

The Client Insourcing Refactoring and Its Applications to Optimizing and Enhancing Distributed Execution

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(ABSTRACT)

Developers often need to re-engineer distributed applications to address changes in requirements, made only after deployment and usage. Much of the complexity of inspecting and evolving distributed applications lies in their distributed nature, while the majority of mature program analysis and transformation tools works only with centralized software. Inspired by business process re-engineering, in which remote operations can be insourced back in house to restructure and outsource anew, we bring an analogous approach to the re-engineering of distributed applications. We introduce Client Insourcing, a novel automatic refactoring that creates a semantically equivalent centralized version of a distributed application. This centralized version can then be inspected, modified, and redistributed to meet new requirements. We demonstrate the utility and value of Client Insourcing in optimizing and enhancing distributed execution to meet the changed requirements in performance, reliability, and security. We realize the reference implementation of Client Insourcing in the important domain of full-stack JavaScript applications, and apply our implementation to re-engineer mobile web applications. The ultimate goal of this dissertation research is to reduce the complexity of inspecting and evolving distributed applications in order to facilitate their re-engineering.

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1 Introduction

Developers often need to enhance distributed applications to address requirement changes made only after deployment and usage. Re-engineering captures evolutionary modifications that range from maintenance tasks to architecture-level changes [1, 9]. A re-engineering effort can involve adding a major feature, protecting against security vulnerabilities, or removing performance bottlenecks. Modifying existing distributed applications requires complex program analysis and modification operations that are hard to perform and even harder to verify. One of the main causes of this complexity is the distributed execution model of distributed applications. In this model, a distributed application’s execution flows across the separate address spaces of its client and server parts. All remote interactions are typically implemented by means of middleware libraries. As a result, the control flow of distributed applications can be highly complex, with their business and communication logic intermingled. That complexity hinders all tracing and debugging tasks. In addition, distributed execution over the network makes web applications vulnerable to partial failure and non-determinism.

Program analysis is central to software comprehension. The distributed application is pre-

dominated by dynamic languages, which defeat static analysis techniques. Hence, to comprehend programs written in dynamic languages, such as JavaScript, requires dynamic analysis. Software debugging hinges on the ability to repeat executions deterministically [35, 38]. However, many distributed applications are stateful, with certain client server interactions changing the server’s state. It can be quite laborious and error-prone to restore the original state to be able to repeat a remote buggy operation [19, 31, 39]. All in all, it is the presence of both distribution and stateful execution that makes it so hard to trace and modify distributed applications.

In this work, we draw inspiration from business process re-engineering that can bring remote operations in-house via *Insourcing*. Once the insourced operations are redesigned and restructured, some of them can be outsourced anew. As argued above, the notion of local operations being easier to analyze and restructure than remote ones equally applies to distributed applications. Specifically, the approach presented herein first automatically transforms a distributed application, comprising a client communicating with a remote server, to run as a centralized program. The resulting centralized variant retains to a large degree the semantics of the original application, but replaces all remote operations with local ones. The centralized variant becomes easier to analyze and modify not only because it has no remote operations, but also because the majority of program analysis and transformation approaches and tools have been developed for centralized programs. After the centralized variant is modified to address the new requirements and the modifications have been verified, it is then redistributed again into a re-engineered distributed web application. Our target domain are distributed applications written entirely in JavaScript, both the client and server parts; such applications are referred to as *full-stack JavaScript applications*. We take advantage of the monolingual nature of such applications to streamline our implementation.

To achieve the stated goals of this research, we propose to: 1) an automated Refactoring, *Client Insourcing*; then by applying the main idea of this refactoring to enhance and optimize ill-conceived distributions of real-world apps, 2) localize and fix bugs in distributed applications, 3) optimize distribution granularity, 4) reconcile the design-time and run-time mismatch in distributed applications.

1. Automating Client Insourcing Refactoring for Full-Stack JS Apps

The focal point of our approach is Client Insourcing, a new automatic refactoring that undoes distribution by gluing the local and remote parts of a distributed Full-Stack JS application together. Our approach can precisely identify the functionality of HTTP middleware—irrespective of its API and in the presence of stateful operations—by combining program instrumentation, profiling, and fuzzing in a novel way. These HTTP middleware APIs tend to differ widely depending on their vendor: the JavaScript ecosystem features numerous dissimilar distribution frameworks and libraries. Rather than encoding domain-specific preconditions, our approach uses domain agnostic semantic to identify the entry/exit points of middleware functionality.

2. Localizing and Fixing Defects in Distributed Applications

Localizing bugs in distributed applications is complicated by the potential presence of server/middleware misconfigurations and intermittent network connectivity. In this work, we present a novel approach to localizing bugs in distributed web applications. The debugged application is to create its semantically equivalent centralized version, thus separating the programmer-written code from configuration/environmental issues as suspected bug causes. The centralized version is then debugged to fix various bugs. Finally, based on the bug fixing changes of the centralized version, a patch is automatically generated to fix the original application source files.

3. Correcting Ill-Conceived Distribution Granularity

Distributed applications enhance their execution by using remote resources. However, distributed execution incurs communication overheads, if these overheads are not offset by the yet larger execution enhancement, distribution becomes counterproductive. For maximum benefits, the distribution's granularity cannot be too fine or too crude; it must be just right. In this work, we present a novel approach to re-architecting distributed applications, whose distribution granularity has turned ill-conceived. To adjust the distribution of such applications, our approach automatically reshapes their remote invocations to reduce aggregate latency and resource consumption by means of a series of domain-specific automatic refactorings.

4. Reconciling the Design and Runtime Mismatch in Distributed Apps

Communicating Web Vessels A mobile web app's performance depends heavily on the underlying network and the client device's hardware capacity. Static distribution allocates some application functionality to run on the client and some on the server, with the resulting allocation remaining fixed throughout the app's execution. If the available network and the client device mismatch those assumed during the static distribution, app responsiveness and energy efficiency can suffer. To address this problem, we propose Communicating Web Vessels (CWV), an adaptive redistribution framework that improves the responsiveness of full-stack JavaScript mobile apps. By monitoring the network conditions, CWV determines whether a dynamic redistribution would improve application performance. It then triggers a redistribution that moves server-side functionalities to the mobile client and vice versa. When CWV moves server-side functions and their reachable state to the client, they are invoked as regular local functions. The moved functionalities are accessed remotely again as soon as the network conditions improve.

Edge Insourcing Edge computing offers novel execution optimization opportunities, however it would be non-trivial to adapt existing the cloud/client to take advantage of edge-based resources. By extending idea of Client Insourcing, *Edge Insourcing* can be naturally applied to enable such adaptation, offering a unique technical perspective for solving this important problem of distributed app engineering.

Proposal Structure: The rest of this Ph.D. preliminary proposal is organized as follows. Section 2 presents the preliminary research we have accomplished. Section 3 discusses the remaining work. Section 4 compares the proposed work with the state of the art. Section 5 outlines the research schedule, and then, Section 6 presents concluding remarks.

2 Preliminary Work

2.1 Client Insourcing Refactoring: JS-RCI

Approach We follow the software engineering methodology of creating a novel domain-specific refactoring and demonstrating its value, applicability, and limitations through a series of case studies of enhancing distributed application execution. Our new domain-specific refactoring—Client Insourcing—is realized as a reference implementation, called JavaScript Remote Client Insourcing (JS-RCI) [5].

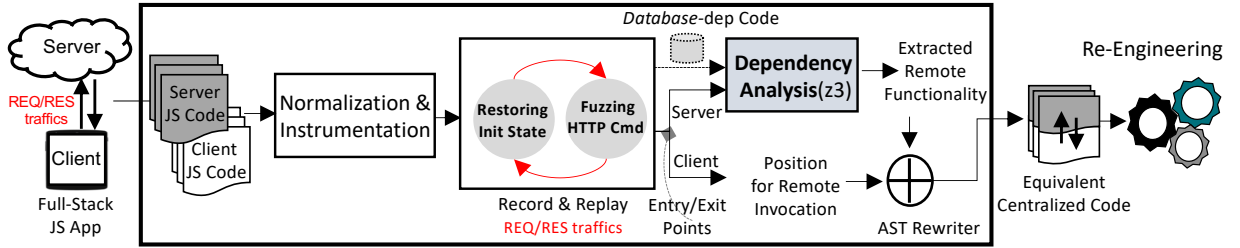


Figure 1: Client Insourcing Refactoring (JS-RCI)

JS-RCI integrates advanced software engineering techniques, such as program synthesis, which identifies which application functionality satisfies a given remote execution’s input and output relationship. JS-RCI also makes use of constraint solving to extract JavaScript server-side functions. The constraint solving functionality is based on declarative logic-based programming, which represents JavaScript program statements and their relationships to each other as logical facts and predicates. As a specific example, consider the relationship that expresses the transitive dependency across the statements, executed between the entry and exit points of a remote service:

//Dependency Analysis to extract a function from server code

$$\text{ExecutedStmts}(stmt_n, V_{unMar}^{uid}, V_{Mar}^{uid}) \leftarrow (\text{DataDep}(stmt_n, stmt_1) \wedge \text{Marshal}(stmt_1, v_1, V_{Mar}^{uid})) \wedge (\neg \text{DataDep}(stmt_n, stmt_2) \wedge \text{UnMarshal}(stmt_2, v_2, V_{unMar}^{uid}))$$

//the entry point at the server

$$\text{UnMarshal}(stmt_1, v_{unMar}, V_{unMar}^{uid}) \leftarrow \text{Write}(stmt_1, v_{unMar}) \wedge \text{Ref}(v_{unMar}, V_{unMar}^{uid})$$

//the exit point at the server

$$\text{Marshal}(stmt_1, v_{Mar}, V_{Mar}^{uid}) \leftarrow \text{Write}(stmt_1, v_{Mar}) \wedge \text{Ref}(v_{Mar}, V_{Mar}^{uid})$$

One of the key functions of a middleware system is *Marshaling* and *UnMarshaling* methods for handling parameters and return values. Marshaling (exit point in server) converts program values to a data format suitable for transmission; unmarshaling (entry point in server) reverses the process by converting the transmitted data format to regular program values. To determine such entry/exit points, JS-RCI instruments the app’s source code statements, which implement HTTP commands, as well as applies advanced testing techniques (e.g., *fuzzing*). Specifically, to identify these points with minimal false-negatives, JS-RCI fuzzes the original HTTP traffic by padding the HTTP header and body data with random data. Since many of these testing techniques requires that the subject be executed repeatedly in a deterministic way, JS-RCI also makes it possible for stateful servers to be executed idempotently by automatically undoing their state changes. Overall process of JS-RCI is shown in Figure 1.

Result We have successfully applied JS-RCI to numerous real-world apps that use different middleware frameworks to implement their client/server (T1/T2) communication and different third-party libraries for database operations (T3).

Subjects (T1,T2,T3)	HTTP Methods	Services	C&P/M (ULOC)		GET /brokers	86/99
					GET /brokers:id	90/103
recipebook (AngularJS, Express,MySQL)	GET	/recipes	22/45	med-chem (fetch,koa.js ,knex)	GET /hbone	9K/9K
	GET/PUT/DEL	/recipes:id	72/172		GET /molecular	9K/9K
	POST	/ingts	25/48	BrownNode (AngularJS ,Express)	GET /u/search	37/65
	GET/PUT/DEL	/ingts:id	74/207		GET /u/search/id	36/64
	POST	/directions	26/57			
DonutShop (Ajax, Express,knex)	GET/PUT/DEL	/directions:id	60/130	Bookworm (JQuery, Express)		
	GET/POST	/donuts	22/88		GET /ladywithpet	394/409
	GET/POST/DEL	/donuts:id	29/155		GET /thedeia	394/409
	GET/POST	/employee	20/71		GET /theredroom	394/409
	GET/POST/DEL	/employee:id	29/138		GET /thegift	394/409
res-postgresql (axios,restify, Postgres)	GET/POST	/shops	16/83		GET /wallpaper	394/409
	GET/POST/DEL	/shops:id	19/128		GET /offshore	394/409
	GET/DEL				GET /bigtripup	394/409
					GET /amont	394/409
				ConfApp (Angular2 ,Express)	GET /findpeakers	13/66
					GET /findSpeaker	15/68
					GET /findSessions	43/117
shopping-cart (Angular2,Express)	GET/POST/DEL	/cart-items	79/130	Emp_Dir (Angular2 ,Express)	GET /findSession	46/119
realty_rest (Angular2,Express)	GET/POST/DEL	/prprts/favs	34/73		GET /employees	22/44
	POST	/prprts/likes	291/304		GET /employees/id	38/60
	GET	/prprts	284/297			
	GET	/prprts:id	287/300			
Total				61		24K/26K

We observed that Idempotent Execution (w/o IdEx) with its Record/Replay phases removes the *false-negatives* in the detected marshaling points for stateful servers. In contrast, Fuzzing (w/o Fuzz) removes *false-positives* for detecting marshaling points.

Client Insourcing creates a redistributable (centralized) application variant that can be *refactored* and *enhanced* using any state-of-the-practice program transformation tools and then *distributed anew* using any state-of-the-art ditribution tools. We applied two JavaScript refactoring tools on our centralized variants: Node-SandBox for security enhancements and extremeJS [52] for redistribution. Node-SandBox prevents untrusted JavaScript code from executing infinite loops or consuming large volumes of heap memory in the isolated code.

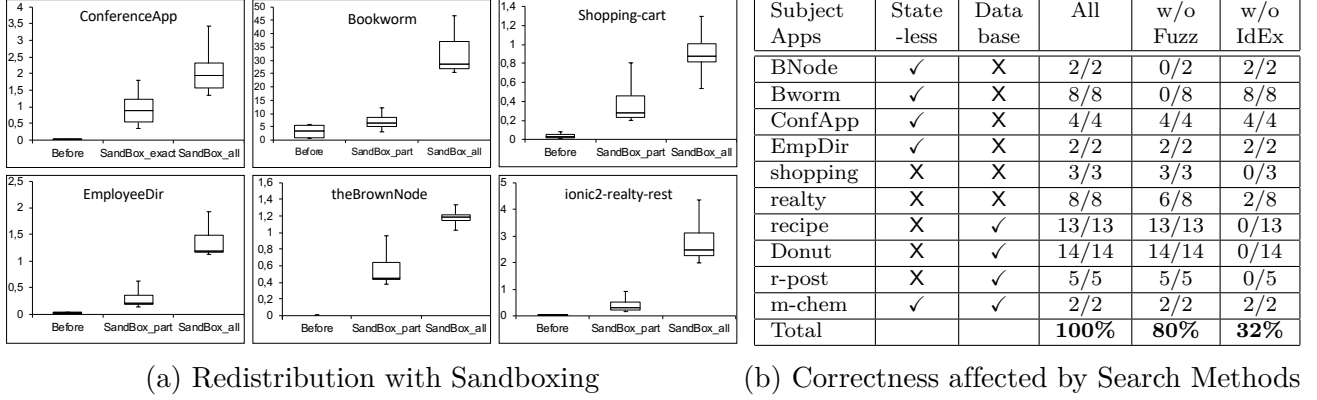


Figure 2: JS-RCI's Value of Redistribution and Correctness

2.2 Debugging Distributed Applications: CanDoR

Approach One application of Client Insourcing is to facilitate the debugging of distributed apps. The underlying idea is to be able to debug the semantically equivalent centralized variant of a faulty app (e.g., performance bottlenecks, memory leak). Our tool CanDoR [4] creates a centralized app variant that can be debugged by means of the numerous existing state-of-art debugging tools for centralized JavaScript programs. This refactoring preserves the app's business logic, while significantly simplifying its control flow. Rather than spanning across two JavaScript engines (client and server), the resulting centralized apps require only one engine (Figure 3). Once the programmer fixes the bug in the centralized variant version with these tools, CanDoR applies the resulting fixes to the actual client and server parts of the original distributed application. To that end, CanDoR automatically generates input scripts for GNU Diff, which executes these scripts against the source files of the original full-stack JavaScript application by using GNU patch. For certain types of bugs, this debugging approach proves to be effective and reducing the required debugging efforts.

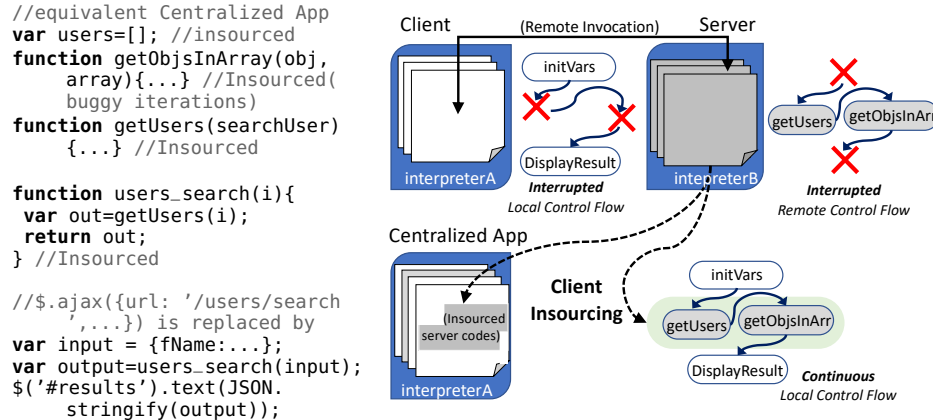


Figure 3: Continuous Control Flow of Distributed Codes constructed by Client Insourcing

Result CanDoR reduces the complexity of debugging distributed apps. It makes it possible to debug the app’s business logic locally, so the app can be executed repeatedly, with the debugging output examined in place. As a result, the required debugging effort decreases. For example, CanDoR reduces the time taken to execute a debugged functionality by more than **90%** on average. Given that debugging typically involves repeated execution, having much faster subjects to debug improves the the debugging process’s efficiency.

To demonstrate the value of CanDoR, we removed 11 performance bottlenecks from both the original subjects and their centralized variants. As it turns out, the bottleneck removals improved the performance of both versions (distributed and centralized) of each subject. Figure 4 summarizes the observed performance improvements. For the original distributed subjects (ΔT_{dist}), the improvements range between 29.5% and 2.0%. For their centralized variants (ΔT_{cent}), the improvements range between 34.8% and 1.6%. We also applied a linear regression analysis to compute how closely ΔT_{dist} and ΔT_{cent} correlate with each other, resulting in $\Delta T_{cent} = 1.0089 * \Delta T_{dist} + 1.556$. This equation shows that ΔT_{cent} and ΔT_{dist} are almost perfectly correlated, so centralized variants can indeed serve as reliable and convenient proxies for an important class of performance debugging and optimization tasks.

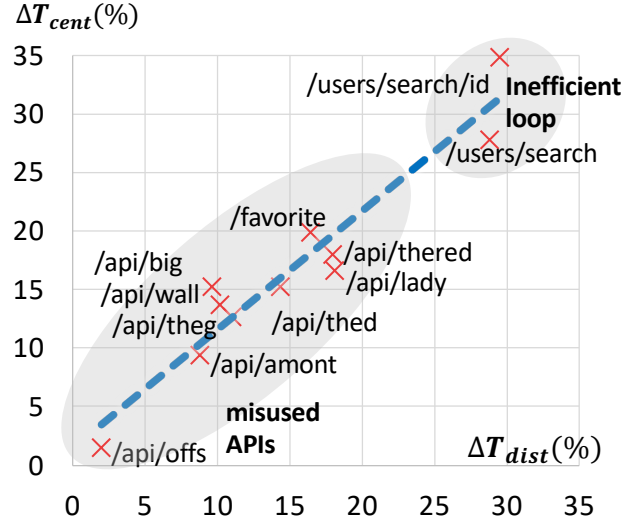


Figure 4: Regression Test for ΔT_{dist} vs. ΔT_{cent}

2.3 Optimizing Remote Execution Granularity: D-Goldilocks

Approach Another application of Client Insourcing is restructuring the distribution of web apps to maximize their performance and efficiency. Our approach, named D-Goldilocks [6], follows the *Goldilocks Principle* [13, 22] to maximize the benefits of distribution. That is, the granularity of a remote service should not be too fine or too crude; it must be just right. For instance, the granularity of *Bookworm* is too crude as shown in Figure 5-(a).

D-Goldilocks re-architects distributed web apps to adjust their distribution granularity as a means of improving performance and efficiency. To that end, using a semantically equivalent centralized application variant, D-Goldilocks profiles the variant’s performance, with the following cost function $\mathcal{C}(r)$, determining how to reshape the original distribution r to improve performance and efficiency.

$$\mathcal{C}(r) = \alpha \cdot \text{latency}(r) + (1 - \alpha) \cdot \sum \text{resource}(r).$$

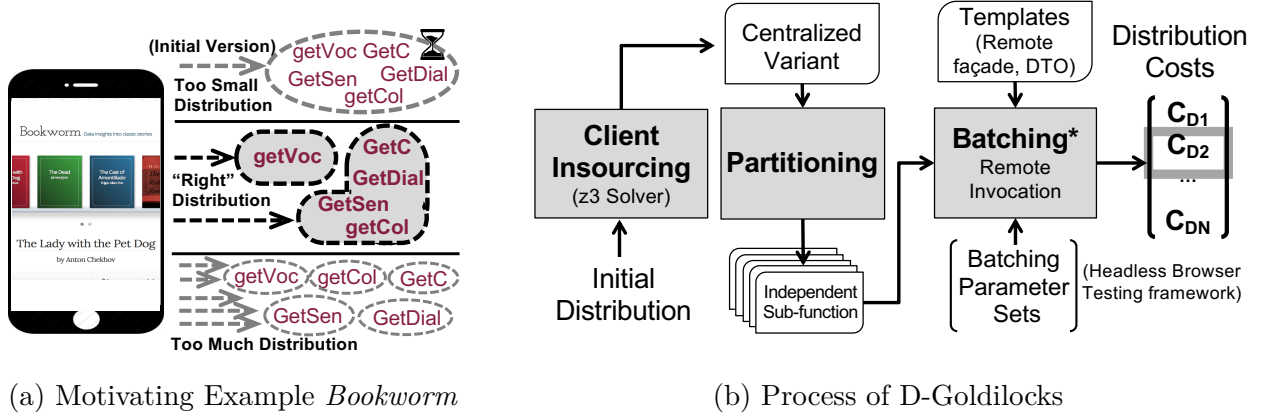


Figure 5: D-Goldilocks for Optimizing Remote Execution Granularity

Extant automatic refactorings (e.g., *partition* and *batch*) are then applied to reshape and redistribute the original remote functionality into a service with a changed granularity. In the end, D-Goldilocks identifies a distribution that minimizes the \mathcal{C} function (Figure 5-(b)).

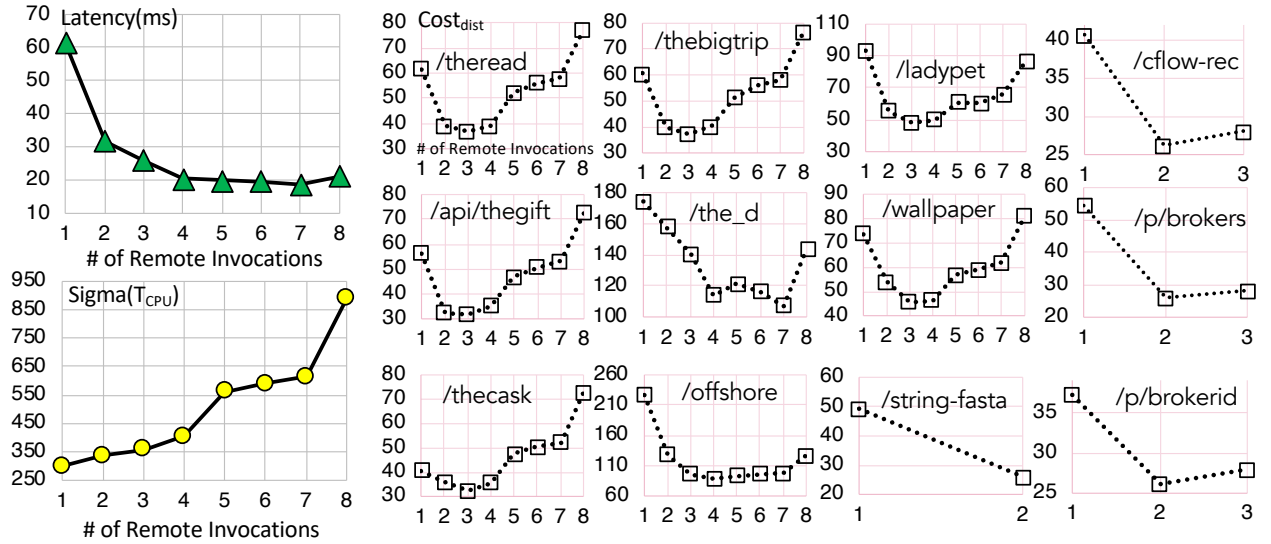


Figure 6: Number of Remote Invocations vs. Cost functions for Subject Remote Executions

Result D-Goldilocks saves programming effort by automatically reshaping the granularity of the remote functionalities of web apps. To determine what the optimal combination of functions is, D-Goldilocks generates all possible combinations of individually invoked functions. For some subjects, D-Goldilocks can save almost 1.6×10^6 lines of code required to discover the optimal granularity. Splitting a single long-running remote function into a small number of asynchronously invoked parts decreases both the aggregate latency and cost. However, as the number of partitions grows, so does the cost, due to the increasing overhead of invoking multiple remote functions (Figure 6).

3 Remaining Work

The remaining work of this dissertation will apply Client Insourcing to adapt distributed applications for their execution environments at runtime and to transform two-tier cloud-based applications to take advantage of edge computing resources. We describe these two remaining work thrusts in turn next.

3.1 Adapting Web Execution at Runtime: CWV

Approach To achieve the best performance for all combinations of client and server devices and network connections, a web app would have to be distributed in a variety of versions. My ongoing research is concerned with adaptively redistributing functionalities of a full-stack mobile JavaScript app to optimize its performance and energy consumption. We have been working on a new framework, Communicating Web Vessels (CWV). In a CWV-enabled web app, the client dynamically instruments and monitors app’s distributed execution for “/service_r”. In response to a deterioration in network conditions, the client can request that the server-side JavaScript code and program state of a remote service be moved to the client, so the service can be invoked locally as a regular function call (*insource*("/service_r")). When the network conditions become favorable, the moved service starts to be invoked remotely again (*revert*(r)). Invoking remote services locally or remotely helps achieve the best possible response time of the web app under the current network conditions. The CWV’s communication protocol defines how and when an app switches between the Original, Insourcing/Reverting, and Local modes described in Figure 7.

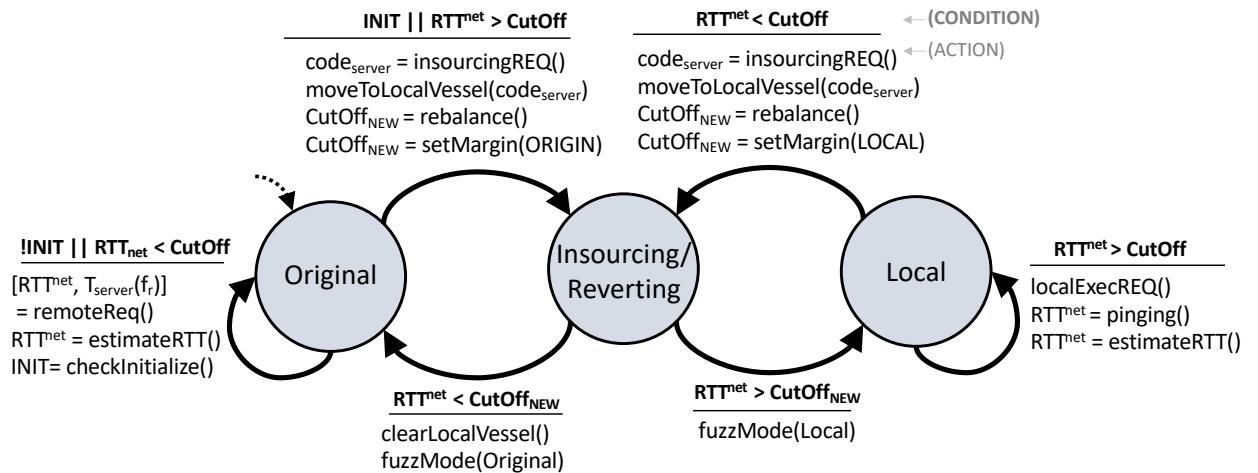


Figure 7: CWV Protocols for transitioning modes

Result so far Preliminary results for CWV show that it effectively adapts web apps for dissimilar networks and two different mobile devices. CWV offers a low performance overhead,

Serv	τ_{cutoff}^{D1}	τ_{cutoff}^{D2}
/ladypet	176ms	421ms
/thedeia	1120ms	2332ms
/offshore	619ms	1528ms
/amondo	194ms	465ms
/thered	158ms	424ms
/thegift	97ms	120ms
/bigtrip	146ms	224ms
/thecask	90ms	102ms
/fastaRepeat	656ms	1424ms
/fannkuch	2576ms	4982ms
/spectral	1896ms	4873ms
/Donuts:id	0.71ms	2.2ms
/dirs:/:id	0.75ms	2.1ms

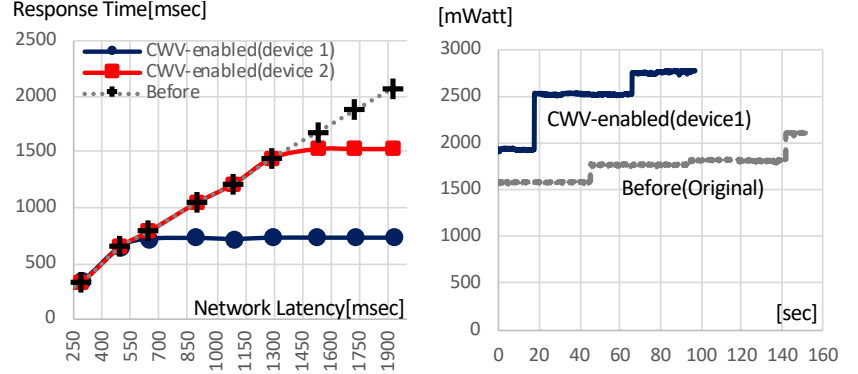


Figure 8: CWV's Redistribution Adaptivity for different Devices and Network Conditions

so CWV-enabled apps improve their responsiveness by adapting to the current runtime conditions (Figures 8-(a) and (b)). Table demonstrates that the *cutoff network latency* of Device 2 (τ_{cutoff}^{D2}) is always larger than that of Device 1 (τ_{cutoff}^{D1}) to minimize the mode switching overhead. Also, these switching points reflect the device processing capacity: Device 1 is about two times faster than Device 2 for running JavaScript code on a CWV-enabled client. CWV's runtime takes into account the client device's processing capacity in addition to the current network conditions.

CWV-enabled web apps can also improve their energy efficiency by as much as **10%** for poor network conditions (Figure 8-(c)). As the longer total execution time still causes larger overall energy consumption even though the device switches into the low power mode during the idle states.

3.2 Edge Insourcing

Cloud-based execution makes it possible to take advantage of superior remote computing resources, thereby improving performance. Consider how cloud computing is used to train machine learning (ML) models on sensor data collected by mobile devices. Mobile and IoT devices feature multiple sensors, used to collect various types of data. This data then is passed as input for training ML models. The resulting models can then be used to optimize and specialize the execution of mobile devices. Since ML model training is a computationally intensive task, taking advantage of powerful cloud computing resources can improve performance. However, as the number and variety of mobile and IoT devices has drastically increased, so has the volume of resulting sensor data, referred to as *sensor data deluge* [47]. It is due to this development, transferring all the collected sensor data to a cloud-based server for processing becomes disadvantageous due to the network transmission bottlenecks. As a solution to this problem, edge computing makes it possible to train ML

models locally, so the collected sensor data would not need to be transmitted to the cloud.

To take advantage of edge processing resources, edge applications can be developed from scratch, an expensive software development task. Another more efficient approach is to modify existing cloud-based applications to integrate edge-based processing. In other words, 2-tier (cloud-device) applications would need to be transformed into 3-tier (cloud-edge-device) applications. This transformation can be quite laborious and intellectually tiresome to perform by hand. To facilitate this transformation, we will create a new domain-specific refactoring, *Edge Insourcing*. This refactoring will take advantage of Client Insourcing but will also introduce its own edge-specific transformations.

Adapting Cloud-Based Code for the Edge: The computing resources of the cloud and the edge differ widely. While cloud resources are powerful and abundant, edge resources are limited and scarce. Hence, cloud-based code cannot be directly insourced to the edge, but it must be properly adapted to consume fewer edge-based resources. To that end, the proposed research will insource only those server-based functionalities that are determined to be failure-resistant. We notice that much of server-based processing handles various erroneous inputs and failed operations. The code responsible for such processing would remain cloud-based, but the rest of server-based functionality can be insourced to executed on edge-based devices. In those cases in which edge-based execution fails, the required failure handling will be offloaded to the cloud.

Formally Verifying the Correctness of Edge Insourcing: Recently the program verification community has made significant inroads in formally verifying the correctness of distributed systems [23, 27, 45, 53]. By leveraging this work, we plan to prove that Edge Insourcing preserves application semantics. The proof strategy would require modeling both distributed and insourced executions and comparing their respective output.

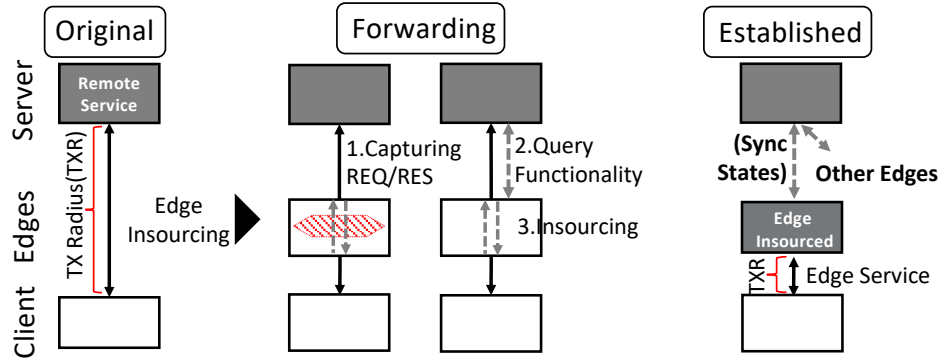


Figure 9: Distributed Architecture for Edge Insourcing

In the envisioned distributed architecture, edge nodes would serve as processing and forwarding proxies for cloud nodes (Figure 9). Initially, all the processing functionality will be hosted by the cloud nodes. An edge node would be able to issue a special insourcing request to a cloud node, receiving some program code and state to execute locally. The

state will be synchronized between the edge and cloud nodes based on a relaxed consistency model, as allowed by different application scenarios.

4 Related Work

Improving various aspects of distributed application execution has been the target of numerous prior research efforts. Since our work applies novel software engineering approaches, techniques, and tools, we limit our coverage of the related state of the art to this area.

Our reference implementation of Client Insourcing, relates to advanced program analysis techniques for JavaScript, due to its target domain—cross-platform mobile applications. Our approach follows declarative program analysis frameworks that statically analyze JavaScript code by means of a constraints solver [20, 30, 34, 49]. The JavaScript language constructs for programming event-based applications that wait for dispatches events or message asynchronously. Some advanced static analysis approaches apply formal reasoning for *callback* and *promises* of web apps based on a calculus [36, 37]. Existing dynamic analysis tools [30, 43] have a scalability problem to analyze entire JavaScript program. Dynamic symbolic execution (DSE) symbolically executes a JavaScript program by applying concrete input values [41] for a faster analysis. For more advanced DSE, MultiSE [44] uses a value summary in Jalangi2 to effectively generate testing input values of a JavaScript program to speed up dynamic symbolic execution.

In JavaScript, choosing one programming implementation over another can make a significant difference performance effect on the overall application [17, 18]. An approach presented in [42] empirically identified reappearing patterns of inefficient JavaScript programs in open source community, so common performance bottlenecks can be automatically detected and fixed by using software engineering techniques.

Some prior approaches automatically change the locality of execution in existing application, a highly complex process, as centralized and distributed execution models differ from each other in terms of their respective latency, concurrency, and failure modes [51]. Researchers and practitioners have greatly studied to facilitate the task of rendering local functionalities remote to take advantage of remote resources. For example, offloading local functionality to the cloud has also been supported as an automated refactoring technique [24, 25, 52, 54].

Client Insourcing can be seen as a variant of program synthesis [8, 10, 11, 12, 14, 15, 21, 46], an active research area concerned with producing a program that satisfies a given set of input/output relationships. CodeCarbonReply and Scalpel [7, 48] integrate portions of a C/C++ program’s source in another C/C++ program by leveraging advanced program analysis techniques. The programmer’s effort is only limited to annotate the code regions to integrate, and then the tool automatically adapts the receiving application’s code to work seamlessly with the moved functionality. Client Insourcing belongs to a category of refactor-

ing transformations that change the locality of application components for various reasons. One prominent direction in this research is *application partitioning*, which is an automated program transformation that transforms a centralized application into its distributed counterpart [7, 32, 33, 48, 50]. Another approach that leverages compiler-based techniques is the ZØ compiler [16], which automatically partitions CSharp programs into distributed multi-tier applications by applying scalable zero-knowledge proofs of knowledge, with the goal of preserving user privacy.

Several middleware-based approach has been proposed to reduce the costs of invoking remote functionalities. APE [40] is an annotation based middleware service for continuously-running mobile (CRM) applications. APE defers remote invocations until some other applications switch the device's state to network activation. Similarly, to reduce the overhead of HTTP communication, events for HTTP requests in Android apps are automatically are bundled into a single batched network transmission [28, 29]. The e-ADAM middleware [26] optimizes energy consumption by dynamically changing various aspects of data transmission scheme. My approach can also adapt the realities of executing full-stack JavaScript mobile apps to optimize the remote execution with a cost function.

No.	Paper	Conference	Area	Authorship
1.	<i>Client Insourcing</i> [5]	Web Conference 2020 (19%, 217/1129)	Web Engineering	1 st author
2.	<i>D-Goldilocks</i> [6]	SANER 2020 (21%, 42/199)	Software Engineering	1 st author
3.	<i>CanDoR</i> [4]	ICWE 2019 (25%, 26/106)	Web Engineering	1 st author
4.	Project1-paper1 [3]	MobileSoft 2018	Software Engineering	1 st author
5.	Project2-paper1 [32]	GPCE 2018	Software Engineering	2 nd author
6.	Project2-paper2 [33]	Journal Of Computer Language 2020	Software Engineering	2 nd author
7.	PhD Symposium1 [1]	ICWE 2019	Web Engineering	1 st author
8.	PhD Symposium2 [2]	Web Conference 2020	Web Engineering	1 st author
Ongoing	<i>Comm Web Vessels</i>	Submitted to ICDCS 2020	Distributed Systems	1 st author
Ongoing	<i>Edge Insourcing</i>	To be Submitted	Distributed Systems	1 st author

Table 1: Publication Records in PhD Course

5 Schedule

The preliminary work is published in conferences, such as the *Web Conference* (WWW), *IEEE International Conference on Software Analysis, Evolution & Reengineering* (SANER), and the *International Conference on Web Engineering* (ICWE). Many people provided helpful feedback on my dissertation topic presented in two doctoral Symposium papers in ICWE and WWW. I also participated in two projects and could publish some papers in there. I was the first author in a paper in MobileSoft and the second author both in the *ACM SIGPLAN International Conference on Generative Programming: Concepts & Experiences* (GPCE) and the *Journal of Computer Language* (Table 1).

We intend to target distributed systems or software engineering venues for the remaining work. Figure 10 outlines the proposed schedule for the remaining work outlined in this document.

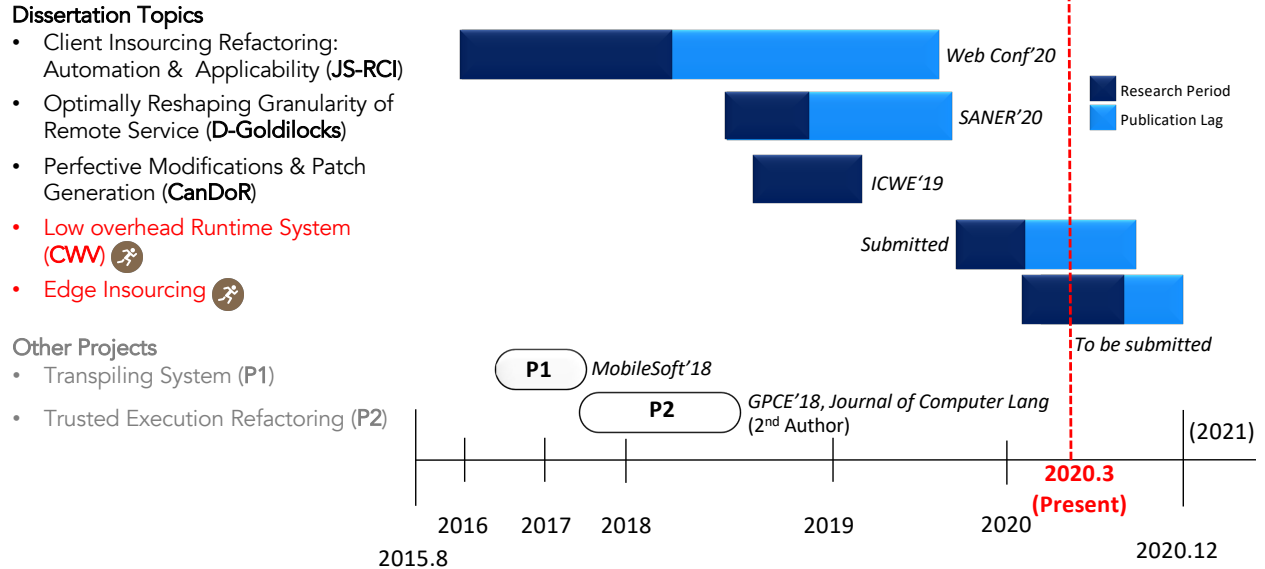


Figure 10: Proposed Work Schedule

6 Conclusion

The ever-changing realities of modern distributed apps put new obstacles on the road of providing a satisfactory user experience. In particular, modern users expect distributed applications to be responsive, reliable, and energy efficient. Distributed application developers need powerful approaches, techniques, and tools that allow them to reach these objectives on time and under budget. This dissertation research innovates in the software engineering space to create novel automated reengineering approaches that enhance and optimize distributed execution. In particular, we introduce a novel domain-specific refactoring, supported by state-of-the-art program analysis and transformation techniques, and apply this refactoring to address some of the most salient problems of distributed execution. This research contributes to the development of development approaches, techniques, and tools with novel designs, new technologies, and strong potential for practical adoption.

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