a basic diagram of how the code works in response to the user and update some visible effect on the webpage.

Users were then asked to use Isopleth to make sense of a website’s feature interaction. We gave users the task to use Isopleth to accurately describe how the source code achieves the interaction, with a time limit of 25 minutes. In our test-tasks for designing this user study, we found that most users completed the task in under 20 minutes. The stop condition of the task was when a user had reached a complete self-assurance that they understood how the interaction worked. Users were free to take notes on paper or in a text editor during the exercise and ask clarifying questions about how to use Isopleth.

Upon completing their exercise, users were asked to describe their findings in a structured manner for 10 minutes. We asked the users to (1) write pseudocode statements describing program flow from start to finish of the interaction, (2) diagram their new understanding of the interaction, (3) describe any differences in their prior understanding of the interaction to their current understanding, (4) describe verbally which features of Isopleth were most effective in their task, (5) describe any programming concepts or design patterns they previously didn't know, and (6) describe any features or functionality they wished Isopleth had.

## 5.7. Isopleth User Study Results

### 5.7.1. How does Isopleth affect conceptual models?

The central aim of Isopleth is to help users make sense of complex code in professional websites, and in analyzing Isopleth's effects on user cognitive models we classify our findings in three distinct patterns: prior model verification, prior model nullification, and prior model augmentation. We define prior model verification as a process of validating a conceptual model or its components through scaffolding, prior model nullification as rejecting an invalid model or components of an invalid model, and prior model augmentation as templating a model and implementing component coordination through scaffolding.

**5.7.1.1. Prior Model Verification.** Five of the fourteen users (four senior, one junior) had a primary behavior of verifying their prior conceptual models through Isopleth and added minor details to their understanding of the test web interaction. Before using Isopleth, the users described an accurate program flow and coordination of logic on their test

website: BBC, XKCD, or National Geographic. The users employed a distinct strategy of searching, filtering, and quick scans through the call graph for familiar logic.

Despite having a valid prior conceptual model, the users in this group were still excited to use Isopleth to validate their assumptions about implementations from other professional developers. At the start of the exercise, one user stated “I’ve done a map-tile implementation before, but I still want to see how they [XKCD] did it.” In using the tool, the user looked for cues in the condensed call graph from different parts of their conceptual map, such as where images are appended and removed from the map. Users in this group wanted to fill in the minor details they could find only by looking at the site’s implementation and used facet filters to search for specifics. “I wonder how long the tiles remain on the page after they’re loaded,” a user said in regards to XKCD. Other minor details from the test include class names, low-level implementation decisions, framework usage, and background tasks like state synchronization frequency.

**5.7.1.2. Prior Model Nullification.** Four junior developers had a primary behavior of rejecting their prior conceptual models while using Isopleth and adapted a completely new conceptual model. In the first steps of the study task, the users provided a vague conceptual model, which consistently described an ambiguous coordination of mouse events and UI updates. One user said, “I think there are a bunch of ajax somethings to get images” in regards to the BBC header’s image loading. Another user said, “this [conceptual map diagram] is how I would construct a quick and dirty version [of an image moving on XKCD], but I don’t think it’s how they’re doing it.” When asked for clarification, the same user stated, “I know how to move an image but not how *they’re* moving the image.”

Users in this classification employed a distinct strategy of slow and careful source code reading with a low reliance on searching or filtering. They started towards the rightmost portion of the condensed call graph and worked backward in time, to the left, to understand nodes in the graph. Through iterative sensemaking (discussed later), the users nullified their prior models with the following findings: (1) BBC adds a lazy-load class to images and sets them to visible, letting a library do the rest. (2) XKCD does move images, but it breaks a big image into tiles and moves the pieces. (3) XKCD listens for mouse actions on its view and tracks the mouse position, updating image locations in synchrony with the mouse. In each of these occurrences, the users overcame specific knowledge gaps with Isopleth: (1) How to coordinate AJAX with image loading. (2) Whether their prior experience in moving images is applicable to this map-drag scenario. (3) How to coordinate mouse actions with moving images in a view.

**5.7.1.3. Prior Model Augmentation.** The remaining five junior users augmented their prior mental models by first describing a rudimentary guess at the architecture of their test website, then using Isopleth to discover how the professional website’s constructs implemented their mental model. For the Histogramy.io task, a user described their prior conceptual model, “there’s obviously a hover binding tracking the mouse location, rendering the line and the dots — but that could be done in HTML or CSS.” On National Geographic, a user said, “These could be SVGs or images, either way they’re getting resized on scroll.” In using Isopleth, these prior models greatly affected their usage strategy: instead of working through nodes in the call graph, the users sought specific functionality through facet filtering, call graph searches, and relational link exploration.

With a confidence about how the implementation might work, the users sought to find evidence to complete their conceptual map of the interaction.

### 5.7.2. Which features of Isopleth support sensemaking?

The ability to improve a learner’s conceptual model of a professional website through sensemaking is the core design claim of Isopleth; this section examines how users performed in the study. Weick describes seven properties that support sensemaking, six of which will be examined here: Retrospect, Enactment, Plausibility, Ongoing, and Extracted Cues. The Identity and Social properties are not yet applicable to Isopleth [75].

**5.7.2.1. Retrospect.** The retrospect property of sensemaking falls under the *sensing* in sensemaking, and users heavily relied on this property through Isopleth’s mutable affordances. Weick defines the retrospect property as *attention to specific meanings that arose in the past*. Eight of fourteen users modified source code in Isopleth and ten users modified node labels. When asked about the purpose of modifying the labels and code, the users considered it a retrospective task for either marking a node as understood, or making note of meaning for review in composition. During the scenario, a user would read the source code for a node and update its label; a user stated, “now that one’s done, I just have three others in this tree I need to look at before I know what’s going on.” In order to discover the full scope of logic in BBC’s header reveal, a junior developer updated node labels to “done” while working through the example. In moving forward, they glanced back at their nodes and relational links to make sense of the order and relationship between showing image content and logging a click analytic event. Another user mentioned the benefit of Isopleth’s graphical layout from left to right in time-ordering: “I really like that



it [Isopleth] is timeline based so I can retrace what happened and know some locations to look back on.”

**5.7.2.2. Enactment and Plausibility.** Isopleth supports the enactment and plausibility properties of sensemaking, or as Weick describes them, the *making* in sensemaking [75]. Enactment is a process of acting and in doing so, creating materials that become constraints and opportunities. Through activity logging, we found that seven of the users engaged in filtering, two of the users created custom filters, all users rearranged nodes, ten users modified the node labels, eight users modified source code, and six users modified the same node labels and source code two or more times. By acting on these affordances, the users created new views containing additional opportunities to act until they made sense of the interaction.

Weick describes the *plausibility* property as motivating sensemaking through plausibility rather than accuracy. A user found that BBC pads extra pixels on the header, but didn’t realize it was for a logged-in state. They said, “I would not have thought to sequentially change heights when expanding, but now I know there’s a benefit there... maybe for some other widget.” In the context of plausibility, the user wasn’t concerned with accurately exposing every piece of logic, but they noticed relational lines in Isopleth’s call graph that iteratively changed element heights and considered it plausible that the state of other components could be affecting the pixel display of the header. Another user said, “I’m not sure why it’s built this way, but at least I can fallback to this sort of understanding when I build in the future.” In this case the user couldn’t accurately portray the website author’s design decisions, but they realized the plausibility of using the technique as a valid technique for their own application.

**5.7.2.3. Ongoing and Extracted Cues.** One of Isopleth’s usage traits is its iterative process, which is a direct implementation of Weick’s sensemaking properties: ongoing and extracted cues [75]. The ongoing property states that users shape and react to the environments they face. In rearranging nodes intermittently throughout the tasks, all users desired to shape a view of the graph that was more meaningful to them. With six of the users labelling and relabelling nodes multiple times, these users treated the labelling process as an ongoing process to elicit meaning from a coordinated group of nodes in the call graph. A user on National Geographic said, “I know I’ve seen this before, but I’m actually not sure where the skyline nodes are getting their ids.” The user previously found a node that builds a selector from a string with an ID, but they hadn’t found where the ID was located. As an ongoing process, the user incrementally added to their working knowledge of the system until no unknowns remained. They later found that the ID’s were stored as properties on DOM elements.

The extracted cues property states that cues from the context are used to help users decide on what information is relevant and acceptable. The starting state of Isopleth shows users a cumulative summation of JavaScript execution over time, and users often treated the right portion of the graph as an entry cue to start at what happened last. Users worked backward through relational links between code constructs to find other constructs meaningful to them. Other users relied on filtering and color coding for cues. A user stated, “At the beginning, there were a lot of nodes, then I applied filters and with the node-coloring it became a lot easier to see where to begin.” In this case, the filtered results and node colors acted as cues to engage with the user in a more familiar setting. Another user stated, “in general I just looked around [the condensed call graph view] for

functions or classes that looked familiar and dove in from there.” Here, the user explained a very common search and amongst all the users — a user would briefly look through a few nodes and scan for syntax patterns familiar to them. Upon finding a familiar pattern, they acted upon the cue to understand logic and relationships.

### 5.7.3. Which features of Isopleth support scaffolding?

Quintonna defines several strategies to scaffold sensemaking in software, and in this section we evaluate Isopleth on a select group of these strategies: visual conceptual organizers, descriptions of complex concepts, providing representations of the underlying data, enabling learners to inspect multiple views, giving learners malleable representations, and facilitating navigation among tools and activities [62].

**5.7.3.1. Conceptual Organizers and Descriptions.** Isopleth implements a visual concept organizer in its condensed call graph view and linked source frames. Descriptions of complex concepts appear as node facet labels. All users understood the hierarchical organization of the condensed call view and heavily relied on its structure in their search and sensemaking processes. A user made a specific remark in regards to the layout, “I think the way it [the call graph view] is laid out helps you see what happened at a high level — then you can drill down as much as you want.” The default facet labels are limited to five predefined facets, but most users relied on the “Mouse” and “Setup” facet labels to scaffold their searches. Many of the test effects were tied to mouse related events such as a click on the BBC header to make it open and show images, and users found the implementation they were looking for through the mouse facet nodes and related nodes.

**5.7.3.2. Multiple Views and Representations of the Data.** Isopleth provides multiple views of source and represents the data in different ways such as facets in terms of inputs and outputs, and most users performed well with these scaffolds. Seven developers used the facet filters to constrain the view of nodes in the condensed call graph, such as Mouse compared to Setup. In doing so, they could more clearly identify a set of nodes to explore from. After renaming some nodes, they could see their changes in multiple views including the node labels and source frame views. Seeing relational links both in the call graph and side-by-side source frame views helped four junior developers determine the relationship between two nodes. A user exploring XKCD’s map class and drag effect said, “I hated jumping back and forth between editors [source frame views], then I clicked a link [call graph edge] and both editors appeared together so I could tell how each variable was declared.” Representing the same relational data in two different ways helped this user determine the link, and the user’s intuitive nature to see more detail in an edge helped them determine the relationship between two views.

**5.7.3.3. Malleable Representations and Navigation.** Isopleth’s signature design characteristic is its mutable interface, where the representation of the data can be changed — helping the user to navigate more easily in terms of their historic interpretation of the data. Ten junior developers modified the labels and eight developers modified source code. All developers rearranged nodes in the call graph to either move nodes away that they didn’t care about, or group nodes together in terms of their meaning. Users moved nodes to more clearly see the scope of their relational links or to see the aggregate of how far the node relationships stretched across the call graph. A senior developer said, “I had fun wiggling the nodes around to see how big the web of their connection was.

I just avoided highly tangled messes at first and moved things around until something looked familiar enough to explore.” Ten developers leveraged the malleable nature of the interface for navigation; in updating the node labels, four of the users considered their updated labels as nodes which were completed and needed no further examination. All users intuitively navigated the relational links of the call graph, realizing that nodes were visually connected, while four junior developers found an advantage in navigating the source frame links for input, output, binding, and effect. During a task a user stated, “I don’t know where this is getting called [a function], but I’ll have a quick look around [the source frame buttons] to see if I can find anything.” The proximity of the parent caller button in Isopleth’s source frame view to the function source allowed the user to quickly navigate to the function’s caller to determine its relationship without losing context of the original function.

#### **5.7.4. How do junior developers’ Isopleth sensemaking strategies differ from senior developers?**

There was a distinct difference in user strategies between junior and senior developers, where junior developers engaged in more node label updates and source code comments, while senior developers visited many nodes quickly in a breadth-first-search style. The ten junior developers regularly modified node labels, while none of the senior developers modified labels. One senior developer added some comments to code. The junior developers regularly traversed through call trees to compose meaning, whereas senior developers rapidly iterated through nodes to verify their assumptions in identifying where functionality was occurring and how it was wired together. A senior developer exploring XKCD

with Isopleth said, “I liked how the code was broken down, like how the mouse bindings were set up and destroyed... I didn’t really need to change anything... I just followed the lines and it seemed to work out.” In this situation the senior developer had a valid prior understanding of how to implement draggable maps and traversed the call trees to validate their assumptions. One junior developer added a customized facet, while the rest spent most of their time composing call trees while occasionally filtering different facet functions. One senior developer added several custom facets to draw distinction between logic handling scroll coordinates and logic interpreting mouse hover locations.

## 5.8. Technical Limitations

Isopleth’s Serialized Deanonymization technique does not capture the path of functions passed via closed variable reference, string key reference, global object reference, or dom element invocation reference (e.g. `onclick=‘MyFunction();’`). Function invocations and asynchronous declaration context are still traced, but Isopleth’s purple lines will not draw connections for functions passed this way. There is an existing effort underway which adds the tracking of variable state to Fondue’s instrumentation technique, thus providing the means to overcome this limitation.

Isopleth extends Fondue [48] for source instrumentation and employing the Serialized Deanonymization technique; and the Wisat architecture (Chapter 4) to bring Isopleth to public websites. Thus it inherits limitations of these approaches: it only tracks source activity from top level website frames, scripts loaded dynamically during a UI interaction will not be instrumented, functions invoked from string via `eval` are not traced. Other

browser rendering techniques are not captured including Canvas, OpenGL, FLash, etc; however, JavaScript calls to these API's are captured.

Isopleth does not involve HTML or CSS in its mixed initiative learning, and modern advances in these languages have increased their abilities in creating performant UI interactions. An existing effort is underway to provide inexperienced developers support in learning dynamic effects in CSS [50]. Isopleth does, however, trace all interactions with these languages from JavaScript, such as manipulating the DOM, adding classes, and manipulating CSS property values (e.g. `translate3d`).

## 5.9. Conclusion

Having evaluated Isopleth's ability to support the sensemaking process of complex code artifacts and identifying patterns surfaced with Isopleth, we revisit techniques that contribute to Isopleth's effectiveness.

### 5.9.1. Enabling Sensemaking through Mixed Initiative Scaffolds

A defining characteristic of Isopleth is its mixed-initiative sensemaking process between the user and system, where each acts as an agent toward a common goal [37] of understanding design patterns and constructs in professional website code. At Isopleth's heart is the JavaScript call graph that results from the user's interaction with a feature on a professional website. In this graph, nodes represent collated function invocations, and edges represent parent-child calls or asynchronous bindings. Isopleth provides a variety of views into this call graph to support sensemaking, enabled by *facets*. Facets define

filters on functions with particular arguments or return values to identify conceptually related functions. With an unbounded number of programming facets and design patterns, it is infeasible to design a fully automated system to learn programming patterns from professional JavaScript. Thus our goal was to create a system that leverages interaction between a user and the system to provide scaffolds for making sense of design patterns in professional JavaScript.

We evaluated Isopleth on 12 test sites in a case study to discover how useful Isopleth could be in making sense of professional website code. For websites that coordinated multiple components to achieve an effect, such as BBC America’s header-open and image-load, Isopleth helped us organize related concepts with its labeled call graph, relational links, and facet filters. Applying filters and following links had a similar feel to following an expert’s guidance through unfamiliar code. For websites with distinctly complex feature implementations, such as Zillow’s search query local store, Isopleth helped us walk through complexity by decomposing features into call trees, collating them together, and providing us with multiple ways to see code constructs and relations in its source frame view. For websites with overwhelming amounts of function activity and complex features, Isopleth helped us narrow in on the activity we wanted to see, and it helped us organize our understanding of logic as we worked through understanding the feature. We were able to scope the call graph by dragging only nodes we cared about into their own view. We created labels that made sense to us in working through a large feature. We created custom facets to both eliminate functionality from view and scope down functionality in view. Each of these affordances streamlined our sensemaking process in the midst of complexity in unfamiliar code.



In our case study, we were also able to identify reusable design characteristics across websites and features. Isopleth’s relational links, facet filtering, and argument inspection helped us discover consistent design patterns across similar features such as login-based content swapping on Starbucks, ArsTechnica, Zillow, and 500px. Isopleth’s sensemaking process, argument, and return value inspection helped us elicit consistent design patterns across websites with different features such as content lazy-loading in the Tesla car picker website and BBC America landing page. We also used Isopleth to discover contrasting implementations for the same feature. Different patterns may be equally valid, but often the pattern highlighted the needs of the application domain, such as a socially integrated login on the BBC compared to a simple form-post login on Stripe. DarkSky, BBC, and Zillow’s autocomplete search techniques varied based on their respective use cases.

### 5.9.2. Informing User Mental Models

Isopleth’s primary user class is inexperienced developers who would otherwise struggle with eliciting professional design patterns due to gaps in conceptual knowledge about professional web programming. Determining functional program flow and relating code constructs from source in JavaScript is nontrivial, because functions can execute asynchronously and often appear in a different runtime order than their initial source order [2, 48]. Our aim in designing Isopleth is to embed expert conceptual models in UI affordances to help learners transition from their current mental model to an accurate professionally-shaped mental model. Further, in developing these models, similarities and differences between design patterns across multiple websites broaden the learner’s conceptual understanding.

We evaluated Isopleth on ten junior web developers with less than one year of professional experience and four senior web developers with greater than five years of professional experience. While we observed and classified changes to mental models in all of the users, we attributed the change in models to features most supportive of scaffolding sensemaking: facet filters, the simultaneous display of call graph and source frames, and the relational links in Isopleth’s call graph. There was a distinct difference in usage patterns and sensemaking strategies when comparing junior and senior developers. Junior developers often renamed and rearranged nodes in Isopleth’s call-graph while viewing relational links. Senior developers primarily used Isopleth to search for and verify their prior assumptions, tuning the interface to minimize the work of their search through custom facets and filtering.

While some users lacked knowledge of JavaScript API’s or only used a subset of Isopleth’s affordances, users managed to derive meaning and fill in gaps in their knowledge from contextual clues in Isopleth. Many users didn’t follow asynchronous relational lines to discover links; seeing that a node in the graph had asynchronous connections helped them view the function in an asynchronous context rather than defaulting to a synchronous context. By using other clues in the interface such as seeing the *Setup* facet label or navigating to a function through asynchronous buttons in the source frame views, users had less incentive to manually follow purple asynchronous lines between nodes. In identifying nodes in the call graph around and connected to a node calling a third-party API, such as `$.getJSON` or `YUI.one`, users derived the meaning of the third-party API call from examining the inputs and outputs of the invocation in Isopleth’s source frame view. Only senior developers added custom facets to Isopleth. We observed junior developers

devoting more of their time understanding existing facets and relationships, with little time left to custom facets. Senior developers skimmed for familiar functionality and focused on tuning the interface to decrease the breadth of their search with custom facets. This helped senior developers to more efficiently see distinctions from their initial mental model.

### **5.9.3. Enabling RALE**

Isopleth is the first system to prove the techniques of RALE as a concept, and its user study shows corrective and constructive effects in conceptual model formation, distinct user sensemaking patterns compared to other systems, and deeper user understanding of the subject matter (i.e. design patterns in professional websites) than was observed in Telescope or Unravel. Isopleth scaffolds sensemaking for users by providing them low-effort entry points into exploring how a web application works while still allowing them to explore code constructs in a fully comprehensive way. Isopleth facilitates mixed-initiative sensemaking by allowing users to create their own custom facets and code refactoring, while incorporating their additions into the recalculation of views and entry points into exploration.

## CHAPTER 6

### Discussion

#### 6.1. Applications of Unravel, Telescope, and Isopleth

The three RALE tools detailed in this dissertation were created sequentially (Unravel, Telescope, then Isopleth) and extend off of each previous tool, yet they have distinct differences in use and applications for their target users class: those who can setup, read, and write basic JavaScript web applications but lack the conceptual knowledge of design patterns used in professional web solutions. Unravel works as a lightweight browser extension, and its user study showed the benefits of applying it as a tool to discover entry points into complex code. Telescope is built on a more complex architecture, but showed promise in its exploratory study for generating small examples (e.g. snippets or fiddles) of dynamic web features and the interplay between JavaScript and HTML. Isopleth extends Telescope’s architecture, but shows relationships in the code and gives users scaffolds to make sense of complexities they encounter. Different from prior work and existing inspection tools, Unravel, Telescope, and Isopleth are specifically designed to help users understand unfamiliar professional web application code by overcoming learning barriers and scaffolding sensemaking.

### 6.1.1. Unravel Applications

When curious about an interesting feature on a website, Unravel helps experts navigate quickly to code likely supporting the feature, and it helps beginners overcome the information barrier of where to begin inspection. Tools created prior to this dissertation [5, 41, 38, 48, 25, 26, 13, 30] are certainly capable of exposing feature functionality but were designed to debug applications under development rather than delve into completely unfamiliar code. For web features with tens of thousands of function invocations, it quickly becomes unclear — even to experts — how the application works due to overwhelming amounts of debugging information. Prior tools for exploring unfamiliar code make contributions to record and diff program state but still are subject to overwhelming users with too much runtime information when recording thousands of function invocations or DOM changes [59, 14, 13, 2]. Unravel uses excessive runtime counts to its advantage by bubbling relevance based on counts and reducing output by unique DOM element and unique call stack. Users look to Unravel to provide sortable filtered lists of DOM changes and function invocations; they can use the lists as an index linking into specific locations in the well-featured Chrome Developer Toolkit.

An example scenario is for a developer who has a vague idea of how to achieve a card-swipe transition effect but wants to check comparable websites to quickly consider and compare other professional strategies. The developer launches Unravel and looks for specific function invocations calling API's like animation, iterating over CSS properties, or invoking frameworks. The developer sees which techniques are being supported by other companies in production. After finding and inspecting a website with a cleaner and

more maintainable pattern, the developer decides to follow their pattern of adding and removing CSS-animate classes via JavaScript.

But beyond finding quick entry points into the application's code, further exploration is inhibited by information barriers in having to navigate large amounts of code. Telescope can be applied to produce low-barrier learning materials from large amounts of code.

### 6.1.2. Telescope Applications

When interested in discovering *all* of the JavaScript and HTML necessary to recreate a web feature in an efficient way, Telescope is able to display relevant source code at variable levels of detail in its composite view. Telescope overcomes Unravel's main limitations of JavaScript observation scope (DOM only) and shallow exploration (simple pointers into the code) by extracting all the code from a website and displaying it in a composite view for the user, condensing JavaScript based on a configurable detail level. Unravel displays HTML and JavaScript function invocation counts in different pains with links to Chrome Developer Tools, while Telescope can display all of the JavaScript and HTML for a website with visual links between the two languages. Telescope enables users to vary the level of detail of JavaScript displayed between: DOM-querying, invoked, library, and all. This helps users see different patterns in JavaScript such as in-memory data management in an MVC architecture. Similar to a fiddle or code snippet, Telescope's output can be used as a starting point to recreate or feature or learn new design patterns in a professional website. While Unravel provides pointers into the browser's web inspector, Telescope pulls out relevant views of JavaScript for the user.

An example scenario involves a developer who wants to recreate a draggable map interface they found on their website, but they aren't aware of any techniques to create this implementation. Briefly searching the web, all of the techniques they find are either overly cumbersome (such as deploying a map-creator SDK) or too dependent on a third-party (such as Google Maps). Knowing they simply want to create a similar solution to what they see, they activate Telescope in the website and identify a simple 60-line starting set of how to construct a draggable-map component in JavaScript. After looking through the code toward the beginning of the timeline, they want to see how code later in the timeline modifies the initial draggable-map component. They move the timeline and increase the detail level to see a set of active event-bindings and listeners. With a set of starting code, users wishing to gain more insight into professional web application development can discover techniques while using parts of the code to craft their own custom solution.

### **6.1.3. Isopleth Applications**

When interested in learning new professional web development techniques more comprehensively, Isopleth provides opportunistic views to learners and scaffolds basic sensemaking through mixed initiative affordances. Somewhat like a worksheet that adapts to its student, users can work through findings in Isopleth and add their own custom facets and names; Isopleth reshapes its views in response. Isopleth captures JavaScript invocations by extending Telescope's architecture, but instead of displaying variable detail levels of relevant JavaScript, Isopleth displays reduced and filtered views of a JavaScript call graph based on facets (i.e. code constructs defined by their inputs and outputs). Users can see

how functions were called, how functions relate to other functions, which hidden asynchronous links exist between functions, and how calls are classified via their facet labels. With these unique views fully decomposing an unfamiliar JavaScript web application, users can study small pieces and relationships in an effort to build an accurate mental model of how a web feature was created. Isopleth is the first of the three tools in this thesis to offer learning scaffolds, which helps inexperienced developers make sense of complex code.

An example scenario is for a frustrated self-starting web developer who is eager to understand how click-and-drag bindings work in JavaScript but is overwhelmed even by Telescope's simplified output, as it lacks program flow and asynchronous relationships. Telescope condenses website code into learning materials, but in doing so loses structures and dependencies in the code necessary to form a deeper understanding. The developer doesn't understand how a function could be run before it is declared; that should not be possible. The developer launches Isopleth and starts examining nodes in the call graph, broken down into small pieces with relational asynchronous links. The developer notices that the function is actually declared in the first tree in the call graph, as it is labeled with a *setup* facet. The developer follows an asynchronous relationship line to the right side of the call graph where a drag function invocation has occurred. It is labeled with a *mouse* facet. After studying the functions and following relationships in their trees, the developer sees how the function was bound to click-drag events at setup and invoked later on. By using Isopleth, the developer has corrected an inaccurate mental model of the application.



#### 6.1.4. Future Toolkit

In the future, it is conceivable to imagine a single tool that encompasses all of the functionality of Unravel, Telescope, and Isopleth without reliance on third party technology. By integrating Isopleth’s instrumentation in a browser’s JavaScript precompile step, all of the information needed to bubble relevance, vary detail, filter libraries, or deanonymize anonymous asynchronous calls would be available to a live inspector. No third party server architecture would be needed. Note: the intended goal of the existing architecture is to be agnostic of browser implementation, but the proposed implementation here would require a customized integration per browser.

### 6.2. RALE: Design Claims and Evidence

This thesis has contributed three systems toward the goal of creating Readily Available Learning Experiences for professional websites. This section details the primary design claims of Readily Available Learning Experiences and reviews evidence of their necessity. In brief, a RALE should:

- Surface hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites.
- Minimize learning barriers while supporting personalized exploration of unfamiliar website code.
- Scaffold mixed-initiative sensemaking to help users walk through unfamiliar complexities in the surfaced resources.
- Scale the conversion of examples into learning resources without additional authorship or maintenance.

### 6.2.1. Surfacing Hidden Patterns, Constructs, and Relationships

RALE addresses a class of users who are frustrated by their knowledge gaps in web development and thus limited in their ability to interpret complex professional code. After completing web tutorials, a beginner might attempt a new project but realize they lack sufficient knowledge to complete their project goals. Inspired by existing professional examples, a beginner might inspect the professional website, but in doing so find that it is unclear where to find and how to interpret design patterns, code constructs, and programmatic relationships. Surfacing patterns, constructs, and relationships from professional websites helps users overcome gaps in knowledge, shortcuts inefficient forms of web foraging such as searching the web for relatable tutorials and Q&A posts, and provides them with opportunities to learn authentically — in a personally meaningful way using multiple modes of the discipline (i.e. web application programming).

Design patterns in this context are defined as reusable techniques or sets of techniques which can be applied in multiple situations to solve similar problems. While many design patterns are well known and have names (e.g. Model-View-Controller, Bootstrapping, Lazy-Loading), naming a pattern is less a concern in RALE than helping a learner build an accurate reusable mental model of a design pattern. A popular unstandardized design pattern in web development involves toggling a CSS class on a DOM element via JavaScript to achieve a show/hide or animation. Test users found this simple yet effective pattern on Tumblr, BBC, Amazon, and Kickstarter using Unravel, Telescope, and Iso-pleth. While none of the tools actually observe CSS, they were successful in identifying the patterns that operate on CSS by surfacing constructs that operate on DOM elements.

Surfacing relevant code constructs and relationships between them informs users about the coordination among components to achieve an effect. Identifying relevance in the constructs provides users with entry cues as to which constructs or relationships should be examined first. Code constructs in this case are functions, sets of procedures, or DOM structures. Relationships are direct or indirect dependencies or operations between code constructs. Together, code constructs and their relationships are the subjects of study in a RALE, which inform higher level design patterns. While Unravel lacks relational information, its construct ordering of function invocations and DOM element changes helps users quickly identify entry points into learning from complex applications. Telescope collects active code constructs together in a composite view, shows invocation counts, and relationally links HTML to JavaScript constructs. Telescope’s exploratory study highlighted the advantages of surfacing a composite view of constructs and their relationships to help the user determine the scope of a feature’s implementation and its interplay between constructs. Isopleth fully decomposes constructs of a web application feature in its call graph and visualizes direct and indirect relational links in JavaScript. With Isopleth users can easily determine the hierarchy and dependencies of constructs as well as links between setup, runtime, and specific facets.

### **6.2.2. Minimizing Learning Barriers**

There are many tools that enable developers to inspect and step through every line of code responsible for a feature [59, 14, 2, 25, 5], yet developers still are overwhelmed in learning from professional websites due to the size and complexity of modern web applications [6, 64, 70]. While these tools are fully featured and support deep inspection into the runtime

of a web application, they were designed to serve purposes of inspection and debugging and thus streamline goals toward program maintenance and implementation. But the comprehensive nature of these tools can introduce additional barriers to a learner when trying to understand complex concepts. In Ko et al's work on *six learning barriers*, they identified barriers such as the Information Barrier where users had helpful information available to them but didn't know to look for it or read it, or the coordination barrier where users were confused with how multiple components worked together to achieve an outcome [45]. Presenting users with detailed stack traces, variable states, and nested program flows could easily introduce additional barriers to a learner. Thus it is a primary goal of RALE to minimize the effects of additional learning barriers created by surfacing hidden details from software.

Most notable in Telescope's user studies and Unravel's controlled study, users greatly benefitted from being shown informational views tuned specific to their goals to help overcome learning barriers. In the early prototypes of Telescope, users were given detailed call stacks and verbose amounts of active JavaScript and function hit counts. While some of the test users appreciated being able to visualize the inner workings of a complex web application, they described confusion in trying to understand the overly verbose output. In three user-centered design iterations, the output of Telescope was reshaped to show JavaScript activity most relevant to visual changes in a web application first, linked to active HTML (i.e. the composition of the rendered website view), with the option to expand detail. These changes diminished the effects of information and coordination barriers, because users were not required to sift through large sets of function invocations or to make

manual connections between HTML and JavaScript. Telescope’s exploratory study revealed that most users appreciated the default views with more limited information to gain an introductory understanding of unfamiliar website code. Unravel’s user study findings highlight the importance of filtering and aggregating large volumes of information to streamline the search for entry points into website runtime activity.

In addition to shaping default informational views to minimize learning barriers, users with different gaps in knowledge are subject to different learning barriers and need flexibility in the display of data. Unravel’s user study showed a strong decrease in efficiency beyond surfacing the first relevant code construct; Unravel only allows for the filtering and sorting of aggregated information rather than expanding upon levels of detail like in Telescope or shaping information display with rich labels, or facets, in Isopleth. Telescope’s final design incorporated user feedback from Unravel and earlier Telescope prototypes that users need to see different levels of detail at different times. In using Telescope with expanded detail beyond just DOM-querying JavaScript, users found richer design patterns such as lazy-loading or view-routing. Isopleth provides users with an interactive call graph and facets to simplify the display of information; when users add new facets to Isopleth, its views are further enriched with their customization. During Isopleth’s user study, participants commonly began their searches at the rightmost portion of its graph for simplicity, but expanded their search backwards in time in Isopleth’s call graph to construct mental models about the program’s constructs and relationships. Therefore, it is important to not only surface information in RALE but to allow for personalized exploration of the data surfaced.

### 6.2.3. Scaffolding Mixed-Initiative Sensemaking

RALE builds upon a rich body of work in automated tutoring [16, 33, 46, 43, 30], program visualization [73, 20, 32, 11], and web application exploration [59, 13, 14] by setting sensemaking and learning scaffold goals based on strongly grounded literature in the learning sciences [51, 61, 62, 75, 1, 76, 52, 56, 17, 18, 19]. Prior tools such as FireCrystal, Scry, and WhyLine expose hidden aspects of program behavior and even allow the user to query parts of their interface as scaffolds for sensemaking, but they are not designed to support a learner’s progression from writing functional code to writing professional-quality software. Specifically, they surface constructs but not design patterns from professional code; they do not decompose complexity into explorable pieces, and they do not allow users to customize or extend the interface. As a result, they lack authenticity and do not provide opportunities for learners to think in the modes of the discipline [62]. RALE furthers the goal of these tools by calling for techniques and affordances to support learners during their sensemaking process and provide them with cues to engage in multiple modes of the web programming discipline such as architecture, implementation, and refactoring.

While many of the prior tools lack evaluations, results from evaluating Unravel and Telescope emphasized the necessity of mixed-initiative sensemaking in designing RALE. Most tools in this body of work, with the exception of Isopleth and Bret Victor’s Learnable Programming [73], fall into either categories of read-only interfaces which tell users about hidden activities [2, 59, 14, 48] in the program runtime or read-and-query interfaces which allow users to query for certain informational views revealing details about hidden program activity [16, 43, 47, 44]. In Bret Victor’s programming environment,

affordances are provided to directly visualize the effects of a user’s design decisions in code while they are attempting to modify or build a project. Ideally a RALE should scaffold sensemaking by allowing users to not only observe information about a program’s runtime, but to modify and personalize that information as a mixed-initiative with the system — each contribution between the user and system provides gains for the user [37] towards the goal of learning new professional programming concepts.

Isopleth is the first system to prove the techniques of RALE as a concept, and its study shows strong effects in conceptual model formation, distinct user sensemaking patterns compared to other systems, and deeper user understanding of the subject matter (i.e. design patterns in professional websites) than was observed in Telescope or Unravel. Isopleth scaffolds sensemaking for users by providing them low-effort entry points into exploring how a web application works while still allowing them to explore code constructs in a fully comprehensive way. Isopleth facilitates mixed-initiative sensemaking by allowing users to create their own custom facets and code refactoring, while incorporating their additions into the recalculation of views and entry points into exploration. In using Isopleth effectively, users were encouraged to modify Isopleth’s source code views, facets, and graph nodes for their personalized goals. This allowed them to work slowly through understanding parts of the program in a bottom-up code comprehension strategy. While some of Isopleth’s study participants described new mental model formation of observed professional website behaviors, others enriched their existing mental models with implementation patterns important to production environments (e.g. caching queries to speed up query results or abstracting authentication to support proprietary and social logins). Though Isopleth was designed for beginning developers struggling to fill their

gaps in knowledge, experts appreciated the efficiency of Isopleth’s scaffolds, entry cues, and filtering in streamlining their searches for functionality. Isopleth’s study participants described the compositional graphing of function invocations as a streamlined way to work through code constructs, where each node is like a simple “to do” in working toward an understanding how the application works.

Much future work remains beyond Isopleth in advancing mixed-initiative sensemaking scaffolds in RALE. Quintonna et al provide rich guidelines for scaffolding sensemaking in software inquiry [62], and the current body of work provides a platform to apply these strategies. The following itemization characterizes how new strategies can be applied given the current platform:

- **Embed Expert Guidance:** Users in Isopleth’s evaluation desired to know more about the design patterns they discovered, such as why one pattern was chosen over another. Future tools can incorporate expert commentary on professional design decisions surfaced by existing tools.
- **Provide Structure for Complex Tasks and Functionality:** Existing tools provide a limited set of techniques to enable source exploration and scaffold sensemaking. For more complex learning tasks, future tools could incorporate additional structures and scaffolds to guide users on a particular learning path, such as sandboxing part of an application and having users incrementally recreate a feature in order to gain authentic practice.
- **Facilitate Navigation Among Tools:** Many tools exist in source code exploration and tutorial-generation, yet without guidance, users are generally unaware of the pros and cons of using different tools. Future work could incorporate a



survey of this body of work, conducting studies on many of the tools lacking evaluation to determine their effectiveness in scaffolding sensemaking, enabling code comprehension, and overcoming learning barriers.

- **Facilitate Ongoing Articulation and Reflection:** The current suite of tools elicits concepts from professional code and provides basic learning scaffolds but lacks ongoing reflection (other than repeat use of the tools). Quintonna states that learners often do not know to articulate their ideas, or they need help to do so productively [62]. Future tools could provide mechanisms for learners to record their findings for review, reuse, and practice in other domains.

#### **6.2.4. Scale Continuously without Burdens of Authorship or Maintenance**

With millions of active learners looking to the web for online learning along with the fast pace of innovation in web programming, teachers and content authors meet only a small portion of the ever-expanding demand for learning materials. The primary goal of RALE is to transform inspiring professional websites into opportunities for learning with no dependencies on authoring. Developers often turn to the web to forage for designs, web features, interactive techniques, and performance optimizations they wish to learn how to create [9]. With limited articles and tutorials keeping up with the pace of innovation, users turn to Q&A networks, chat rooms, web tutorials, and MOOCs. Social platforms like Q&A and chat rooms have social norms; they can seem abrasive to newcomers who aren't familiar with the correct terms in which to ask their question [53]. Web tutorials are limited and can grow outdated or even contradict one another in terms of best practices or design patterns to use (e.g. do or don't lazy-load content). After completing MOOCs,

significant gaps in knowledge can remain when trying to transition from the pre-authored material to new project scenarios. Therefore, a central claim of RALE is that it must scale continuously across its medium without burdens of authorship (i.e. manual creation of learning materials) or maintenance (i.e. manual support for unwinding technological features into learning content).

Unravel, Telescope, and Isopleth were designed with the goal to scale to the domain of professional websites on the open web, which enables both authentic learning and the continuous creation of learning materials. Prior tools either required users to perform technical workarounds to gain full access to web code [48, 2, 59] or only provided views of DOM-querying JavaScript [13, 14, 16]. To support authentic learning, systems should (1) surface the rich details from professional websites that are missing from training examples while (2) providing users with opportunities to think in multiple modes of the discipline (i.e. software engineering), and (3) embed programming concepts and implementation techniques that are used by professionals when creating scaffolds for users to explore. To avoid additional barriers to learning, these systems should not require users to have knowledge of advanced inspection techniques to surface learning materials or scaffolds. Unravel, Telescope, and Isopleth are each deployed via one-click workflows when users encounter professional websites of interest. Learning materials are surfaced for them, and scaffolds are created automatically. Each of these tools currently supports discovery on the web and will continue to support future discovery.

## 6.3. Broader Applications of RALE

### 6.3.1. RALE in Software

Beyond learning from source code in professional websites, broader applications exist for RALE in other programming disciplines. The central design claims of RALE described in this thesis generalize to other venues of professional source code for future development of RALE tools. By extending the instrumentation and graph analysis techniques in Theseus [48], Telescope, and Isopleth, mixed-initiative sensemaking scaffolds could be created across many languages such as Java, Python, and C++. In each new application of RALE it is important to understand common barriers users face when learning from professional source code and surface which techniques or patterns they seek to understand. For example, in a Java web REST API, it would not make sense to surface facets in a call graph about mouse, keyboard, and DOM-modifying code. It would be more appropriate to surface API endpoints and the relevant operations on web API request (e.g. scaffold the user through discovering Java controllers, services, and repository accessors). By extending RALE to new programming disciplines, new opportunities are introduced to draw parallels and distinctions among patterns in multiple technologies.

Design Techniques from Unravel, Telescope, and Isopleth have broader potential in other programming disciplines. Unravel demonstrated techniques to surface relevance in code by bubbling invocation counts and UI changes, with links into code inspection. Telescope provided a composite of a minimal set of code comprised of invocation counts, runtime timestamps, and library filtering with interactive visual lines to UI code. Isopleth provided mixed-initiative sensemaking scaffolds on function invocations linked by

direct and indirect calls. Similar programming techniques are present in a wide array of programming languages, and with more languages adopting functional design and lambda expressions, the need for visualizing and learning from complex construct relationships is increasing. Ko et al’s learning barriers exist in many languages [45], calling for new solutions to guide incoming learners. Potential drawbacks to applying RALE techniques in other disciplines stem from the availability of source code. Proprietary packaging or compilers could make RALE generation difficult. While the source code of many professional software products may not be available, large public open source repositories such as Github can serve as a rich repository of open source code. It is common to find many of the same professionals who have developed proprietary technology developing open source and publishing on a company-sponsored public repository (e.g. Adobe, Google, Microsoft, Amazon).

### 6.3.2. Learning Technique Trade-offs

Broader applications for RALE have learning tradeoffs when compared to existing learning techniques in each domain. 1-on-1 tutoring, mentoring, or formal courses are excellent ways to prepare for professional work, however the supply of tutors and mentors is not scalable and formal courses are not accessible to many. Further, the learning resources provided are finite and thus not fully comprehensive across a domain of potential professional applications. RALE can be helpful in scaling authentic learning beyond the current learning system’s limitations. However, while RALE relieves limitations in authoring, there is currently no supported technique to inform users that materials generated from professional products might be either outdated, invalid, or contain bad practices.

Even though code may be developed by professionals, it may not always meet high standards in software engineering. Authored tutorials, guides, books, and lectures often have indicators as to their timely relevance, such as publication date, community comments, software versions, and compatibility. These indicators may be unavailable through the RALE technique of automating learning materials. A potential solution for this is to incorporate communities of learners to discuss and reflect upon design patterns or techniques they have discovered using RALE. Communities for discussing techniques and patterns already exist in different domains <sup>1 2</sup>, thus there exists a potential to leverage communal knowledge to overcome risks in RALE quality.

### 6.3.3. RALE in Other Disciplines

Even more broadly speaking, it is not understood yet which claims in RALE are generalizable to other knowledge domains, such as art or physics. For example, by surfacing techniques used to create a professional painting and scaffolding learning about the purpose and usage pattern of said techniques, an aspiring artist could bridge gaps in their knowledge of the discipline. Professionally developed products or deliverables capture and inspire learner interest and promote new opportunities for a RALE to enable authentic learning. Given new techniques to access the underlying constructs that formulated a product, or access the intentions and purposes for which specific techniques were used (e.g. in art), a RALE could be envisioned that operates on data about the underlying constructs or techniques by lowering learning barriers, scaffolding sensemaking, and continuously scaling to new products in the domain. Beyond professionally developed

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<sup>1</sup>Stack Overflow Documentation <https://stackoverflow.com/tour/documentation>

<sup>2</sup>Gitter: Developer Chat per Open Source Repository <https://gitter.im/>

products, objects and interactions in nature raise interesting questions for what RALE could enable. Stemming from the central claims of RALE, a RALE could be envisioned for learning why an object occurs and behaves the way it does in nature — given some techniques to expose physical data (e.g. sensors). For example, as an apple falls from a tree, a RALE in nature could surface information about the underlying physical laws and variable states of mass, gravity, friction, and momentum while minimizing learning barriers, scaffolding sensemaking, and scaling continuously across multiple examples of falling objects and gravity. While many questions remain for extending RALE to other disciplines, its central claims can be revisited to conceptualize basic frameworks for guiding learners in new applications and domains.

## CHAPTER 7

### Conclusion

This thesis introduces Readily Available Learning Experiences (RALE) for professional web applications. Its goal is to help inexperienced learners who wish to become professional contributors but lack the means necessary to advance beyond their gaps in knowledge. The central claims of RALE are (1) surfacing hidden design patterns, code constructs, and relationships (both direct and indirect) from professional websites, (2) minimizing learning barriers while supporting personalized exploration of unfamiliar website code, (3) scaffolding mixed-initiative sensemaking to help users walk through unfamiliar complexities, and (4) scaling the conversion of examples into learning resources without additional authorship or maintenance. To conclude, this chapter will summarize the main contributions and discuss future directions of research.

#### 7.1. Summary of Contributions

The systems and corresponding studies in this thesis more broadly contribute techniques to support reverse engineering, create low-barrier learning materials, and scaffold users into opportunistic sensemaking processes.

- **Unravel: Reverse Engineering:** Unravel’s conceptual contribution is the idea of tracing, identifying, and organizing the most relevant functionality to help users find interaction code quickly in complex professional website code. Unravel’s technical contribution is a lightweight *API harness* technique designed

to capture specific source code traces to an API. Unravel’s evaluation measures the effectiveness of its reverse engineering techniques on novice and professional programmers.

- Telescope: Creating Low-Barrier Learning Materials:** Telescope’s conceptual contribution is the idea of helping users understand complex website code by generating low-barrier learning materials from features of interest. Telescope’s technical contributions are the *Wisat* architecture and *Sleight-of-Hand* technique; they enable the capturing of comprehensive runtime JavaScript traces on public websites. Telescope’s evaluation measures its performance, effects, and limitations of generating low-barrier learning materials on professional websites.
- Isopleth: Scaffolding Sensemaking:** Isopleth’s conceptual contribution is the idea of scaffolding sensemaking of complex professional code by surfacing hidden relationships between code constructs and providing a mixed-initiative process to interactively explore, label, and identify system components and how they relate. Isopleth’s technical contribution is a Serialized Deanonimization (SD) technique that places unique identifiers in all functions in a web application’s JavaScript source to trace how functions are bound, passed, returned, and invoked asynchronously. Isopleth’s case study measures its capabilities in making sense of concepts in a website, and its user study measures its effectiveness in sensemaking and mental model formation.



## 7.2. Future Directions

Research in designing, developing, and evaluating RALE has just begun. With a continuum of curious builders and tinkerers, there are many potential venues for RALE to grow in its application space. This section addresses the next logical direction for RALE to continue in the context of professional web applications.

### 7.2.1. Learning Communities

Based on the techniques from Telescope and Isopleth (Chapters 4 and 5), professional website UI features now have a potential be transformed into portable and indexable learning-examples for users to share and build upon. Shareable real-world examples could provide the basic blocks to build learning communities, as they are inherently relevant and meaningful to learners eager to gain professional experience.

Creating a UI interaction implementation library could help developers with varied experience levels discover techniques used on the web. Junior web developers struggle with creating UI interactions, and experienced web developers have difficulty keeping up with the latest techniques. For example, a user might search for an autocomplete implementation and have the option to compare source code underlying well designed interfaces from Google, Twitter, and Facebook. Further, indexed UI traces from telescope code could be used in-context within IDE's through technologies like Codeletes and Blueprint [58, 8]. With labeling and UI metadata, learning material output could be indexed for mining UI *behaviors*, or the combination of user-prompted interaction and underlying source code traces. Output from this mining could be used to elicit implementation patterns or best practices across websites.

### 7.2.2. Developer Tooling

The output of the systems in this thesis could be integrated into research tools with similar learning goals. This integration could create new opportunities to receive help while developing software [22, 8], provide micro explanations of code constructs [33], or train classifiers in context-based variable naming and unminification [63]. Enhancing Telescope to support *webstrates* would allow bidirectional modification of a website UI, giving users the opportunity to “sandbox” their UI discovery with a real website [42]. To maintain the consistent goals of RALE, subsequent research should continue to construct effective technical solutions that are well-grounded in the learning sciences.

### 7.2.3. Learning Pathways

While this thesis has addressed the extraction, creation, and design of learning materials for making sense of professional websites, much work remains in guiding the growth of a learner *during* their transition from learner to professional contributor. For example, it is unknown how to create guides for learning in RALE, such as a curriculum-design or learning goals. Providing users with learning pathways could give them clear direction of how to achieve specific learning goals with the materials they have from RALE. Helping users reach learning milestones or achievements could provide them with newfound confidence in their abilities to professionally develop software.

Learning to code should be more accessible to everyone. With platforms and techniques that enable Readily Available Learning Experiences in professional websites, I aim to continue lowering the barriers to learning in Computer Science.

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## APPENDIX A

## Supplemental Figures



Figure A.1. "Compiling", XKCD, by Randall Munroe. [xkcd.com/303](http://xkcd.com/303)