Visualizing Compiler Passes with SecondPass

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1 Introduction

A compiler from a high-level language down to an assembly-like language traditionally involves a sequence of compiler passes, each of which performs a specific transformation on an input program to produce an output program for the next pass. In an undergraduate compilers course, the goal is to understand why these passes are necessary and how each pass is constructed. One difficulty in the learning process is that the compiler pass implementation itself may be too abstract to gain an intuitive understanding of its purpose, while merely reading the source and target programs does not reveal much about how the pieces of the programs were transformed.

In this paper, we present SecondPass[1], a multi-pass compiler visualization for UBC's upper-year compilers course (CPSC 411) that aims to elucidate the connections between source and target program substructures and to provide an intuitive understanding of the kind of structural transformations that compilers do. Given a particular source program, it presents intermediate and final programs – the results of multiple stages of compilation – side by side, with interactive flows between related components of source and target programs.

We limit the scope of this project to only two particular fundamental compiler passes: A-normalization and instruction selection, described in detail in Section 2. Furthermore, as this is primarily a pedagogical tool, it focuses on effective visualization of relatively small input programs, as opposed to existing visualizations which focus on large source code files or optimizing compiler passes.

1.1 Motivation

In the fourth week of the UBC's CPSC 411: *Introduction to Compiler Construction*, a student and her two project teammates are tasked with introducing control flow to their compiler. As with every week, she looks at the language specifications introduced in weekly batches, selects an arbitrary 7 of the 21 tasks presented, and starts working.

Unknown to her at the time of task selection, two of her selected tasks amount to *half* of this week's work for the entire team (when measured in hours of effort or lines of code). Oblivious, she continues work on her team's compiler.

One large task has her scrolling up and down on the course website, comparing the definitions of two languages that define the input and output of a particular program trans-

[1] formerly FirstPass[2]
[2] formerly Untitled Compiler Pass Visualization

formation. She attempts to build a mental model of what the transformation is meant to be by looking at the static definitions one at a time.

The complexity of the compilers in CPSC 411 grows with each passing week. Debugging equates to going back to the language specifications and performing manual language transformations before comparing them to her generated output.

Building a compiler is hard enough already without misestimating the distribution of work, poring over scattered, static language definitions, or getting too few examples of how to make it *right* in the exact situations where students' bugs arise.

With our new compiler visualization, SecondPass, we aim to reduce these student frustrations by providing a tool that visualizes the programs before and after transformation to effectively present *what* a compiler is doing – without giving away too much of the *how*. As domain experts who have taken undergraduate compilers courses (including CPSC 411) and are intimate with their struggles, and who have worked on other compilers as well, we have the experience and the expertise to identify the relevant problems and propose an effective solution.

We begin in Section 2 with a description of the domain details relevant to the CPSC 411 compilers course. We then outline the primary tasks students are expected to complete throughout the course in Section 3, as well as an abstracted representation of programs and compiler passes which we manipulate in Section 4. Section 5 discusses relevant work in visualizing code and compilers, and how existing solutions fall short of our tasks. We introduce our proposed visualization in Section 6 and detail its design and implementation. Finally, our milestones and schedule can be found in Section 7.

2 Background

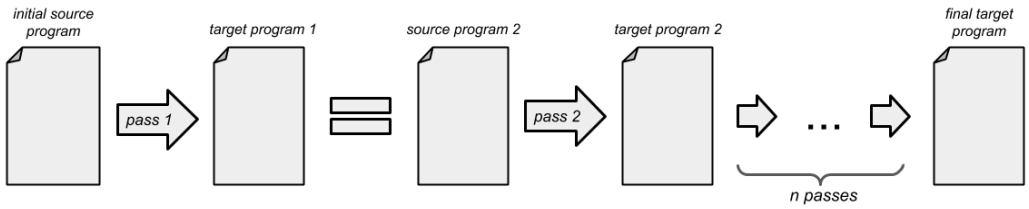


Figure 1: An overview of a multi-pass compiler. The initial source program gets transformed by the first pass into the first target program, which is equivalent to the source program of the second pass. The second outputs a second target program, which becomes the source program for the next pass. This process repeats until the final target program is reached. The intermediate source programs are often written in an intermediate language (IL).

In CPSC 411, a compiler begins with a *high-level program* and ends with an *assembly program*. But it doesn't compile directly from the former to the latter in one go, as a *single-pass* compiler would. Rather, it is a *multi-pass* compiler, divided into many *compiler passes* which sequentially compile a program in a high-level language to programs in several *intermediate languages*. The program that a compiler pass compiles is called the *source*

program and its output is the *target program*. These programs are often written in different languages, whose syntax can be specified by a *BNF grammar*. The process of a multi-pass compiler is summarized in Figure 1.

As mentioned, we will focus on two specific compiler passes:

1. **A-normalization**, which sequentializes necessary computational steps and makes control flow explicit; and
2. **Instruction selection**, which sequentializes the program further by converting function calls to jumps.

To compile a program, a compiler pass inspects and manipulates the structure of a program. A program consists of an *expression*, which itself may contain further *subexpressions*. Passes operate recursively, transforming expressions and subexpressions of the source language into expressions of the target language. Programs are internally represented as *abstract syntax trees* (ASTs), where a root node is an expression and its children nodes are subexpressions.

A compiler pass, in general, is a function that takes a source program in one language and returns a target program in another language. However, what we want to visualize is not the general, abstract compiler pass, but rather the effects of a compiler pass on a specific, *concrete* program. We will then refer to the associations between subexpressions of source and target programs as a *concrete compiler pass*.

3 Task Analysis

For each CPSC 411 assignment, student groups of three are given some base compiler and some new language features, and are tasked with augmenting existing compiler passes to support them or adding new compiler passes. As an aid for the assignments without revealing exactly how the compiler passes are implemented, SecondPass takes a source program and provides a visualization for each compiler pass. We divide the tasks students can accomplish with SecondPass in the following categories:

T1. Comparing the complexity of compiler passes:

- **1.** Comparing the amount of generated target code to the amount of source code
- **2.** Comparing the amount of change in the structure of the target code from the source code
- **3.** Estimating the distribution of work needed to implement the compiler passes

T2. Understanding the nature of the compiler passes:

- **1.** Comparing how different kinds of expressions are compiled
- **2.** Exploring how the program contexts of expressions change due to compilation
- **3.** Identifying the correct target code given some source code

We integrate these tasks into the scenarios presented in Subsection 1.1.

3.1 Pass Triage

To begin tackling a CPSC 411 assignment, student groups must figure out how to divide the work among themselves. This requires an understanding of the complexity of the compiler passes. Specifically, a compiler pass that generates more target code is considered as more complex (**T1.1**), but one that moves code around a lot is more complex as well (**T1.2**). These can be gleaned from the overview visualization of the compiler passes given some well-chosen source programs. With this knowledge, students are ready to create an informed distribution of labour within their teams (**T1.3**).

3.2 Compiler Exploration

While students are given language definitions of the source and target programs for each compiler pass, the relationship between the source and target languages is not always clear, and may require additional pages of documentation to explain. Furthermore, these language definitions, which come in the form of a BNF grammar, are static and abstract, often making it more difficult to intuitively get a sense of how the textual documentation links to the symbols of the BNF grammar and their relationships across languages.

In order to gain insight about a compiler pass, students must create a concrete source program, map the concrete program back into the abstract BNF grammar, glean the semantic relationship to the target language through the textual documentation, and then map the target language's BNF grammar down to some concrete target program generated by the reference compiler. A student's mental model of a compiler pass is frailly constructed through frequent context switches between a student's IDE, the reference compiler, the textual documentation, and the source and target language specifications, costing students time and efficiency! There are too many links that must be maintained in the student's memory.

Students require a way to explore a compiler pass, browse its transformations, and gain intuition about what the compiler pass *does* and how it works (**T2.1**). This model should reduce the number of contexts that a student must use to build their understanding. Lastly, a student must be able to discover semantic information about the compiler pass without compromising the a context that provides both concrete source and concrete target programs (**T2.2**).

3.3 Compiler Debugging

As with all complex systems, compiler passes are prone to error. When students have a failing test case, they can refer to SecondPass to see what the given test case should produce, but most importantly they understand *why* by following the flow of source expressions. In this way, the visualization is acting as an interactive and executable documentation of the behaviour of a certain pass. Students require a method for querying a reference compiler to gain a deeper understanding how certain complex aspects of passes are implemented (**T2.3**). Equipped with this better understanding, they are better prepared for creating correct compilers.

Data	Attribute (Type)	Cardinality	Mark
Node	Name (Categorical)	Dozens	Shape (text)
Intra-AST Link	None	Dozens	Containment (indentation)
Inter-AST Link	Pass name (Categorical)	Dozens	Connection (flows)

Figure 2: A summary of our network data with attributes, cardinality, and mark.

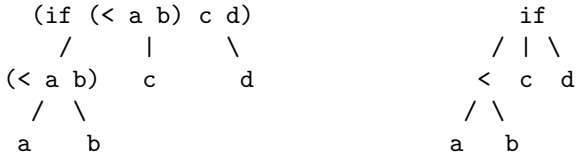
4 Data Abstractions

A summary of our data abstraction is shown in Figure 2. We now describe how programs are represented as trees (ASTs), with intra-AST links representing program indentation and inter-AST links representing compilation.

4.1 Program Representation

Recall that the internal representation of a program is an AST. This is merely a specialized tree, which in turn is a directed acyclic graph where nodes have at most one parent. Although we will be dealing with more general graphs, for clarity we continue to refer to the portion of a graph that corresponds to a program as an AST.

Each node of an AST is a subexpression of the program, and directed edges between nodes point from parent nodes to children nodes. These nodes only have one attribute: the name of the subexpression. Often we will fix the orientation of the tree so that edges implicitly point downwards. For instance, given the program `(if (< a b) c d)`, the AST looks like the following tree on the left:



Some representations will use only the prefix of non-leaf expressions as the nodes, like in the tree on the right above. Although more concise, we will not be using this representation, since we want to highlight each subexpression; a compiler pass is ultimately a recursive transformation of an AST by inspecting each subexpression.

A node may also have several relevant derived attributes. An important one the *node depth*, a sequential attribute counting how many edges it is away from the root. A compiler visualization can use this information to show how much a given pass "flattens" a program. Another sequential attribute is the number of target nodes pointed to by a source node for a given pass, which can be useful in visualizing how much that pass "expands" a program.

There is one more property of programs to consider: geometry. Students and programmers don't deal with the abstract tree-form of programs, but rather with source code directly, which often has a fixed shape on the screen. A compiler pass visualization, then, must take into consideration the position of subexpressions relative to each other in a given program. This can be done by grouping expressions with parentheses and/or indentation.

4.2 Compiler Representation

A concrete compiler pass involves the ASTs of a source program and a target program. The pass transforms a node from the source AST to zero or more nodes in the target AST. Therefore, we have additional directed edges from source nodes to target nodes, and we can define a concrete compiler pass as a set of these edges from target to source nodes. For example, if the above program compiles to `(let ([p (< a b)]) (if p c d))`, then the `(< a b)` source node may point to the target nodes `(< a b)` and `p`. Note that these directed edges are distinct from the edges within a single AST. Formally, we assign each directed edge a categorical attribute, where inter-AST edges are marked with the relevant compiler pass name, and intra-AST edges are marked with some null value.

4.3 Dataset

The total dataset that we work with for some arbitrary source program is then a directed graph consisting of the three ASTs representing the source, intermediate, and target programs, and two sets of directed edges from source to intermediate and intermediate to target ASTs representing the two concrete compiler passes. For the tasks at hand in Section 3, we expect to see small source programs with AST node sets in the cardinality range of dozens, which we infer from the set of test programs used for the reference compiler for CPSC 411. Correspondingly, the cardinality of compiler pass edge sets is also in the range of dozens.

5 Related Work

We separate related work into three subsections: visualizations of internal compiler implementations for educational purposes, visualizing compiler optimizations for correctness, and visualizing transformations over source code directly. We find that our solution more closely matches transformations over source code directly, rather than visualizing compiler implementations or optimizations.

5.1 Visualizations of Compiler Implementations

Visualizing compiler implementations for educational purposes has been studied in the field of computer science education for many decades, dating back to the late 1980s. One of the first instances of this was the University of Washington Illustrated Compiler (ICOMP) (2). ICOMP was a tool in conjunction with the course compiler Mplzero, which students had to understand and modify throughout the course. ICOMP allowed the students to visualize the data structures used internally by the compiler (such as an AST or finite state machine) and updated the visualizations at various breakpoints during compilation. Multiple windows and highlighting linked the visualization with the tabular format of the data structure, as well as highlighting the source program text, if applicable. The authors specified that the visualization worked over "moderately large source programs" given by the user. The visualization enabled a better understanding of the internal data structures used by the compiler, and how they transformed through the compilation process.

VAST (1) is another tool for visualizing compiler instrumentation. This tool is specifically designed to aid students' understanding of parsing source program text into an AST. A student sees the textual representation of the source program highlighted as the parser steps through the program text. A corresponding AST is constructed and displayed as a

triangular vertical node-link diagram. The authors specify that they expect the generated trees to be "big and without any fixed structure (symmetry, width or height)". As a result, VAST has a larger window showing a focused subtree and a smaller overview window with the entire AST.

While the overall goal of our visualization is similar to both VAST and ICOMP, there are some key differences. In CPSC 411, the students build their own compiler, so we cannot include the source code in our visualization as ICOMP does. Additionally, this compiler does not have to perform any parsing to create an AST. Furthermore, the ICOMP compiler is a single-pass compiler, whereas the CPSC 411 compiler is a multi-pass compiler. Finally, as mentioned previously, our proposed solution deals with source program text rather than the AST directly.

5.2 Visualizations of Compiler Optimizations

VISTA (7) is a system for interactive code improvement, specifically for the domain of embedded systems applications. VISTA works over assembly and Register Transfer Language (RTL) programs. It displays source program instructions in squares representing blocks with arrows between them indicating control flow. The left-hand side of VISTA displays a list of transformations that can be performed, as well as buttons labelled with arrows that allow the user to step through applying a transformation. As the user steps through a transformation, the instructions that change are highlighted.

CCNav (4) is another tool for visualizing compiler optimizations in assembly code. CCNav displays the source code text directly beside the disassembled binary code text, along with multiple other views of the call graph and function inlining. Since a single line of source code may span multiple lines of assembly code, CCNav has a separate window for displaying a highlighted source code line with its corresponding assembly code without context, that is, not in the view with both programs side by side.

VISTA and CCNav display source program text directly, similar to our solution. However, in VISTA, transformations are done in place, and changes between transformations are highlighted in the transformed program. To prevent the user having to step back and forth to see the program changes, our solution displays the programs side by side for easier comparison, like in CCNav. Since our solution focuses on passes that perform small changes on the source program, we will not encounter the issue of a single line of code spanning multiple lines.

5.3 Visualizations of Transformations over Source Code

MieruCompiler (5) is an educational compiler with similar goals to ICOMP. However, MieruCompiler also visualizes the static source code and assembly code, and implements "horizontal slicing". Horizontal slicing is highlighting a particular expression in the source program text along with the corresponding compiled code in the target program text, and vice versa. The static source program text and assembly text are displayed side by side. However, MieruCompiler compiles a subset of C directly to assembly in a single pass, so there is no visualization or horizontal slicing of intermediate languages.

Code Flows (6) visualizes detailed changes to source code for understanding fine and mid-level scale changes between C++ files. This visualization allows programmers to get a global overview of the changes to a source code file as well as find where code may have been deleted, split, or merged. Versions of a file are displayed as horizontally mirrored icicle

plots side by side, with paths between matching fragments of code. These paths are shaded as tubes and coloured cyclically to better differentiate between them.

Vis-a-Vis (3) is a "meta-visualization" linking the source code of a visualization algorithm to the generated visualization. It enables comparison of the visualizations generated by the algorithm as the user edits the source code. When hovering over a visualization in a certain state of the algorithm, a tooltip appears showing the differences between the source code at that state compared to the current state.

These projects are the most similar to our solution. However, the MieruCompiler does not trace the flow between expressions in the source program to the compiled program, but uses highlighting instead. This makes it difficult to get an overview of the changes made to the source program. In contrast, Code Flows does visualize the flow between expressions in different versions. However, Code Flows is better optimized for larger programs, as it does not display the source program text directly. The visualization also is static, and does not allow for selecting particular expressions to track their flow. Vis-a-Vis is interactive, but heavily geared towards visualization algorithms and comparing visualizations across versions of the algorithm.

6 Visualization

Our proposed solution is to create an interactive visualization, where students may input an arbitrary source program to see an overview of the compilation process. By analyzing this overview, the students may pinpoint a particular pass that is of interest, then switch to a detailed view of the pass. Alternatively, if the student is implementing a particular pass, they may query multiple source programs and analyze how the programs change in the detailed view of the pass. We elaborate on these views in the following subsection, and conclude with some high-level implementation ideas.

6.1 Design

6.1.1 Overview

Figure 3 presents a preliminary mockup for our overview visualization. Given some source program, the target programs after A-normalization and instruction selection will be displayed next to it from left to right. The prefix of all parent AST nodes are circled, with newly-generated nodes (i.e. target nodes that do not directly result from some source node) in a darker hue. This provides an easy way to judge at a glance how much new code is generated (**T1.1**).

Source nodes are connected to target nodes with lines, with a different hue for each pass. If the lines cross each other a lot, this indicates that a lot of structural changes in the code have occurred (**T1.2**). However, this can be misleading: In the instruction selection pass, many crossings occur only because two large chunks of code have swapped places. We may also consider bundling lines together to distinguish simple swapping of code blocks from the more subtle but more complex structural changes, such as those in the A-normalization pass.

If we scale up to more passes, the overview would expand horizontally. Note that the difference in hue is only to distinguish neighbouring passes; for more than two passes, we can alternate between two distinct hues, rather than choosing a hue for each pass.

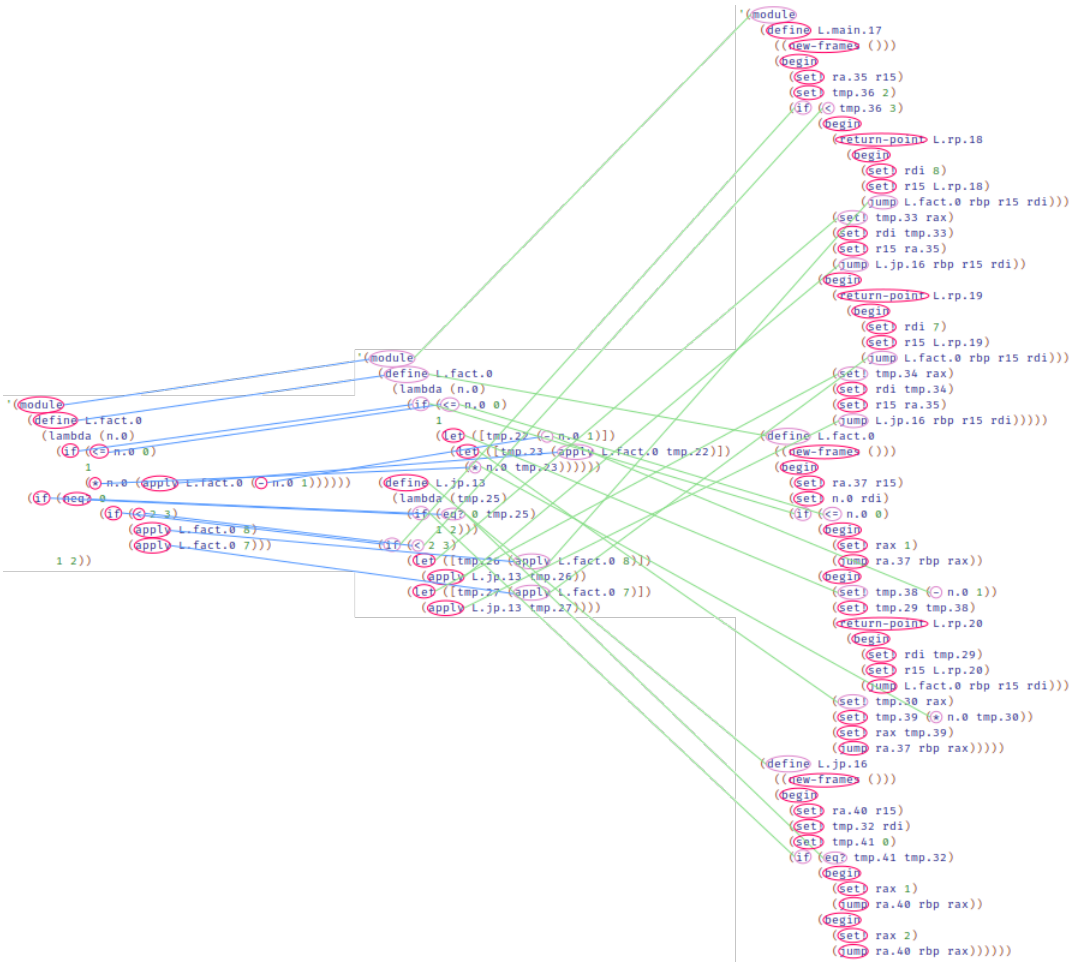


Figure 3: A mockup of an overview visualization of the two passes.

6.1.2 Detailed View

Figure 4 presents a preliminary mockup for our detailed visualization, focusing only on the A-normalization pass from the overview. Now, entire subexpressions are highlighed; this makes it clear what source subexpressions will be compiled into (**T2.1**). The user can select two expressions in the program. If they are nested, then the outer expression is highlighted, while the inner subexpression is boxed. The highlighted areas and the boxed areas are connected across a compiler pass, respectively. This allows the user to not only identify what an expression compiles to, but also what its outer context compiles to as well (**T2.2**).

We will add an interactive component to the detailed view: When the user hovers over some subexpression, it and the corresponding subexpression in the other program will both be highlighted, and when the selection is made by clicking on the subexpression, the connection appears.

We have not yet determined the best way to travel from the overview to the detailed view and back. We may also consider more features in the detailed view, such as the ability

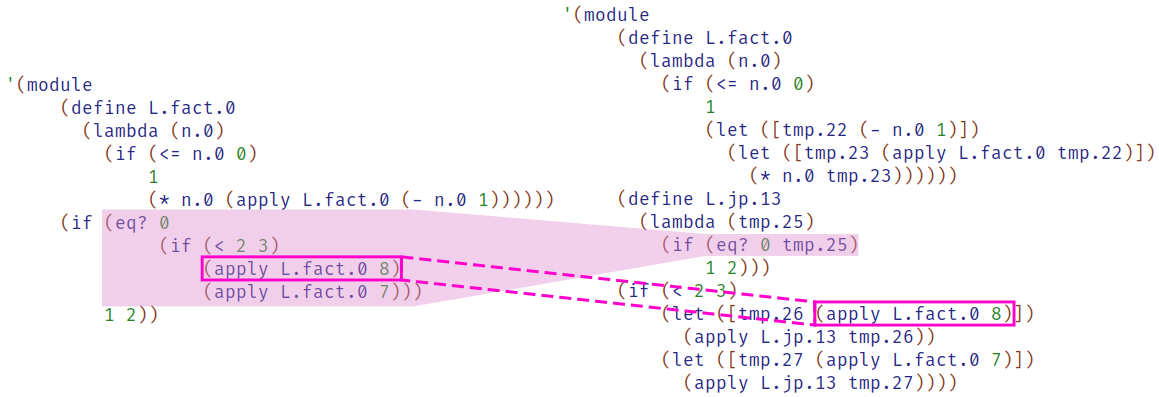


Figure 4: A mockup of a detailed view of the A-normalization pass.

to select more than two expressions, or a detailed view that focuses on parts of all three programs.

6.2 Implementation

To implement our proposed solution we have divided our system into three packages.

1. **The Racket Compiler**: We seek to instrument the reference compiler for CPSC 411 written in Racket.[3] This compiler does not connect source expressions with target expressions in each pass, so this is a necessary instrumentation step. We will be writing the instrumented compiler in Racket so as to reuse as much of the reference compiler as possible and not rewrite it.

2. **The Server**: We will run a Node[4] and Express[5] server written in TypeScript[6] which will serve The Frontend, reroute requests to The Racket Compiler, and process the dataset into a usable JSON format. Node, Express and TypeScript were selected as they are familiar and require minimal overhead to set up.

3. **The Frontend**: The client side piece of our system will be written in TypeScript using React[7] and axios[8] to handle requests. We will leverage the D3.js[9] framework to display the interactive visualization to users. We anticipate this piece of our system to house the majority of its complexity and time in implementation. We have chosen to use D3.js despite unfamiliarity with the framework for its popularity and apparent flexibility.

All services will be hosted on the Software Practice Lab's website, https://se.cs.ubc.ca/.

[3] https://racket-lang.org/
[4] https://nodejs.org/en/
[5] https://expressjs.com/
[6] https://www.typescriptlang.org/
[7] https://reactjs.org/
[8] https://github.com/axios/axios/
[9] https://d3js.org/

Currently, we foresee the largest challenge to our implementation as being our collective unfamiliarity with D3.js (or any other visualization framework). Spending more time learning how to use this framework may cause small changes to our current implementation plans if we find it will not service our needs.

6.3 Results

Following the creation of SecondPass, we seek to facilitate the following scenarios, each analogous to one task in Section 3.

6.3.1 Pass Triage

A CPSC 411 student and her team have been given 21 compiler passes to implement in seven days. Looking to evenly distribute the work of the compiler passes between herself and her two teammate, she uses SecondPass. She visit the overview page and inputs a sample source program, and mouses over expressions looking to discover passes that incur large changes to its program, whether that be by reordering or locating nodes in the graph with high degree. Armed with an intuition for which passes will require the greatest effort, she assigns passes to each team member.

6.3.2 Compiler Exploration

Confused reading the documentation for a compiler pass named `select-instructions`, the student returns to SecondPass and enters the detailed view. Inputting a sample source program and viewing the `select-instructions` pass, she explores the mechanics of the program transformation. She clicks a subexpression to keep its flow highlighted and continues mousing over other subexpressions to highlight their flows and compare how they differ. She begins to coalesce an understanding of what `select-instructions` *does*.

6.3.3 Compiler Debugging

While finishing up work on the `select-instructions` pass of her compiler, the student gets stuck on a particular failing test cases. She sees one expression in the target output and has no idea where it originated from. She again returns to SecondPass, visits the detail view and inputs the source program from her failing test case. She then mouses over the seemingly extraneous expression in the target program and traces it back to the an expression in the source program, and begins to make sense of her mistake.

7 Milestones and Schedule

Our proposed development schedule of SecondPass is as seen in Table 1. In this section we discuss our progress so far, as well as look to the rest of the schedule ahead of us.

7.1 Development So Far

So far we have built a proof of concept overview page that reacts to mouse-over events with red highlighting as seen in Figure 5, and as well we have successfully instrumented the Racket Compiler.

```
(module
  (define L.fact.0
    (lambda (n.0)
      (if (<= n.0 0)
          1
          (* n.0
             (apply L.fact.0
               (- n.0 1))))))
  (if (eq? 0
           (if (< 2 3)
               (apply L.fact.0 8)
               (apply L.fact.0 7)))
      1
      2))
```

```
(module
  (define L.fact.0
    (lambda (n.0)
      (if (<= n.0 0)
          1
          (let ([tmp.22 (- n.0 1)])
            (let ([tmp.23 (apply L.fact.0 tmp.22)])
              (* n.0 tmp.23))))))
  (define L.jp.14
    (lambda (tmp.25)
      (if (eq? 0 tmp.25)
          1
          2)))
  (if (< 2 3)
      (let ([tmp.26 (apply L.fact.0 8)])
        (apply L.jp.14 tmp.26))
      (let ([tmp.27 (apply L.fact.0 7)])
        (apply L.jp.14 tmp.27))))
```

```
(module
  (define L.main.15
    (new-frames)
    (begin
      (set! ra.28 r15)
      (set! tmp.29 2)
      (if (< tmp.29 3)
          (begin
            (return-point L.rp.16
              (begin
                (set! rdi 8)
                (set! r15 L.rp.16)
                (jump L.fact.0 rbp r15 rdi)))
            (set! tmp.26 rax)
            (set! rdi tmp.26)
            (set! r15 ra.28)
            (jump L.jp.14 rbp r15 rdi))
          (begin
            (return-point L.rp.17
              (begin
                (set! rdi 7)
                (set! r15 L.rp.17)
                (jump L.fact.0 rbp r15 rdi)))
            (set! tmp.27 rax)
            (set! rdi tmp.27)
            (set! r15 ra.28)
            (jump L.jp.14 rbp r15 rdi)))))
  (define L.fact.0
    (new-frames)
    (begin
      (set! ra.30 r15)
      (set! n.0 rdi)
      (if (<= n.0 0)
          (begin
            (set! rax 1)
            (jump ra.30 rbp rax))
          (begin
            (set! tmp.31 (- n.0 1))
            (set! tmp.22 tmp.31)
            (return-point L.rp.18
              (begin
                (set! rdi tmp.22)
                (set! r15 L.rp.18)
                (jump L.fact.0 rbp r15 rdi)))
            (set! tmp.23 rax)
            (set! tmp.32 (* n.0 tmp.23))
            (set! rax tmp.32)
            (jump ra.30 rbp rax)))))
  (define L.jp.14
    (new-frames)
    (begin
      (set! ra.33 r15)
      (set! tmp.25 rdi)
      (set! tmp.34 0)
      (if (eq? tmp.34 tmp.25)
          (begin
            (set! rax 1)
            (jump ra.33 rbp rax))
          (begin
            (set! rax 2)
            (jump ra.33 rbp rax))))))
```

Figure 5: An early work in progress screenshot of SecondPass

After building our first prototype with D3.js, we began considering switching to jquery, as it may be too heavyweight for our current implementation goals in the frontend, however do not anticipate this change to affect our current schedule.

Another, unscheduled, task that grew in scope to a significant milestone has been the transformation of the compiler's output data into JSON useable by JavaScript libraries in the frontend. This new schedule item is seen typeset in red in Table 1.

7.2 Schedule in the Future

We intend to spend upward of 140 hours, and have distributed 137 of them generously in the schedule. We aim to have our minimum viable product deadline as early as possible to create a buffer for unforeseen complications.

Development of the frontend, the core visualization, and conducting small user studies are all to be joint efforts. However, Paulette and Jonathan took the lead on the Racket compiler, while Braxton led service orchestration and server development.

Table 1: Project Schedule. Updates from the proposal are typeset in red.

Milestone	Description	Hours	Deadline
Pitch	Prepare slides, record video	1	Oct. 1
Proposal	Refine ideas, write proposal	10	Oct. 23
Learn D3.js	Read documentation, experiment with D3.js	12	Nov. 1
Scaffold Project	Set up the repository, gather dependencies	4	Nov. 1
Build Prototype	Hard coded minimal prototype	20	Nov. 10
Racket Compiler	Instrument the reference compiler	16	Nov. 10
Data Transformation	Write transformation program	5	Nov. 10
Updates	Refine abstractions, update writeup	5	Nov. 17
Peer Project Review	Prepare for project exchange	4	Nov. 19
Build MVP	Build SecondPass	20	Dec. 1
Polish Viz	Iterate on MVP	10	Dec. 6
Final Presentation	Record video, rehearse for Q&A	10	Dec. 10
Final Report	Finalize the paper	20	Dec. 14

References

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