Fusing Industry and Academia at GitHub (Experience Report)

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GitHub hosts hundreds of millions of code repositories written in hundreds of different programming languages. In addition to its hosting services, GitHub provides data and insights into code, such as vulnerability analysis and code navigation, with which users can improve and understand their software development process. GitHub has built SEMANTIC, a program analysis tool capable of parsing and extracting detailed information from source code. The development of SEMANTIC has relied extensively on the functional programming literature; this paper describes how connections to academic research inspired and informed the development of an industrial-scale program analysis toolkit.

Additional Key Words and Phrases: effects, Haskell, data types, industry

1 INTRODUCTION

GitHub is a service that provides storage for repositories of source code tracked with the Git distributed version control system. It is the largest such service in the world, supporting over 65 million users and storing petabytes of source code across hundreds of millions of repositories. The size of the corpus of code on GitHub means that analyzing that code is a source of significant business value. While GitHub boasts a large engineering staff, we report the experience of Semantic Code, a team formed in 2015 to create tools that analyze the corpus of open-source and proprietary code stored on GitHub. One of these tools is a framework called SEMANTIC, a program analysis tool that supports diffing, code navigation, and abstract interpretation. SEMANTIC is implemented in the functional programming language Haskell and is available as open-source software.1

In order to extract up-to-date data from a user’s codebase, code analysis services such as SEMANTIC must operate whenever a user uploads a code change to GitHub. This means that code analysis must be able to handle tens of thousands of requests per minute, with thousands of simultaneous connections, while producing useful data in a timely fashion. Such systems present significant engineering and scaling problems. Industrial approaches to the development of such systems are sometimes ad-hoc, but ad-hoc approaches often suffer in terms of performance and comprehensibility, both of which are hard requirements at GitHub’s scale. In order to avoid these pitfalls, the Semantic Code team heavily draws on the literature associated with functional programming research, including algebraic and scoped effects, data types à la carte, recursion schemes, abstract definitional interpreters and generalized LR parsing.

We have found that FP allows us to find mistakes, test our assumptions, build prototypes, and to experiment within a given problem domain. By leveraging techniques from this literature, the Semantic Code team both solved pressing business problems and ended up with production-tested

1https://github.com/github/semantic

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libraries that we were able to release as open-source software. This illustrates the bidirectional nature of exchange between industry and academia: by drawing on academic techniques, industry can contribute to software ecosystems at large.

In this paper, we describe the history of the Semantic project over the seven years since the establishment of the Semantic Code team and its initial prototype of the system (Section 2), the techniques we used to scale this prototype so that it could cope with production traffic (Section 3), and the production applications powered by Semantic (Section 4). We then discuss the specific techniques for modelling effects that we have employed and refined (Section 5), the varying levels of success we have had with a range of functional programming techniques (generalized LR parsing, algebraic effects, data types à la carte, recursion schemes) and some of the lessons we have learned along the way (Section 6). Finally, we conclude (Section 7). We hope that this experience report provides perspective on the scale of industrial problems, illustrates the process of iterating on solutions within a given problem space, elucidates real-world applications and connections to academic research, and affirms that the academic community’s work is worthwhile and relevant to the challenges faced in industrial software development.

2 THE BEGINNING

Semantic has its roots in the realm of diffing, a process of determining a representation of a change to some source code. A diff is a representation, often textual, of a set of changes within a given software project. The process of computing, applying, and displaying diffs is a foundational responsibility of Git and other version control systems. However, diffs of the sort emitted by the git-diff program are not always the most readable rendition of a given change. Many diffs can span more than tens of thousands of lines, with large diffs sometimes numbering in the hundreds of thousands; as they increase in length, they tend to decrease in readability. The Semantic project began in 2015, with a prototype of a new diffing algorithm, intended to produce a more readable and informative diff than the basic git-diff program—a semantic diff that is aware of the structural and syntactic qualities of programming languages. Such a diff would use information derived from syntax trees to recognise structural changes in a program, such as moving a function definition from one file to another, rather than registering these changes as purely textual. (Note that a semantic diff does not involve the denotational or operational semantics of a program.) The fact that diffing is a core capability of version control systems, and of the GitHub web application itself, motivated us to explore whether semantic diffing could provide business value for users.

2.1 Parsing

Though GitHub hosts code written in thousands of different programming languages, manpower constraints led the Semantic Code team to target a subset of most popular programming languages on GitHub: Python, Ruby, JavaScript, TypeScript, PHP, and Go. In order for Semantic to operate on this diverse set of programming languages, we required a comprehensive approach to parsing and analyzing source code. Real-world programming languages use varied techniques and algorithms for parsing source code: the Ruby programming language uses a LALR(1) parser generated with GNU Bison, whereas the Python language generates its own parser out of a parsing expression grammar (PEG). The choice of parsing algorithm becomes critical when considering syntactic structures that require capabilities beyond that of some parsing algorithms. An example of this is Python’s with statement, which requires multiple tokens of lookahead to distinguish parenthesized expressions from multi-line grouped expressions in its argument. CPython originally used an LL(1) parser, supporting only one token of lookahead, which led to deficiencies in the implementation\(^2\) that were

\(^2\)https://bugs.python.org/issue12782
only remedied when the parser was rewritten in PEG style. We needed a parsing toolkit that provided a consistent approach and application programming interface (API) across several languages and also provided sufficient expressive power to parse these languages correctly, regardless of the capabilities of their canonical parsers.

Our chosen approach was built around the Tree-sitter parser generator [Brunsfeld 2018]. Tree-sitter, a toolkit originally developed at GitHub to provide syntax highlighting for the Atom text editor, uses the generalized LR algorithm (GLR), first described by Lang [1974] and first implemented in 1984 by Tomita [1986]. The GLR algorithm can recognize any context-free grammar, including ambiguous grammars and those requiring arbitrary token lookahead. These capabilities allow Tree-sitter and its grammars to serve as a lingua franca for the world of programming languages: regardless of the language under discussion, Tree-sitter is powerful enough to recognize it, and its API is consistent across languages. Programmers use a JavaScript domain-specific language (DSL) to express Tree-sitter grammars, which generates a dependency-free C program, compilable to machine code or WebAssembly, that any editor or programming tool can use to yield a syntax tree from program text. By virtue of choosing Tree-sitter to power Semantic’s parsing support, we were confident we could extend chosen approaches to any language, as long as that language has a Tree-sitter grammar. The success of Tree-sitter parsers in other applications and problem domains, such as GitHub’s syntax highlighting service, the Neovim text editor, and the Radare reverse engineering toolkit, made us confident that the parsers themselves could correctly handle languages as syntactically complex as TypeScript and Ruby. Additionally, Tree-sitter parsers are tolerant of syntax errors: should a source file contain invalid syntax, the error condition will be confined only to that point in the syntax tree, and the remaining syntactically-valid code will be present and accessible. This is a hard requirement, given that we cannot assume all code in a repository is well-formed.

2.2 An Initial Prototype

Satisfied with our solution to the difficulties of cross-language parsing, we wrote our initial prototype of a semantic executable in a beta version of the Swift programming language. The Semantic Code team had prior experience with Objective-C, Swift’s predecessor, which made it an attractive platform given its additional type safety atop familiar Objective-C APIs. While the prototype worked, it suffered from poor performance and poor developer experience. Though the diffing algorithm was clearly not optimized yet, there was too much friction in writing deployment-ready code in Swift: given its beta status Swift was evolving rapidly and its rapid language changes and sometimes-unstable toolchains distracted from larger engineering goals. Since our code was written in a functional style, we looked for more established languages that would preserve the functional style without compromising performance or readability. Haskell seemed an appropriate choice, given its decades of history, its mature, native-code Glasgow Haskell Compiler (GHC), and its success in other industrial settings such as Meta’s Sigma anti-spam system [Marlow 2015; Marlow et al. 2014]. Moreover, Haskell’s foreign-function interface (FFI) made it easy to link to Tree-sitter generated parsers.

We were astonished by the speed with which we converted our Swift code to Haskell. After less than a day’s engineering effort, our Haskell implementation outperformed the Swift code by a factor of two; this was doubly remarkable given that this was the team’s first experience writing Haskell in industry. GHC’s FFI support allowed us to operate on syntax trees via the C-based

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3Accessible at commit d23d646 of the Semantic repository.
4Accessible at commit 95c2850.
Tree-sitter API, and we generated Haskell data types suitable for differencing and analysis by passing these syntax trees as the seed value to an anamorphism [Meijer et al. 1991].

3 SCALING THE PROTOTYPE WITH FUNCTIONAL TECHNIQUES

Buoyed by the ease of implementing this prototype with Tree-sitter and with Haskell, we turned to the next issue facing us: how were we to take this prototype and build something capable of handling GitHub’s stringent engineering requirements and considerable production traffic? Scaling a prototype is not just a matter of performance: it also involves planning to keep code complexity under control. A single programming language is complicated enough to implement and analyze; we feared that the complexity associated with a naïve approach to implementing a multi-language analyzer would impair the development of any interesting analysis features.

3.1 Syntactic Sharing

Both empirical studies [Haefliger et al. 2008] and the team’s anecdotal experience indicate that code reuse is an effective method for managing complexity. The team decided to achieve a degree of code reuse by sharing the representation of ASTs across our target programming languages. As an example of this, many languages share syntactic features that are relatively similar, such as simple arithmetic operations, functions, assignment statements, and comments. Manually defining a Comment syntax type for each language would be both tedious and complicated. Other language variants overlap more substantially, such as in the case of TypeScript, which is a superset of JavaScript: given their degree of shared semantics, it was our goal to reuse analyses written for TypeScript on JavaScript codebases.

Our chosen solution for syntactic sharing would let us compose a language’s syntax types out of smaller, shared parts. We decided to use a data types à la carte [Swierstra 2008] methodology, which meant defining ASTs as a coproduct of endofunctors, each representing the shape of a kind of node (a string literal, a function call, etc.), tied into a recursive shape with a simple fixpoint. Another fixpoint, defining recursive positions as either a copy, insertion, deletion, or replacement of ASTs, gave us a representation for diffs. All syntax types were functors parameterized in terms of an additional data type representing a node’s annotation; this polymorphism allowed us to track source locations and to annotate, in the case of differencing, whether a node was added or removed. Syntax errors in the tree were represented with a shared error type.

```haskell
1  import Data.Sum (Sum)
2  import Control.Comonad.Cofree (Cofree)
3  import qualified Syntax
4  import qualified Syntax.Literal as Literal
5
6  type JSONSyntax =
7    [ Literal.Null,
8      Literal.List,
9      Literal.Boolean,
10     Literal.Hash,
11     Literal.Decimal,
12     Literal.KeyValue,
13     Literal.TextElement,
14     Syntax.Error -- for ill-formed nodes
15    ]
```

Proc. ACM Program. Lang., Vol. 1, No. ICFP, Article 42. Publication date: January 2020.
An advantage of representing syntax trees as fixed points of coproducts of endofunctors is that such a representation is compatible with recursion schemes [Meijer et al. 1991]. The team employed recursion schemes whenever the shape of data permitted it, as in our experience operations written with recursion schemes are often more flexible, readable, and type-safe than those written with explicit recursion. We used catamorphisms and anamorphisms to implement operations that generated, manipulated, and serialized syntax trees, and used paramorphisms for operations such as term rewriting and dead code elimination that required additional context.

Every engineering decision comes with trade-offs, and choosing data types à la carte provided us with compositionality and fluent recursion but sacrificed a degree of type safety: because these types are functorial with respect to their children, we cannot constrain the types of the children without giving up functorial map. Another downside of this representation was that it required a preprocessing stage, dubbed assignment, an unparser that converted a Tree-sitter syntax tree to a sum-of-products Haskell type, based on an anamorphism implemented once per desired language. This code resembled a construct dual to the Tree-sitter specification of the parser, but had to be written manually. Despite these drawbacks, we grew comfortable with the use of coproducts of functors to represent ASTs, turning then to improving the performance of the program itself.

### 3.2 Algorithmic Improvement

Our algorithm was initially simple, essentially treating a given syntax node as a tuple, a list, or a dictionary. We diffed tuples—nodes with a fixed set of children—in $O(n)$ time by diffing corresponding members. Lists represented nodes with arbitrarily many children, and were diffed with an approach based on the classic shortest edit script (SES) problem [Myers 1986], initially using a naïve, compare-everything-to-everything-else algorithm running in $O(n^2)$ time. Dictionaries, mapping keys to values, were diffed via set reconciliation of the keys. All of this was wrapped up in a small DSL implemented using a free monad, giving us a high-level vocabulary capable of understanding and executing diff scripts generated automatically or by hand, supporting all of our target languages. Breaking syntax down into sums of small syntax functors eventually allowed us to define what we called sub-structural diffing, where a piece of syntax can nominate some sub-syntax as mediating its identity; this allowed us to diff functions by comparing their identifiers.

In 2016, performance concerns and a desire to eventually detect code moves and renames, and other non-minimal features of readable diffs, led us to borrow parts of the RWS-Diff algorithm [Finis et al. 2013], which applies techniques from computer vision to the problem of comparing trees. While we found this suboptimal due mainly to its use of a pseudorandom number generator and its consequent unpredictability, it did improve our algorithm’s efficiency, particularly when combined with other approaches. For example, we decided to improve the naïve $O(n^2)$ diffing algorithm that we had written originally for variable-arity branches, and eventually as a preflight pass applied before RWS. The diffing system was improved by implementing an $O(nd)$ time algorithm by Myers [1986] where $d$ is the size of the difference, which was extremely efficient, particularly in the expected case that more has remained the same than has changed. Fixed-arity branches continued using sequential diffing, running in linear time.
4 PRODUCTION APPLICATIONS

Having achieved acceptable performance, our next course of action was to replace the diffs shown on the github.com website, particularly on pull request views, with syntactic diffs emitted from Semantic. This section explains why we had to abandon this approach for non-technical reasons, and how our goal shifted instead to applications related to source code navigation and comprehension.

4.1 Production Showstoppers for Semantic’s Diffs

We had come to a point where Semantic was able to output its diffs in a format compatible with git. We could therefore integrate these diffs into the github.com interface as a drop-in replacement for files in supported languages. However, non-technical factors led us to abandon this course of action: specifically, the fact that diffs on GitHub would differ from those generated by the standard git-diff program was deemed an insurmountable barrier to widespread adoption. Although Git itself can be configured to use syntactic diffs emitted from a semantic binary, it would require users to download, install, and understand an extra tool, one less battle-tested than git-diff itself.

We then turned to another feature. With diffs represented as syntax trees where some nodes have been replaced by patches, we had all the information we needed to compute summaries of the patches occurring within a diff in a high-level, readable description of what had changed. Unfortunately, while collecting the changes was a matter of a trivial fold, producing a high-level, intelligible description from these proved to be much harder, especially given that these were changes to source code which itself is difficult to summarize. It turns out to be quite a challenge to do better than just presenting the changes verbatim, at least for a user base largely consisting of experienced programmers. We arrived at no formulation that substantially improved on the act of reading a textual diff.

4.2 Table-of-Contents Analysis

Our subsequent engineering efforts focused on a table of contents feature. The table of contents associated with a given diff provides a summary of the files and functions changed in that diff. This feature was shipped to the public [Rix 2017]. A remote-procedure call (RPC) server called semiotic, written in Go, listened for requests for a table of contents, executed the semantic binary out-of-band to analyze that diff, and returned the table of contents data over the wire, encoded in Google Protocol Buffers format [Google 2008]. This information was then decoded by the Ruby on Rails application that powers github.com and rendered appropriately in its interface (Figure 1). Though this feature performed well and provided users with useful information, it did not see wide user adoption, possibly due to its limited space in the pull request UI. GitHub now has a side-bar view, inspired by the table of contents feature, that is displayed on all pull requests.

Fig. 1. The GitHub table of contents feature as rendered to users.
The fact that this service yielded useful customer data at GitHub levels of scale considerably increased the project’s momentum. One of the Semantic Code team’s central goals is to build solutions that require zero configuration from users. GitHub already provides a powerful analysis tool in CodeQL, and supports custom analysis tools in continuous-integration pipelines implemented with GitHub Actions, but these solutions require manual configuration for each repository in order to integrate with users’ build processes. At this point, our goal shifted from diffs and diff analysis to the navigation and comprehension of source code itself, without requiring the repository owner to perform any work to yield its benefits.

4.3 Code Navigation

Our first effort after the table of contents feature was to improve an internal experimental prototype code navigation system. The archetypal code navigation feature, common to many text editors and IDEs, is jump to definition. This allows a user, when faced with an unfamiliar function or variable, to travel immediately to its definition. Dual to this feature is find all references, which, given the definition of a function or variable, locates all parts of the program that reference or invoke that entity. Given that GitHub users often use the github.com web interface to browse code, we anticipated that code navigation as a GitHub feature would be profoundly helpful to those trying to navigate and understand large or unfamiliar codebases.

The prototype code navigation system was used internally by GitHub staff, and proved a helpful tool in the maintenance of the large and complicated Ruby on Rails codebase that underlies GitHub itself. While this prototype worked well enough for internal purposes, there were concerns that it would not scale to a production system visible to all GitHub users. The original system was written in Ruby and extracted data from source code by invoking and parsing the output of the external ctags(1) Unix utility. We wanted to bring reliability, performance, and breadth of utility to this service, without the user having to configure any aspect of the system, and decided to build a prototype of this feature atop our Haskell codebase. We considered an approach built on the code navigation capabilities of external language tooling, over the Language Server Protocol (LSP) standard, but discarded it due to the operational difficulty associated with deploying a separate software stack for each targeted language, as well as the impedance mismatch between LSP capabilities and our tree-oriented view of the world.

Though sharing the syntax tree provided a high degree of reusability when implementing a ctags analysis for several different programming languages, the complexity of these languages reared its head again. An example of this is Ruby’s support for allowing function calls that omit parentheses in parameter lists, similar syntactically to invocation of Unix shell commands. This syntactic quirk means that it is not possible to distinguish syntactically between a zero-argument function call and a reference to a variable. Analyses must keep tables of local variable declarations and use these tables to disambiguate them from zero-argument function calls.

Implementing code navigation was a matter of defining a type class that emitted tag information and implementing this class for every relevant node. This was made available through semanticd, an HTTP-based RPC service, written with the Servant web API library [Servant 2014] and linking in Semantic as a library, that wrote tag information to a MySQL database upon pushes to GitHub repositories and fetched that information based on user queries. The resulting system performed
admirably when deployed to production, handling tens of thousands of requests per minute, deployed and scaled via the Kubernetes [Google 2014] container management system. semanticd proved reliable at GitHub scale: the primary source of crashes was a vendor-specific hardware bug that the GHC maintainers promptly remedied.\footnote{https://gitlab.haskell.org/ghc/ghc/-/issues/18033}

4.4 Semantic Analysis

With the infrastructure for simple code analysis such as diffing and table of contents in place, the next goal of the project was to perform more sophisticated code analysis on repositories to drive features for end users. The goal was to have multiple forms of analysis over multiple different languages. Without a principled approach to modularity, this problem would easily become an engineering nightmare: if supporting \( m \) features for \( n \) languages requires \( m \times n \) amount of work, it becomes increasingly untenable to support new features on languages with a small team, and completely unreasonable to expect the same from third-party contributors. Focusing our attention on the top five most-used languages is already a problem, as general-purpose languages are often quite large, and language size is an important factor in the effort required.

An optimal solution would reduce this to an \( m + n \) problem where each new feature or programming language need only be implemented once. Now the effort required by the team is much more tractable, and third-party contributors can more reasonably add support for new languages.

Further, since both our team and teams likely to be clients of these services lacked prior experience with program analysis, our solution needed to be approachable; we expected to serve a variety of different end-user-facing products, and so we needed it to scale to multiple analyses; and we knew we would need to be able to experiment to tune both performance and precision of the results to suit the constraints of each use case.

Finally, while we could already serve some needs by means of syntactic analyses, typically implemented as folds over syntax trees and diffs, properties which depended on any of a program’s dynamics, for example computing the set of exception types that can be thrown through a given call site, or collecting the set of instructions unreachable from a given set of inputs, remained outside of our reach. Therefore, we knew we needed a truly semantic analysis, justifying for the first time our toolkit and team’s heretofore aspirational names.

Serendipitously, it was at about this time that the team recognised that work by Darais et al. [2017] on Abstracting Definitional Interpreters (ADI) was relevant to these problems. All ADI requires of us is an evaluator written in an open-recursive style against a set of capabilities based on the work of Van Horn and Might [2010]. Implementing an evaluator for an entire language is a non-trivial task, but allows us to support the vast majority of analyses, and hence end-user features, without additional effort, reducing our \( m \times n \) problem to \( m + n \) at a stroke. Furthermore, motivated third parties such as communities of language users can contribute to an evaluator, just like they already do with parsers. This reduces the burden on our team, while often also allowing bugfixes to be provided with a faster turnaround than could otherwise be the case.

Further, ADI gives us a large number of levers to control the performance and precision of analyses. Conveniently, these are the two metrics by which we tune an analysis. For example, the monadic nature of the evaluator’s targeted interface allows semantics to be altered simply by switching the ordering of the handlers of the various components of the abstract machine. (Note that in the paper, these are implemented via monad transformers, while our implementation employs algebraic and scoped effects [Wu et al. 2014].)

To some degree, this began as a solution in search of a (specific) problem: it was clear that we would need this suite of capabilities for future developer productivity features, but it wasn’t at all
obvious what they should be. At one time, we planned on implementing code navigation using
abstract interpretation, but in the end that implementation was pursued in a Rust service using
a notion of stack graphs [Creager 2021] inspired by scope graphs [van Antwerpen et al. 2018],
which allowed us to express scope-aware code navigation without the time and effort associated
with developing full abstract interpretation for all targeted languages. This finer-grained solution
proved more expedient for us given our time constraints, and by implementing it as an addition
to tree-sitter allowed us to avoid the overhead of serializing between Tree-sitter and SEMANTIC.
However, we continue to explore definitional interpreters for analyses more sophisticated than
those required for code navigation.

5 EVOLVING APPROACHES
SEMANTIC’s successful production deployment confirmed our belief that academic research was an
effective source of techniques and approaches. However, working in a problem space as complex
and diverse as analysis of real-world programming languages presented confounding factors to
which we had to adjust. Some of these factors stemmed from runtime performance issues, some
from compile-time performance, and some from our desire to manage complexity more fluently.

5.1 Effective Haskell
As our grasp of syntax became more precise, our need to express the capabilities of operations on
these types grew: we wanted to delineate what operations could and could not happen where. We
found that the complexity associated with rigorously expressing capabilities with the Haskell type
system was justified, given the clarity that these types provided and the errors that they prevented.
We found that one of the appeals of Haskell in an industrial setting is that it is clear in showing
what you can and cannot do.

Haskell programmers most commonly use a finally-tagless approach [Carette et al. 2007] when
expressing the capabilities of code in the type system using the monad transformer library MTL,
to express computational effects [Jones 1995]. This approach suffers in that it requires a separate
monad transformer for each effect’s interpretation, and each monad transformer must implement
an instance per effect, which became infeasibly complex given that our most complicated analyses
sometimes involved invocations dozens of effects deep. We reached instead for algebraic effects
[Plotkin and Power 2001], a family of techniques that, instead of using type class instances in the
manner of MTL, represent effects with data constructors and handlers that interpret invocations
of these constructors. We forked and modified an existing effect system developed by Dev and
King [2016]. Our successful experience with the Kiselyov and Ishii formulation of algebraic effects
established it as a foundational tool for subsequent work in research and in production systems.

We saw an early example of the utility of algebraic effects during the development of our diffing
algorithm. During the debugging process, we needed to dump the state of the $O(\text{nd})$ algorithm
during its operation. In order to do this, we implemented effect handlers that both performed
diffing algorithm and emitted its intermediate states as SVG (Scalable Vector Graphics) files.
Effect handlers made it straightforward to implement the algorithm and allowed us to customize
its interpretation when we needed it to emit additional data.

5.2 Effects and Interpretations
Several issues led us to conclude that we needed an effect system which could represent not only
algebraic effects, but also effects which themselves contain effectful actions.

Some effectful actions take effectful computations as parameters. One example is the Reader
effect, which is equipped with two primitive actions: ask returns the “environment” value and
local $f$ p modifies the environment value, using the function $f$, but this modification is local to
the computation \( p \). The standard algebraic effects approach implements \( \text{ask} \) as a constructor and \( \text{local} \) as an interpreter.

As pointed out by Wu et al. [2014], when combined with other effects, implementing \( \text{local} \) and similar operations as interpreters leads to surprising, and often undesired behavior. We ran into this hard-to-debug pitfall on multiple occasions. This convinced us of the need for an effect system capable of modelling not just algebraic effects, but also non-algebraic \textit{scoped} effects—effects which delimit the scope within which some behaviour—locally shadowing a variable, catching an exception, forking a computation using cooperative multitasking, etc.—will be applied.

Though \texttt{Mtl} is the \textit{de facto} effect system for developing Haskell applications, it was unsuitable for implementing the system described by Darais et al. [2017], as the implementation relies on the ability to have multiple state types, with multiple interpretations, in a given monadic computation. \texttt{Mtl} prohibits this approach due to the fact that its effect type classes, to aid in type inference, prohibit multiple instances of these classes for a given monad transformer. The recommended solution for this is to create more monad classes, and to implement these classes for all monad transformers, which is the \( O(n^2) \)-instances problem discussed previously. Despite this drawback, \texttt{Mtl} performs very well, orders of magnitude better than a freer-monad approach, due to the fact that the GHC optimizer is eager to inline type class methods [Peyton-Jones and Marlow 2002], avoiding the overhead of constructing type class dictionaries. However, GHC is generally reluctant to inline recursive code, and the act of handling algebraic effects is inherently recursive, given that one handler might need to delegate to another. Our solution needed to introduce as few performance changes as possible, both out of performance requirements and ability to implement effects such as telemetry-based performance monitoring: adding effects needed to avoid altering the performance characteristics of the code under examination. As such, we had to recover a degree of the inlining characteristics of \texttt{Mtl}.

\section*{5.3 Fused-Effects}

The aforementioned deficiencies in our freer-monad effect system caused us to look at alternatives. We looked, again, to the literature to help us overcome these problem. Work by Wu et al. [2014] provided a formulation of effect handlers capable of handling scoped operators. Wu and Schrijvers [2015] demonstrated that GHC’s reluctance to inline recursive effect handlers is remedied by expressing these handlers as type class methods. Additionally, work by Schrijvers et al. [2019] allowed us, by limiting ourselves to modular effects, to remove occurrences of the freer monad entirely, instead using the well-attested and GHC-friendly monad transformer approach. We implemented \texttt{Fused-Effects}, an effect system based on these techniques, and immediately observed considerable speedups in analysis benchmarks. The \texttt{Fused-Effects} support for scoped effects with multiple interpretations rendered it trivial to implement effects such as telemetry. We have released \texttt{Fused-Effects} as open-source software\(^6\), as well as associated packages providing integration with common libraries such as \texttt{haskel1ne} and advanced approaches to data manipulation such as profunctor optics [Pickering et al. 2017]. With more than 10,000 downloads to date, \texttt{Fused-Effects} has seen substantial community adoption and industrial use outside GitHub.

\section*{6 Lessons Learned}

We consider functional programming to have been a clear win for \texttt{Semantic}. In practice, some techniques applied better than others; nevertheless, we learned a great deal in the process of applying and evaluating a variety of approaches.

\(^6\)https://github.com/fused-effects/fused-effects
6.1 GLR Parsing

Tree-sitter and the generalized LR algorithm it provides have proven rock-solid at industrial scale and sufficiently expressive to parse even languages, such as Ruby and TypeScript, that display tremendous syntactic complexity. Tree-sitter’s JavaScript-based DSL is sufficiently expressive to cover most aspects of PL syntax, and for languages with complex lexing rules, such as Ruby’s support for nested heredoc strings, Tree-sitter allows hand-written lexers in C or C++. On the occasions we had to extend Tree-sitter’s capabilities, such as to emit information about a grammar’s syntax types for code generation (see Section 6.4), doing so proved straightforward. The Tree-sitter ecosystem continues to expand, thanks to its significant community adoption, and we anticipate that it will continue to serve as a fundamental building block for the Semantic Code team’s engineering efforts. The fact that language communities themselves can maintain their language’s Tree-sitter grammar allows GitHub to provide useful code intelligence features, without having to commit GitHub engineering time to language support itself. Given the plethora of programming languages hosted on GitHub, this is an elegant solution to manpower and time constraints, one that also benefits language communities.

6.2 Algebraic Effects

From the project’s inception, our use of algebraic effects was pervasive and profound. We conjecture that Semantic is among the largest Haskell projects developed without any direct dependency on Mtl. We found algebraic effects an elegant, effective, and expressive way of writing effectful code in Haskell.

The monadic computations described in Darais et al. [2017] require multiple State and Reader types in their transformer stacks, and the paper’s artifacts accomplish this by defining a bespoke monad transformer library, alongside macros to ease the composition of monad stacks. Expressing these computations using Mtl would be tedious, as every duplicated State or Reader effect would need to be wrapped in its own finally-tagless monadic interface, alongside a concrete transformer type that would require instances for all associated monad transformer classes. This is the classic \(O(n^2)\) instances problem at work. Because Fused-Effects’s effect invocations are more polymorphic than those provided by the Mtl interface, this posed no difficulty, allowing us to port the aforementioned interpreters from the Racket implementation in Darais et al. [2017] to Haskell with a minimum of fuss and effort. Though Mtl yields better type inference thanks to the functional dependencies of its effect classes, GHC’s support for visible type applications [Eisenberg et al. 2016] allowed us a pleasing syntax for disambiguating any ambiguous invocations.

An example of the utility and flexibility of algebraic effects is an effect we developed to extract telemetry data from our production Haskell systems. A hard requirement for production systems is that they emit data about the state of the system, in order for their maintainers to have insight into the behavior of a program during the operating and debugging process. Examples of such include log messages and associated key-value data; remote metrics such as counters, timers, and statistical distributions; and execution traces that describe the control flow paths taken by a given request or action. These data are sent to internal services that store, aggregate, categorize, and display them in a manner that aids comprehension. Algebraic effects provided us a rich vocabulary for aggregating and collecting these data, as well as the ability for this aggregation and collection to operate differently in different contexts.

Timing the execution of a given code block is an example of a scoped effect: the yielded telemetry data are limited to the code around which the timing invocation is wrapped. However, sometimes we wanted different behavior, especially during local development: data aggregators are intended for production, rather than development, but the statistics generated are still useful and relevant.
during the development cycle. In a production context, we wanted these data to be uploaded to an aggregator; in a development context we wanted to see them reported on the command-line; and when running automated tests, we wanted to discard them entirely. Furthermore, our solution needed to introduce as few performance changes as possible, lest the act of measuring some code’s execution time alter the performance characteristics of the code under examination. With FUSED-Effects, it was trivial to define a Telemetry effect and associated interpreters to handle the three above cases, thanks to FUSED-Effects’s support for reinterpreting scoped effects. A simpler effect system that did not support such reinterpretation would not have sufficed.

6.3 Data Types à la Carte

Our initial experience with data types à la carte was positive. Expressing a language’s syntax with a type-level list (see Section 3.1), thanks to GHC’s support for type-level programming, and then parameterizing the associated type with that list, provided an elegant and uniform interface to querying and analyzing syntax trees. The fact that we shared common syntax nodes, like Comment and Integer types, between languages allowed us to generalize functions and analyses across said languages. Performance problems associated with a recursively defined notion of subsumption led to us developing a library called FASTSUM, released as open-source software, that unrolled this recursive loop within the Haskell type system, which bypassed performance problems associated with large languages such as TypeScript, which contains hundreds of distinct syntax nodes.

The utility of the data types à la carte approach was ultimately limited due to the variance in semantics between languages with what superficially appeared to be the same kinds of syntax. For example, object-oriented programming languages that support implementation inheritance provide a construct that instructs the language to invoke a superclass method. In Python, Java, and Ruby, this construct is written super(), suggesting that they should be modeled by a single syntax type. However, Ruby provides an unusual variant of super(), known as “zsuper”, short for “zero-argument super” and written without trailing parentheses. When invoked in a method taking one or more arguments, zsuper implicitly forwards all arguments in scope to its superclass’s implementation. We defined a Ruby-specific zsuper syntax functor, and made similar compromises when dealing with other quirks of real-world programming languages: ultimately, this problem domain is sufficiently complicated to, at times, actively resist abstraction.

Additionally, an à la carte approach is ultimately untyped: even though syntax trees generally permit type invariants on their subtrees, our approach discarded this information. Though this made it easy to represent nodes that can appear anywhere, such as comments or parenthesized expressions, it complicated tree rewrites, as we had to anticipate the possibility of such occurrences at any given position in the syntax tree. For example, an operation that requires portions of a syntax tree may be valid in a case without comments present in the syntax tree, but if comments can appear at any point in a syntax tree, that operation must account for the presence of a comment as well as preserve its position in the syntax tree. Correctly accounting for edge cases such as these involved many runtime type checks, which obviated many of the gains from choosing a strongly typed implementation language. Furthermore, the assignment stage, the language-specific anamorphism mapping a Tree-sitter tree to a coproduct of functors, proved a significant maintenance burden: any update in a language grammar required modifications to the assignment stage. Assignment code had to be written manually, held us back from upgrading language grammars regularly, was difficult to debug, and proved to be a reliable source of bugs.

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7 https://gitlab.haskell.org/ghc/ghc/-/issues/8095
8 https://github.com/patrickt/fastsum
6.4 From à la Carte to Code Generation

The team ultimately chose to move away from an à la carte representation of syntax trees, electing instead to generate Haskell data types directly from type information emitted by the Tree-sitter parser generator. This approach, described and implemented by Nadeem [2020], proved superior in several aspects: it retained the type information that the à la carte representation lacked, the generated types required no maintenance by hand, and it eliminated the need to implement an assignment stage altogether! Because syntax trees yielded from Tree-sitter may not be well-formed, the fields of syntax types are wrapped in an \texttt{Err} functor isomorphic to \texttt{Maybe}.

\begin{verbatim}
-- Terminal nodes and their textual contents
data True a = True {ann :: a, text :: Text}
data False a = True {ann :: a, text :: Text}
data Number a = Number {ann :: a, text :: Text}
data Null a = Number {ann :: a, text :: Text}
data String a = Number {ann :: a, text :: Text}

-- Nodes with children
data Array a = Array {ann :: a, children :: [Err (Value a)]}
data Pair a = Pair {ann :: a, key :: Err ((Number :+: String) a), value :: Err (Value a)}
data Object a = Object {ann :: a, children :: [Err (Pair a)]}

-- Toplevel choice node representing JSON values
newtype Value a = Value ((True :+: False :+: Number :+: Null :+: String :+: Array :+: Object) a)
\end{verbatim}

A simplified representation of the syntax types generated from the Tree-sitter grammar for JSON. Ultimately, the utility of reusing grammar descriptions outweighed the utility of reusing hand-maintained syntax types. Though a code-generation approach creates more syntax data types than does an à la carte representation, the elision of the complicated and error-prone assignment stage made this a sensible tradeoff in light of our engineering requirements. Despite à la carte syntax proving ultimately unsuitable, it showed that code reuse is more effective when it integrates with high-level data descriptions, such as the JavaScript DSL that specifies a grammar description.

6.5 Recursion Schemes

Recursive operations are a fundamental building block of idiomatic Haskell, and as such a toolkit providing a generalized vocabulary for many different types of recursion proved helpful for a wide array of tasks. The Haskell \texttt{recursion-schemes} library provides a sophisticated vocabulary for catamorphisms, anamorphisms, paramorphisms, and histomorphisms, alongside an API that integrates well both with standard Haskell data structures and with our hand-written syntax types, which, being functorial with respect to their subterms, were already compatible with the standard fixpoint encoding of codata in Haskell. An example of recursion schemes’ applicability came during the prototyping of a DSL for term rewriting; expressing the DSL’s interpreter with a paramorphism elided all explicit recursion and generalized the DSL to any data type compatible with recursion-schemes. Even the more exotic recursion schemes proved themselves useful, such as histomorphisms during our experiments with diff summaries and hylomorphisms as part of our implementation of RWS-Diff.
The problems with recursion schemes emerged most notably when transitioning to the generated syntax types described in Section 6.4. These generated types are functorial in terms of their annotation type rather than their subterms, and as such the traditional encoding of recursion schemes via a fixed point of functors does not apply. There exist approaches that generalize the data types à la carte to mutually-recursive, well-typed trees [Bahr and Hvitved 2011], but the incidental complexity is high, and the sheer size of syntax trees like those of TypeScript precluded traditional encodings of sums and subsumptions (hence our development of FASTSUM). Defining a higher-order equivalent of the traditional Traversable type class, as well as the required code to derive these instances generically [Magalhães et al. 2010] recovered a degree of expressivity when recursing into subterms, though at the cost of flexibility when compared to the à la carte formulation.

7 EPILOGUE

This section summarizes Semantic’s current situation and future plans, and then concludes.

Current Situation. While the Haskell implementation of code navigation was a success, it was later replaced by a domain-specific language for querying syntax trees. This decision did not stem from deficiencies in Semantic itself: rather, our manpower constraints precluded the use of heavy-duty language stacks. Due to the considerable number of programming languages in use, we needed to enable external contributors to maintain their own code navigation rules without having to write Haskell code. Haskell’s considerable ecosystem, large compiler, and learning curve made it an unsuitable choice for language maintainers unfamiliar with Haskell. (The same is true of Rust, Tree-sitter’s implementation language). Our goal was to eliminate all possible barriers to entry. Because the query language we developed is useful in other contexts, we implemented it directly in Tree-sitter, adding to its existing suite of tools. Our production systems now invoke the Tree-sitter code directly, rather than being mediated by Semantic. The lowered barrier to entry afforded by the use of the domain-specific query language allowed the Elixir programming language community to contribute and maintain their own rules for code navigation, and we anticipate future external contributions from language communities.

Future Plans. Semantic continues development at GitHub, where we are using it to explore future product features that require high-level program analysis and abstract interpretation. We have defined compatibility interfaces to bridge the output of Tree-sitter DSL operations to perform analyses that would be inconvenient to express in the DSL or without the Haskell ecosystem. We are now experimenting with abstract interpretation to track exceptions.

Further work remains to generalize the hardcoded Err functor (see Section 6.4) wrapping child nodes (to handle the fact that Tree-sitter parsers’ error-tolerance means that some subterms may be syntactically invalid) to a type parameter, rendering them types of kind ($\star \rightarrow \star \rightarrow \star$). This approach, thanks to the flexibility associated with customizing the shape of contained data, can recover the convenience and flexibility of the unityped version without compromising type safety. For example, though generated syntax nodes have no fields representing comments, parameterizing these nodes with a functor containing comment text will allow us to associate them with comments. Using a three-valued functor (usually known as These) allows us to recover diffing capabilities by associating nodes with additions, subtractions, or unchanged sections in a given diff.

Conclusion. Even though Semantic is no longer part of the code navigation pipeline, we consider it a successful application of FP techniques, which allowed us to iterate quickly on a solution, draw from well-researched avenues of thought, and express complex thoughts concisely, all the while retooling our approach in the face of evolving business requirements and use cases. We are pleased
both with the utility of SEMANTIC as a tool at GitHub’s disposal and as a source of open-source software and community interest.

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