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HyperAST: Enabling Efficient Analysis of Software Histories at Scale

Quentin Le Dilavrec
Univ Rennes, IRISA, Inria
Rennes, France
quentin.le-dilavrec@irisa.fr

Arnaud Blouin
INSA Rennes, Univ Rennes, IRISA, Inria
Rennes, France
arnaud.blouin@irisa.fr

Djamel Eddine Khelladi
CNRS, Univ Rennes, IRISA, Inria
Rennes, France
djamel-eddine.khelladi@irisa.fr

Jean-Marc Jézéquel
Univ Rennes, IRISA, Inria
Rennes, France
jean-marc.jezequel@irisa.fr

ABSTRACT
Abstract Syntax Trees (ASTs) are widely used beyond compilers in many tools that measure and improve code quality, such as code analysis, bug detection, mining code metrics, refactoring. With the advent of fast software evolution and multistage releases, the temporal analysis of an AST history is becoming useful to understand and maintain code.

However, jointly analyzing thousands versions of ASTs independently faces scalability issues, mostly combinatorial, both in terms of memory and CPU usage. In this paper, we propose a novel type of AST, called HyperAST, that enables efficient temporal code analysis on a given software history by: 1/ leveraging code redundancy through space (between code elements) and time (between versions); 2/ reusing intermediate computation results. We show how the HyperAST can be built incrementally on a set of commits to capture all multiple ASTs at once in an optimized way. We evaluated the HyperAST on a curated list of large software projects. Compared to Spoon, a state-of-the-art technique, we observed that the HyperAST outperforms it with an order-of-magnitude difference in search time.

90% average of declarations with the HyperAST, 91% and 31 min vs. 83% and 22 min for Spoon. We observed that the HyperAST outperforms Spoon by a factor of 100× compared to Spoon, a state-of-the-art technique, we observed that the HyperAST outperforms it with an order-of-magnitude difference in search time.

2 INTRODUCTION
The emergence of distributed version control systems (VCS), such as GitHub or GitLab, has permitted accessing a massive quantity of software and their histories. This offers golden opportunities for both researchers and engineers to perform code analysis of software at large.

Researchers have been analyzing software code histories from different angles, such as recovery of traceability links [2, 3], refactorings [46], edit scripts (aka. Diff) [14], duplicate code [29], bad smells and their origins [47], or mining of fixes for program repair [23]. Engineers in the software industry developed code analysis tools at scale, such as Copilot1 for code completion, LGTM2 for bug detection, or CodeQL3 for querying the code.

To do so, relying on structured code representation, namely the Abstract Syntax Trees (AST), has become a foundation for many of the above-mentioned tools and software engineering activities.

One of the intrinsic property of software is its continuous evolution [30] and its growing complexity as it evolves. This new dimension asks for temporal code analysis of software histories. In particular, to consistently analyze code elements through their evolutions (i.e., different commits and releases) and also linking their analysis. Such a temporal code analysis can focus, for instance, on origin of code smells [48], bug prediction [36], class stability [41] throughout commits, co-evolution [25, 26] by linking impacting changes and their resolutions.

However, a temporal code analysis requires to simultaneously handle multiple ASTs, corresponding to the different versions of the corresponding software across its history. Unfortunately, doing so on large set of commits for large sized software faces major scalability issues both in terms of memory and CPU usage. With state of the art analysis tools, the whole computation is indeed typically redone from scratch for each version, i.e., commit, even if the commit under analysis is almost identical to previously analyzed ones [25, 26, 48]. Boldi et al. [6] proposed to compress the file structure of a software history without considering the content and for storage purposes of the archive. Alexandru et al. [1] rely on a vertex compression algorithm to share AST nodes among revisions. However, without sharing identical code subtrees independently of their position.

The contribution of this paper is to add a time dimension to an AST, that is to turn it into a HyperAST capturing all of it history. The goal is to ease temporal code analysis at large scale on a large timeline of a software history. To do so, the HyperAST is built incrementally on a set of commits. It integrates the ASTs of the different versions in one place by leveraging on the code redundancy through space (between code elements) and through time (between versions). This stems from the observation that for a set of commits in a software history, most of the ASTs’ elements are similar since most often only small code changes are applied in each commit compared to the rest of the code base. In its core, the HyperAST is a

1https://copilot.github.com/
2https://lgtm.com/
3https://codeql.github.com/
Direct Acyclic Graph (DAG) where nodes are unique, allowing for an efficient reuse of nodes in a single version and across versions if unchanged. Moreover, intermediate computation results on top of the HyperAST, such as hashes and references, are calculated and stored as metadata along the nodes of the HyperAST. Thus, allowing for an efficient reuse of the metadata across versions. The goal of metadata is also to serve as basis for a further in-depth temporal code analysis. To the best of our knowledge, the HyperAST is the first attempt to offer an optimized AST covering multiple versions at once in contrast to maintaining multiple ASTs for each version.

We evaluate the HyperAST on three levels: (1) its feasibility, (2) its scalability, (3) its usefulness on a practical scenario of usage, namely finding references of declarations.

In particular, we evaluate the HyperAST on a data set of 18 real-world and representative Java projects taken from GitHub, by comparing it on a sample of thousand of commits per project to a state-of-the-art tool as a baseline, namely Spoon [38]. Our results show the HyperAST correctly represents a software history of a set of commits. It always was able to serialize the code back to its files in 99.98% and 0.02% were due to erroneous code in its original state. Moreover, we were able to scale on large repositories with an order-of-magnitude difference between the HyperAST and Spoon, from 6 up to 8076 in CPU construction time and from 12 up to 1159 in memory footprint. The minimum and a maximum of construction time in CPU for the HyperAST ranged from 1 min and 2 h 22 min, while it ranged from 1 h 14 min and 93 h 31 min for Spoon. Besides, The minimum and a maximum of memory footprint for the HyperAST ranged from 63 MB and 7.2 GB, while it ranged from 16 GB and 2.2 TB for Spoon. Thus, the gains in construction time varied from 83.4% to 99.9% and the gains in memory footprint varied from 91.8% to 99.9%. Finally, we also compared the scenario of finding references of declarations with Spoon and with our implementation of the same scenario on top of HyperAST. We observed on average 90% precision and 97% recall, respectively, ranging from 68.2% to 98.2% and from 84.4% to 97.7%. Results also show better search time with the HyperAST up to medium-sized projects and better search time with Spoon for large-sized projects. Overall, results are promising towards opening new perspectives for scalable temporal code analysis on large software histories at once.

The main contributions of this paper are:

1. a novel kind of AST, namely the HyperAST, that aims to enable efficient large scale temporal code analyses on software histories;
2. an open-source implementation of the HyperAST;
3. an evaluation that demonstrates the feasibility, the scalability and the relevance of the HyperAST;
4. a replication package for open-science.

The rest of the paper is structured as follows. Section 2 motivates the problem using an example, classifies temporal code analyses, and introduces mandatory background concepts for the paper. Section 3 presents the HyperAST. Section 4 details the evaluation. Section 5 discusses the related work. Section 6 concludes the paper. The remaining text includes images and code snippets that are not included in the text representation.
HyperAST: Enabling Efficient Analysis of Software Histories at Scale

different versions. Thus, such temporal analysis requires to keep in memory elements of each AST to perform analysis. With no manual and ad-hoc optimization, this leads to a memory and CPU over-consumption preventing the analysis to scale, especially on thousands of commits. Moreover, on new commits, one must re-execute the process (i.e., analyzing prior commits to spot related evolutions) to analyze the code issues that appeared in those commits and their history. Therefore, the same computations are likely to be repeated multiple times.

Current pitfalls. To summarize, performing temporal code analyses, i.e., analyzing the AST of the same program at different times, faces the following issues:

- Stakeholders have to write and maintain boilerplate glue code to put in relation multiple ASTs, such as in [25];
- As a consequence of the previous point, analyses may consider evolutions at the class or method level only, such as in [34], while temporal analyses might require more fine-grained evolutions (e.g., instructions);
- Analyses may face memory and CPU over-consumption when several ASTs have to be compared or analyzed together (i.e., not a batch process), thus preventing them to scale, as detailed in [25];
- Stakeholders have to re-analyze the program history on every new analysis;
- Current temporal code analysis approaches (e.g., [1]) support the computation of syntactical metrics in a sequential batch way as a temporal code analysis.

2.2 Background

This sub-section details the background on code histories necessary for the paper.

There are mainly two approaches of building a code history. First, the history is represented as a change set. For each version, the difference of the current state with the previous state is stored. Mercurial uses this approach. Second, each state is stored as a snapshot. To scale, this approach needs to share data between versions, hence, storing only the changed objects and files. Git uses this approach and is based on a Merkle DAG to manage the history of snapshots. Each element of the Merkle DAG is uniquely identified by the hash of its content. By definition, an element of a Merkle DAG is shared between multiple versions if it has the same content. Other representatives of the snapshot-based approach are software-heritage [12] and Piper [39]. The HyperAST applies the same principles on the code level, and hence, on the ASTs.

Let us focus on the second type of approach as used in Git. In Git, elements of the Merkle DAG are named Objects. Objects have a unique identifier called Oid that is the hash of the content of the Object. Figure 2 depicts the three major kinds of Objects: a Blob object (square) corresponds to the content of a file; a Tree object (triangle) corresponds to a directory, it maps by name other Tree objects but also Blob objects; a Commit object (circle) is a snapshot of the codebase. It points to a Tree and its parent Commit objects. For the sake of simplicity, these objects are referenced as Blob, Tree, and Commit in the rest of the paper.

3 THE HYPERAST APPROACH

This section details the concept of HyperAST, that improves scalability when analyzing large software histories. The first enabling hypothesis is about 1) redundancy in space between code elements in a single version, and especially 2) redundancy in time among consecutive commits, where small changes are applied compared to the overall size of the codebase [51]. The second hypothesis is that various computations can be done once on code subsets [11, 14] then reused multiple times in space and time.

This section first gives an overview of the HyperAST and then describes its structure. After that, it details how the HyperAST is constructed and updated with every new commit. Finally, we detail how to use the HyperAST on a code analysis use case.

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1[https://www.mercurial-scm.org](https://www.mercurial-scm.org)
2[https://git-scm.com/docs/gitglossary](https://git-scm.com/docs/gitglossary)
3.1 Overview

Figure 3 shows the overall workflow of the approach of building the HyperAST incrementally on new commits. Given the Git the Merkle DAG of a software history, per commit (green circle), the construction process explores the hierarchy of directories through the Git Trees (blue triangles), and parses the code files represented by Git Blobs (red squares). We rely on Tree-Sitter [31] that parses the code into a CST (Concrete Syntax Tree). For each git object treated, the construction process associates its Object Identifier (OId) to its corresponding node in the HyperAST and stores it into a cache. Thus, if encountered again in following commits, those nodes are not inserted and simply reused across versions. Moreover, when processing an element to insert in the HyperAST, the process first extracts identifying data and checks whether the element is already inserted. If not, metadata are computed and inserted as well.

3.2 HyperAST structure

This section introduces the structure of the HyperAST. A HyperAST is a Direct Acyclic Graph (DAG).

Let \( \text{HyperAST} = (V, E) \), such that:
- \( V \) is the set of nodes,
- \( E \subseteq V \times V \) the set of directed edges between nodes.
- A node is a tuple \( V = (\text{type}, \text{label}, \text{children}, \text{metadata}) \).

A HyperAST node is uniquely identified by its type, label, and children resulting of the code parsing. This characteristic is essential as it allows reusing structural clones (i.e., unchanged part of the code) from a commit to other ones.

**type**: refers to a rule name of the language grammar, such as class, method declaration, assignment.

**label**: The textual content of a token in a grammar. It is mandatory for leaf nodes but optional for the parent nodes. For example with the given variable declaration "\texttt{int } i = 0; ", \( i \) is the label of the variable identifier and 0 is the label corresponding to the literal assigned to \( i \). The parent node’s label of the variable declaration is empty.

**children**: A list of references to other nodes in the HyperAST.

**metadata**: A persistent storage for intermediate results or computation of code analysis on the local sub-tree throughout versions. It helps in reducing redundant and unnecessary computation when analyzing code histories. Its exact definition depends on how stakeholders plan to use and augment the HyperAST to fit their needs. For example, it could be complexity metrics or hashes.

3.3 HyperAST construction

This section details the construction of a HyperAST by first focusing on the tree construction, and then on metadata computations.

3.3.1 Tree construction. The construction process of a HyperAST is a tree-to-tree transformation. It starts by processing the commits and their trees of a git’s Merkle DAG recursively. This thus maintains the structure and hierarchy of the history in terms of directories and code files, facilitating the serialization of the HyperAST back to the code. When reaching a Blob, it is parsed as a CST to be processed before to be inserted into the HyperAST. So, the produced HyperAST keeps the same structure as the original git’s Merkle DAG where Blobs are replaced by CSTs. Compared to Git, this increase of granularity enables code analysis and allows further code deduplication.

The construction of the HyperAST can be considered as append-only. Thus, it is incremental in its nature since the approach processes each commit separately and appends all elements related to the commit in the HyperAST.

Moreover, node insertion and metadata computation are done only if the node is absent from the HyperAST. To check whether an element is already present in the HyperAST, the approach uses
its hash (see Hashes in Section 3.3.2) to detect a structurally similar node. In the following, we explain how to handle the different Git objects and the parsed CSTs to construct the HyperAST.

Handling a Commit: Each commit has a corresponding root node added to the HyperAST.

Handling a Tree: To insert a Tree in the HyperAST, the approach first inserts its children (i.e., post-order mode). To computationally benefit from the Merkle DAG, the HyperAST keeps a temporary association table as a cache between an Oid (git Object Identifier) and references to HyperAST nodes. This allows quickly checking the presence of a node in the HyperAST. The construction approach handles each child of a given Tree as follows:

- **Tree Child** is handled recursively.
- **Blob Child** is parsed to produce a CST, which elements are handled recursively.

Finally, a Tree is inserted in the HyperAST as a node with its type set to 'directory' and its label as the Tree name, and with references to its processed children.

Handling a CST element: A CST is also a recursive structure, which is processed following the same steps as for handling a Tree in post order. Finally, a processed CST element is inserted in the HyperAST as a node with its: original CST element type; label; and references to its processed children.

We now take the first two commits in Figure 1 as an example to show the constructed HyperAST. Figure 4 depicts the constructed HyperAST at the second commit Vx + 1. The left part (white) depicts the HyperAST after its construction on the first commit Vx. The right part (green) depicts the new elements added to the HyperAST after the second commit is treated: the addition of the parameter int value a1(), and the argument value in the constructor invocation new B(). This example shows how both commits exist in the same HyperAST. For sake of readability, Figure 4 does not illustrate the nodes’ metadata. The entry points in the HyperAST corresponds to the handled commits (Vx and Vx + 1). Thanks to the structural similarities between Vx and Vx + 1, Vx + 1 can reuse all unchanged parts of the code and their already computed metadata, depicted by the green arrows: this is reuse of redundancy in time. Finally, it is worth noting that nodes are shared even in a single version, i.e., redundancy in space, such as the id: "value" node in dashed green.

### 3.3.2 Metadata provisioning.

The goal of metadata is to provide developers with intermediate pre-calculated results to be reused for a posteriori temporal code analysis across versions. We designed the HyperAST to be extensible to add other types of metadata either during or after its construction by appending the newly computed metadata. This section discusses two concrete kinds of metadata that we are going to use during the evaluation.

**Similarity metrics.** During the construction of a HyperAST, hashes [8, 9, 14] are computed as metadata to help in comparing sub-trees: a structural hash; a structural and label hash; a syntactical hash. The structural hash only uses the type of nodes, while the structural and label hash also uses nodes’ labels. The creation of a HyperAST also computes for each sub-tree a syntactical hash that considers its serialized code. This metric aims to help in comparing and indexing versions of code.

**Index of references.** Given a declaration, finding all its references is a standard feature in most code analysis tools. It often implies maintaining an association table between declarations and references. This works fine in the case of a single version. However, maintaining such global tables and ASTs for multiple versions requires heavy maintenance work to keep those numerous tables synchronized. Instead, one could use an oracle capable of answering with certainty when a reference is absent from a given piece of code, i.e., from a sub-tree. Thus, only exploring the sub-trees that may contain references.

To do so, we rely on Bloom filters [4], a probabilistic data structure efficient for supporting an oracle that checks whether an element is a member of a set, in our case a reference in a given sub-tree. Bloom filters also have a substantial space advantage over other data structures, as they do not store the data items at all (i.e., the resolved references) as done in an association table. In essence, a bloom filter is an array of n bits all initially set to 0 and a set of hash functions. For each resolved reference, the Bloom filters use those hash functions to get a set of integers indexes. They set to 1 the corresponding indexes in the bit array to indicate the presence of the resolved reference in the sub-tree. Thus, rather than storing the reference, the HyperAST basically indexes it. The HyperAST stores the Bloom filters as a metadata with the inserted nodes. Thus, the reference resolution can be reused across multiple versions.

### 3.4 Use case usage: Finding References

This section discusses how to use the HyperAST and its metadata for a classical task: navigating in the code from a given declaration to all its references, in particular, across the code history. This is a basic functionality needed for numerous tasks, such as code smells [48], bug prediction [36], class stability [41], and co-evolution [25, 26]. Given declarations, and based on the indexed references, we reuse the bloom filters and their same hash functions to quickly query our oracle for the presence/absence of references in the various sub-trees, recursively until finding them. The goal of this use case is to show its feasibility. Furthermore, we will evaluate on its use case the performance and correctness of the HyperAST (Section 4).

### 3.5 Tool Implementation

We implemented the HyperAST in Rust, a performance-oriented programming language. The HyperAST is a DAG stored in an Entity-Component-System database [33], inspired from Silva et al. [43] that showed high performance gains. The code of the HyperAST implementation is open source and freely available6. The implementation interacts with Git to obtain the history of a given repository through its Merkle DAG. The implementation then uses Tree-Sitter [31] to parse the code of each Git Blob. Tree-Sitter is an incremental and resilient parser that tries to fix erroneous CSTs to a certain extent. Tree-Sitter is thus able to handle commits with erroneous code that a compiler would not.

### 4 EVALUATION

This section presents the evaluation of the HyperAST. First, we present the research questions to then discuss the results. Then, we present the data set and evaluation process. We finally discuss

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6https://github.com/quentinLeDilavrec/HyperAST
We now formulate the research questions as follow:

**RQ1** Can we compute the HyperAST correctly over several versions? This research question aims to investigate the sound construction of the HyperAST.

**RQ2** How does the HyperAST perform and scale compared to a traditional approach? This aims to position the scalability of performance contribution over a long evolution history with an established state-of-the-art solution.

**RQ3** How does the HyperAST perform and scale on the code analysis task of finding references compared to a traditional approach? This aims to investigate whether a code analysis task can leverage on the HyperAST, thus opening a new perspective to work with the evolution/time dimension rather than on only a single version at a time.

### 4.2 Data Set

This section presents the data set used in the evaluation and its selection process. The source of our data set is GitHub. We aimed to select real-world Java projects that compile, are widely used, and continuously maintained with a rich evolution history. To gather such data, we follow this process:

1. We first curated a list of software organizations that are present on GitHub. Among the organizations we selected are Apache, Google, QuarkusIO, AWS, Alibaba, Junit-team, Mockito, ReactiveX, Spring, Facebook, Bazel build, Jenkins, etc. To which we added other organizations that deliver known software, such as JavaParser, Netty, FasterXML, Jacoco, Qos, Inria.
2. To ensure that the software builds correctly, we focused on projects that use a build automation process that successfully passes. We selected Maven projects for this purpose. We also selected projects that support up to Java 14 included since it was imposed by the baseline tool to which we compare to.
3. We selected the most popular projects (based on their number of ‘stars’ on GitHub) and with more than one thousand commits. We finally reached 18 real-world and representative software projects: industrial and academic projects, small to very large-sized projects, monolithic and modular, and simple to complex projects.

Table 1 describes our curated final list of software projects.

### 4.3 Results

We empirically evaluate the key properties of the HyperAST. To do so, we can classify the properties in two categories. A property can either be objectively checked with a simple assertion, e.g., identity of parsing and re-serializing, or needs a comparison with an existing tool, e.g., for CPU/memory performance and finding references. We choose to compare the HyperAST against Spoon [38] as it is a well-known tool in the community, which is used to analyze and modify Java code. Thus, we observe differences of performances between Spoon and the HyperAST both in time and in memory for construction and finding references.

#### 4.3.1 RQ1

To answer RQ1 we implemented a serialization service to parse the code and pretty-printing it back to the file level. We can thus evaluate the sound incremental construction of the HyperAST with the following equivalence.

\[
\text{code} \equiv \text{prettyprint} (\text{parse} (\text{code}))
\]

Therefore, the goal is to show that the construction of the HyperAST is a sound transformation of the Git Merkle DAG and the code Blobs. To do that, we performed the above verification for each project using a set of Java file Blobs uniformly sampled from the Git object database.

On a total of 299,041 Java Blobs from all commits, the HyperAST was able to parse and to serialize 299,007 them back successfully with an exact equivalence. Thus, achieving 99.98% correctness. We looked at the remaining 34 Blobs and found that it was caused by Tree-Sitter: these Blobs contain errors in the code with missing tokens, which the Tree-Sitter parser corrected by adding the most likely tokens that respect the Java grammar rules. This feature of Tree-Sitter allows the HyperAST to analyze even erroneous code in contrast to existing tools.

Therefore, we can answer RQ1 positively. Ensuring the sound construction of the HyperAST is essential for code transformation purposes, such as patch application or code refactoring.

### Table 1: Data set characteristics.

<table>
<thead>
<tr>
<th>Projects</th>
<th>Java LOC</th>
<th>Java files</th>
<th>Commits</th>
<th>Contrib.</th>
<th>Stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apache Hadoop</td>
<td>1.63M</td>
<td>10.2k</td>
<td>25,749</td>
<td>435</td>
<td>12k</td>
</tr>
<tr>
<td>Apache Flink</td>
<td>1.5M</td>
<td>13.2k</td>
<td>30,587</td>
<td>1,037</td>
<td>1.8k</td>
</tr>
<tr>
<td>Netty</td>
<td>317k</td>
<td>2.78k</td>
<td>10,789</td>
<td>569</td>
<td>29k</td>
</tr>
<tr>
<td>AWS SDK Java v2</td>
<td>265k</td>
<td>3.15k</td>
<td>8,766</td>
<td>88</td>
<td>1.4k</td>
</tr>
<tr>
<td>Apache Dubbo</td>
<td>197k</td>
<td>2.81k</td>
<td>5,437</td>
<td>393</td>
<td>37k</td>
</tr>
<tr>
<td>Apache Log4j2</td>
<td>183k</td>
<td>2.32k</td>
<td>12,031</td>
<td>132</td>
<td>2.8k</td>
</tr>
<tr>
<td>Jenkins</td>
<td>181k</td>
<td>1.69k</td>
<td>32,252</td>
<td>701</td>
<td>19k</td>
</tr>
<tr>
<td>Javadaparser</td>
<td>179k</td>
<td>1.67k</td>
<td>8,031</td>
<td>166</td>
<td>4.1k</td>
</tr>
<tr>
<td>Inria Spoon</td>
<td>154k</td>
<td>2.06k</td>
<td>3,891</td>
<td>106</td>
<td>1.3k</td>
</tr>
<tr>
<td>Apache Maven</td>
<td>92.5k</td>
<td>1.05k</td>
<td>11,567</td>
<td>150</td>
<td>31k</td>
</tr>
<tr>
<td>Apache Spark</td>
<td>85.6k</td>
<td>1.06k</td>
<td>32,821</td>
<td>1,805</td>
<td>33k</td>
</tr>
<tr>
<td>Apache SkyWalking</td>
<td>84.7k</td>
<td>1.58k</td>
<td>7,022</td>
<td>397</td>
<td>1.9k</td>
</tr>
<tr>
<td>Jackson Core</td>
<td>52.3k</td>
<td>283</td>
<td>2,925</td>
<td>59</td>
<td>200</td>
</tr>
<tr>
<td>Alibaba Arthas</td>
<td>44.2k</td>
<td>586</td>
<td>1,726</td>
<td>155</td>
<td>29k</td>
</tr>
<tr>
<td>Jacoco</td>
<td>38.8k</td>
<td>633</td>
<td>1,749</td>
<td>46</td>
<td>3.2k</td>
</tr>
<tr>
<td>JUnit4</td>
<td>31.2k</td>
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<td>2,486</td>
<td>151</td>
<td>8.3k</td>
</tr>
<tr>
<td>Google gson</td>
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<td>212</td>
<td>1,850</td>
<td>124</td>
<td>21k</td>
</tr>
<tr>
<td>SLF4J</td>
<td>13.5k</td>
<td>256</td>
<td>1,956</td>
<td>61</td>
<td>1.9k</td>
</tr>
</tbody>
</table>

*RQ1 insights:* Results show the soundness of the HyperAST construction with 99.98% of correctness. It is a preserving transformation for correct code into the HyperAST. Erroneous code is slightly corrected at the token level in 0.02%.

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Figure 5: Megabytes of memory taken for each commit, legend: orange=spoon, blue=hyperAST, with total, x order-of-magnitude difference, and + gain. Note: we do the analysis starting from the last commit published corresponding to the commit n°0.

Figure 6: CPU time taken to construct each commit, legend: orange=spoon, blue=hyperAST, with total, x order-of-magnitude difference, and + gain. Note: we do the analysis starting from the last commit published corresponding to the commit n°0.

4.3.2 RQ2. This RQ investigates the difference between the HyperAST and traditional approaches in terms of memory footprint and execution time for building ASTs over versions. To do so, we selected the most recent thousand of commits in each project to analyze for a fair comparison between Spoon and the HyperAST. For the memory footprint, we measure the heap with and without the constructed structures, i.e., the HyperAST and the Spoon ASTs.

For construction time, we measure the time in CPU cycles from the start to the end of the construction.

With the HyperAST we use the Rust functions Instant::now() and Instant::elapsed().as.nanos() for time measurement and jemalloc library for memory measurement. With Spoon, we use the Java function System.nanoTime() for time measurement and the functions runtime.totalMemory() and runtime.freeMemory() for memory measurement.
Figures 5 and 6 give the measured memory footprint and the construction time for both Spoon and the HyperAST. Note that since we started by treating the latest commit in the history and went back in time to treat the other commits, the depicted figures show the results in that order of commits, i.e., left (0) being the most recent commit. Overall, the HyperAST outperforms Spoon.

We observe less memory footprint and less construction time for HyperAST than Spoon.

Regarding the memory footprint, the HyperAST outperforms Spoon in all projects, as shown in Figure 5. On minimum and maximum, respectively, the HyperAST consumed 63 MB in Jacoco and 7.5 GB in Hadoop of memory compared to 17 GB in Gson and 2.3 TB.
in Hadoop for Spoon. We observed the smallest and the biggest gains in memory footprint of +91.8 % and +99.9 %, respectively, in the Jenkins and Jacoco projects. The order-of-magnitude difference in memory footprint between the HyperAST and Spoon varied from $\times 12$ in Jenkins up to $\times 1159$ in Jacoco. Note that the sudden drop in the Spoon project is due to erroneous code in the commits that could not compile, whereas the HyperAST can still handle them thanks to the robustness and resilience of Tree-Sitter.

Regarding the construction time, we also observe benefits for the HyperAST over Spoon, as shown in Figure 6. The HyperAST outperforms Spoon for the analyzed projects. On minimum and maximum, respectively, the HyperAST took 1 min in Sil4j and 2 h and 22 min in Dubbo of construction time, compared to 1 h 14 min in Jacoco and 93 h 31 min in Flink for Spoon. We observed the smallest and the biggest gains in construction time of +83.4 % and +99.99 %, respectively, in the Jenkins and Jacoco. The order-of-magnitude difference in construction time between the HyperAST and Spoon varied from $\times 6$ in Jenkins up to $\times 8076$ in Jacoco. It is worth noting that the HyperAST outperforms Spoon even though we run it on a single CPU core (no parallelization) in contrast to Spoon with the JDT. Thus, we actually consumed less computing power per commit. Parallelization would improve the construction time i.e., latency, but, is left as future work.

Figures 5 and 6 confirm that the memory footprint and the construction time of the HyperAST is always paid initially and then are much lower for later commits. Therefore, the HyperAST depends on the code size only for the first commit and then only depends on the commit size, i.e., code changes. For Spoon, it is rather dependent on the code size as expected, where the larger the code is, the more memory and time it consumes to construct its AST.

Finally, we clearly see the issue of scalability with Spoon only on a thousand of commits. However, a thousand of commits did not stress test the HyperAST. To do so, we took the Hadoop project that showed to be the most costly to build, and we built the HyperAST on all its history of 25 749 commits. The measured memory footprint was 71 GB and the construction time was 18 h 21 min. Compared to Spoon with a thousand of commits, we are still outperforming it with gains of +72 % in construction time and +97.4 % in memory footprint. Resulting in an order-of-magnitude difference of $\times 3.6$ for construction time and $\times 38$ for memory footprint.

**RQ3 insights:** The HyperAST shows significant results in performance compared to Spoon. It provides scalability gains in memory footprint from +91.8 % to +99.9 % and in construction time from +83.4 % and +99.99 %. Some observation holds when the HyperAST takes all the 25 749 commits of Hadoop.

\[
\text{precision} = \frac{\text{ResolvedReferences} \cap \text{ExpectedReferences}}{\text{ResolvedReferences}}
\]
\[
\text{recall} = \frac{\text{ResolvedReferences} \cap \text{ExpectedReferences}}{\text{ExpectedReferences}}
\]

The comparison of references is not based on their labels, as this is not a guarantee of finding the same references. Rather, the comparison is based on the start and end characters in the code. This is a more restrictive comparison that further would discriminate our approach while increasing confidence in the results.

Figure 7 shows the different measured precision and recall in our case studies for the HyperAST. The measurements are per commit where the left (0) represent the most recent commit as we went back in time up to the thousand commit. We observed on average 90 % precision and 97 % recall. Precision ranged from 68.2 % to 98.2 % in Spoon and Sil4j projects, while recall ranged from 84.4 % to 99.7 % in Spoon and Jenkins projects. In the projects where precision was low, namely Spoon, Jacoco, and Junit4, we investigated the found references by the HyperAST and Spoon. We found that many discrepancies are due to minor shift in the start and end characters, mainly due to the inclusion of comments to the found references. However, other cases were due to an over-estimation of the HyperAST for possible shadowed or overridden references.

Figure 8 shows how the HyperAST compares to Spoon in terms of searching time to find all references. It shows that it is similar on average to Spoon for small-sized projects up to 180 k of LOC. We observe that our prototype of finding reference over preforms for medium-sized projects up to 300 k of LOC and it under performs for large-sized projects with millions of LOC. However, in the Hadoop and Flink projects, Spoon out performs the HyperAST by roughly 10 min per commit. Nonetheless, in contrast to Spoon that is only capable of calculating all references for all declarations at once, the HyperAST can calculate the references for a single declaration at a time whenever needed. Therefore, depending on the usage scenario, the HyperAST will outperform Spoon in case of finding references for some given declarations and not all of them.

**RQ3 insights:**
Results show the validity of finding references based on the HyperAST. We observed an average 90 % precision and 97 % recall without a significant difference in search time but a difference of 10 min in large-sized projects.

### 4.4 Discussion and implications

Our evaluation shows promising results at scaling the representation of the software history at the AST level. Hence, the HyperAST could be used as a basis to scale temporal code analysis. We have identified several use cases that could benefit from the HyperAST and that we will explore in future work.

**Use case #1:** The first practical use case that could benefit from the HyperAST are the syntactical code analyses that are performed in a batch way on the software history, i.e., sequentially repeated for every commit without requiring relations between those ASTs. For example, counting syntactical structures of individual files to compute the cyclomatic complexity of classes [1], or detect bad smells in Java files [19, 35, 48].
Use case #2: The second practical use case benefiting from the HyperAST are the semantic code analyses that are also performed in a batch way on the software history. For example resolving reference relations with compilers [38], or parsers with reference solvers [18, 42, 45] to provide goto functionalities and enable static impact analysis.

Use case #3: The third practical use case that would benefit from the HyperAST are the temporal code analyses linking and tracing code elements across history. For example, understand when a null pointer issue or a bad smell appeared in a commit [10], tracking the evolutions of a given method [15, 17], measuring the stability metric of a class [41] [14, 15, 17], or understanding the evolution of a method complexity [28], computing change- and error-proneness of a given code element [5].

Use case #4: The fourth practical use case that could benefit from the HyperAST are the temporal code analyses that investigate complex relationship between code evolutions. In particular, between impacting evolutions and repairing evolution. For example, studying when and how code and tests were co-evolved [25, 26] or identifying causes for bugs code repair [27, 32].

4.5 Threats to Validity

4.5.1 Internal validity. Considering performance measurements, we choose to measure CPU and memory consumption for each processed commit. Our goal was to show to what extent the HyperAST scales on complex real-world software with large histories while quantifying it per commit to observe the scalability tendencies. Measuring once for all commits would not have accurately reflected variations of analysis costs, as during development a software might change in quality, complexity and size. Measuring in finer grain than a commit, say for a module, a package or a class, may also be biased, as the measurements could overweight the actual processing cost itself. Thus, measuring performance per commit gives more confidence in the results.

Moreover, as spoon compiles the code, some commits could not be analyzed with Spoon. Whereas, we still were able to analyze them and insert them in the HyperAST thanks to the resilience of Tree-Sitter for ill-formed code. In addition, for the validity check with precision and recall, we had to select the commits that Spoon successfully compiled on which it computed the association tables. Thus, being able to compare the found references on both approaches. Our goal here was to show that the HyperAST can be used in a code analysis efficiently. However, we did not measure the effort of developing the service of finding references, as this was not the goal of the present contribution. Nonetheless, this is left for future work.

4.5.2 External validity. We implemented and evaluated the HyperAST approach for Java with maven build system. Our conclusions in theory could generalize to other programming languages with similar features than Java (e.g., strong static nominal typing). Nonetheless, further experimentation remains necessary on other languages to generalize our results. Note that Tree-sitter is able to support other languages (e.g., C, JavaScript). Thus, making the HyperAST extensible beyond Java by integrating the Tree-sitter grammars of other languages. However, the goal of this paper was not to support multiple languages but to show the scalability benefits provided by the HyperAST. Further experimenting with other languages is left for future work. Moreover, we relied on Spoon as a baseline, mainly due to its popularity as a frontend to the Java development tools (JDT). Hence, we cannot generalize the observed benefit of the HyperAST compared to Spoon for other AST toolings, such as Javaparser as it also resolves the references. This is left for future work to enhance the comparison results.

Finally, the HyperAST considers Git histories. As discussed in Section 2.2, the HyperAST can operate on any snapshot-based history similar to Git. For the other cases (e.g. SVN), a classical technique consists in converting a repository to Git similarly as Software Heritage [12] initiative does before archiving repositories.

4.5.3 Conclusion validity. Our evaluation gave promising results, showing that the HyperAST allows to save a lot, respectively, with an order-of-magnitude difference from 6 up to 872 in construction time and from 12 up to 1158 in memory footprint. The evaluation results also showed providing a reliable service for finding references with an average precision and recall respectively of 90% and 97%. Even though we evaluated it on 18 projects, we plan further evaluation is needed on more projects to have more insights and statistical evidence. Yet, our curated list of projects represents real-world complex software with very large histories.

5 RELATED WORK

Multiple approaches aim to perform temporal code analysis, but face scalability issues. Sousa et al. [44] proposed to detect multiple interrelated refactorings, called composite refactorings between $v_i$ and $v_{i+1}$. They consist in detecting smells in version $v_i$. However, to do so, they had to run through the commits to find the bad smells, then to run again to find refactorings before linking them.

Cedrim et al. [7] similarly proposed to understand the impact of refactorings on bad smells. Thus, detecting refactorings in $v_{i+j}$ and bad smells in version $v_i$. Thus, both [7, 44] having several ASTs for the studied commits, which limits the scalability of their studies.

Pantiuchina et al. [37] illustrate this challenge explicitly. They quoted several points: "the choice of selecting a subset of the 303 projects was dictated by the computationally expensive data extraction process adopted in our study". and "This process took three months on a 56-core server". "we computed 42 product- and process-metrics (e.g., code quality metrics, change-proneness of classes) for each of the 213 102 commits in the studied projects."

The HyperAST aims to be as support for scaling, especially by reducing redundancy and reusing computed results for parts of the code that do not change across commits.

Moreover, Kim and Notkin [20] surveyed matching approaches of code elements that can be used for multi-version program analyses. With the HyperAST, this is partially done by construction where the same nodes are shared across versions. For the changed parts of the code, a matching per sub-tree can be applied, hence, only computing the matching on the changed parts of the code across versions.
Larose et al. [24] proposed to merge AST nodes into supernodes to speed up the run-time performance of Truffle-based interpreters [50] in GraalVM. The idea behind is to reuse similar nodes in behavior and in a single version. Protzenko et al. [40] also proposed to merge the ASTs for the purpose of real-time collaboration. However, both [24, 40] reason on the space dimension of the AST and not on the time dimension. In the HyperAST we reuse structurally similar AST nodes and across versions.

Code analysis tools (use case #2 in section 4.4) such as Spoon and JavaParser propose to build the AST and to resolve the references with association tables. GitHub also developed tools, in particular related to our work Semantic [42] and Stack-graphs [45]. The former relies on Tree-sitter to parse the code and resolve the AST symbols for code navigation. The latter is inspired from Scope Graphs [21, 22, 49] to resolve name bindings necessary for resolving references of declarations. The HyperAST proposes the same (i.e., parsing and resolving references) but with a different strategy based on an oracle and bloom filters while taking advantage of the structure of the HyperAST.

Furthermore, Boldi et al. [6] proposed to compress the archive of Software Heritage [13]. However, they do it only on the file structure without considering the content and for storage purposes of the archive. Hartel et al. [16] used incrementazation theory to incrementalize the processing of repository resources and artefacts. Grund et al. [15] proposed an approach to track changes at the method level across time. Higo et al. [17] also proposed an approach to track methods changes based on Git. All [15–17] (use case #3 in section 4.4) are complementary to our approach as they can be implemented as strategy on top of the HyperAST.

One similar approach to the HyperAST aimed at improving temporal analysis by making use of the temporal coherency of revisions. Alexandru et al. [1] proposed an approach called LISA. It is a graph oriented database that relies on a vertex compression algorithm to share AST nodes among revisions, where structural relations between AST nodes are constrained by ranges of revisions [1]. Compared to the HyperAST, LISA misses a large reduction of redundant computation as metadata because it does not support sharing identical code subtrees independently of their position. In addition, Alexandru et al. [1] only discusses LISA in the context of the computation of syntactical metrics, such as cyclomatic complexity (use case #1 in section 4.4). Whereas we present a semantic analysis (i.e. resolution of references and declarations needed for impact analysis) that is more challenging to compute.

To the best of our knowledge, the HyperAST is the first approach to propose an AST that lives with the evolution history of a software. This was possible based on the redundancy both in space between AST elements and in time between versions.

6 CONCLUSION

This paper proposes a novel type of AST, namely the HyperAST that permits temporal analyses to scale across large code histories. The evaluation on 18 large projects shows that we were able to scale with thousands of commits with an order-of-magnitude difference between the HyperAST and Spoon, from x6 up to x8076 in construction time and from x12 up to x1159 in memory footprint. While the HyperAST requires up to 2 h 22 min and 7.2 GB for the biggest project, Spoon requires up to 93h and 31 min 2.2 TB. The gains in construction time varied from +83.4 % to +99.9 % and the gains in memory footprint varied from +91.8 % to +99.9 %. These benefits and gains were also observed when we built the HyperAST on the whole 25 749 commits history of the Hadoop project in contrast to only a thousand of commits with Spoon. We further compared the task of finding references of declarations with the HyperAST and Spoon. We observed on average 90 % precision and 97 % recall without a significant difference in search time.

As future work, we first plan to enlarge the scope of the HyperAST to other languages by integrating more grammars from Tree-Sitter. We will revisit existing approaches discussed in section 4.4 on top of the HyperAST. Finally, we will explore the possibility to offer an engine capable of running a temporal analysis taken as a query to be executed on the HyperAST. Thus, facilitating its usage by a wider audience.

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