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Using the Uniqueness of Global Identifiers to Determine the Provenance of Python Software Source Code

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Abstract We consider the problem of identifying the provenance of free/open source software (FOSS) and specifically the need of identifying where reused source code has been copied from. We propose a lightweight approach to solve the problem based on software identifiers—such as the names of variables, classes, and functions chosen by programmers. The proposed approach is able to efficiently narrow down to a small set of candidate origin products, to be further analyzed with more expensive techniques to make a final provenance determination.

By analyzing the PyPI (Python Packaging Index) open source ecosystem we find that globally defined identifiers are very distinct. Across PyPI's 244 K packages we found 11.2 M different global identifiers (classes and method/function names—with only 0.6% of identifiers shared among the two types of entities); 76% of identifiers were used only in one package, and 93% in at most 3. Randomly selecting 3 non-frequent global identifiers from an input product is enough to narrow down its origins to a maximum of 3 products within 89% of the cases.

We validate the proposed approach by mapping Debian source packages implemented in Python to the corresponding PyPI packages; this approach uses at most five trials, where each trial uses three randomly chosen global identifiers from a randomly chosen python file of the subject software package, then ranks results using a popularity index and requires to inspect only the top

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result. In our experiments, this method is effective at finding the true origin of a project with a recall of 0.9 and precision of 0.77.

Keywords software provenance, source code tracking, identifiers, open source software, python

1 Introduction

In modern software development, applications are rarely built from scratch. Rather, software is for the most part [45,50] built reusing existing free/open source software (FOSS) components, mixing in varying amounts of custom in-house code. A 2014 survey claims that at least 75% of organizations rely on open source as the foundation of their applications [45]; a 2020 analysis [50] by an industry player in the field of mergers and acquisitions reports that 99% of audited code bases contain FOSS components, with 70% of all audited code being itself open source software.

In terms of development practices, reuse of open source code happens in different forms: from retrieving and integrating entire FOSS components (also known as “software vendoring” [54]), to simply copying chunks of publicly accessible code and pasting them into the source code files of the software under development. While useful for speeding up development and believed to have benefits on code quality, coding efficiency, and maintenance [18], FOSS code reuse requires proper management of the software supply chain to avoid nefarious side-effects [22]. From a security perspective, for example, operation engineers will need to monitor the status of all software components deployed in production and keep them updated when newer versions that fix security flaws are released. As a matter of concern, 88% of applications audited in the previously mentioned study contained open source dependencies that underwent no development activity over the two previous years [50].

From a legal point of view, when the source code of an application made available to end-users contains parts copied from other FOSS components, the software distributor is responsible to ensure that all involved licenses (open source or otherwise) are mutually compatible and consistent with the applicable end-user software license [40]. Short of that, the distributor might incur significant legal and financial risks due to potential copyright violations.

The state-of-the-art approach to minimize both security and legal risks related to the reuse of FOSS components is based on a set of practices and tools that are plugged into the software build process [38], e.g., as part of continuous integration (CI) pipelines. The software being built is automatically analyzed to determine what are the main software components it contains—a process known as Software Composition Analysis, or SCA [35]—which results in the production of a Software Bill of Material, or SBOM [48]. Then, licensing and security information about each identified component are retrieved and verified for adherence to custom in-house policies, failing the build and triggering further audits or decisions when necessary.

A key ingredient of these pipelines is the ability to **identify where the source code being built comes from**, that is, **determine the provenance of software source code artifacts** at various granularities: entire source code trees, individual source code files, brief code snippets. A failure in identifying the provenance of source code can result in overlooking relevant information about security or licensing issues, with potentially severe consequences. In addition to this *correctness* requirement, and due to the need of deploying provenance tracking solutions as part of automated workflows, lookup *efficiency* is often a key factor in deciding whether an approach is practically usable or not.

Several techniques are available today to determine the provenance of source code artifacts. However, searching for the occurrence of an entity in vast bodies of open source code remains challenging. For instance, applying conventional clone detection methods such as text-based comparison and AST matching is computationally expensive and quickly becomes impractical. Conversely, methods based on exact file matching, e.g., based on cryptographic hashes, will fail to identify relevant software origins when even very minor file changes are applied. A satisfactory software provenance identification technique should be fast, scalable, and capable of finding matches even in the presence of some code changes, in order to be practically useful.

Contributions. In this paper **we propose a lightweight approach to determine the provenance of source code artifacts based on the uniqueness of identifiers**—i.e., the names chosen by developers to reference common programming abstractions like variables, data types, classes, methods, etc. We aim to show that, by first *indexing* the set of identifiers found in a large corpus of open source software components, and then *querying* the index using as input the identifiers found in a given source component of unknown origin, it is both practically possible and efficient to determine its provenance (within the corpus). Specifically, we consider the software ecosystem consisting of open source Python packages available from the Python Package Index (PyPI)¹, for a total of 244 thousand packages as of March 2021.

As foundational empirical evidence to validate the proposed approach we will first answer the research question:

RQ1 How frequent are global identifiers among open source Python packages?

We will answer this question at package level. We define the *frequency* of an identifier as the number of software products (or “packages”, according to PyPI terminology) that define such identifier within a given corpus. More generally we will characterize the distribution of global identifier popularity. We find that global identifiers declared by programmers tend to be unique. About 76% of class and function names uniquely identify a software product among the 244 K packages in our corpus (have frequency equal to 1); and that up to 93% of them are found in at most 3 different packages (frequency 3). This

¹ <https://pypi.org/>, accessed 2021-11-15

characteristic makes identifiers ideal candidates to base software provenance methods upon.

However, in some cases a given identifier will not be enough to *uniquely* identify the origin software product. Hence, to explore the practical applicability of the proposed approach as a basis for provenance detection, we will answer the research question:

RQ2 How many global identifiers are needed to *narrow down* the origin of a given source code artifact to a small set of candidates, within the open source Python ecosystem?

Based on the answer to this question we can leverage the proposed approach to efficiently reduce the search space from all the software products in the corpus to a handful of candidates (and then potentially apply more expensive methods—such as clone detection techniques—to find the final result). We explore this answer at different granularities, from individual files up to entire packages, as well as different methods for choosing the identifiers to query starting from the input source artifact. We find that on average it is enough to chose 3 *non-frequent* (within the corpus) global identifiers from a given source code file to narrow down the software origin to no more than 3 products with 89% probability.

As our last contribution we validate the practical usefulness of the proposed approach by using it to determine the origin of Python packages shipped by the Debian GNU/Linux distribution. By independent means (not based on identifiers) we establish a ground truth correspondence between 2181 packages included in the Debian Buster release and the PyPI packages they originate from. We then first use the proposed approach to narrow down candidate origins for each Debian package, and then rank candidates by pertinence using SourceRank [43]. We find that this approach returns the correct origin as the first candidate with a recall of 0.7 and precision of 0.8 when using 3 identifiers from only one file, and a recall of 0.8 and precision of 0.9 when using 3 identifiers from 3 different files. Furthermore, by repeating the search at most 5 times, and only inspecting the top result in each search, the recall improves to 0.9 with a precision of 0.77.

Paper structure. We review related work in Section 2. Section 3 details the conceptual model of software provenance that underpins the approach proposed in this paper. The main body of empirical work is presented in Sections 4 to 6: Section 4 establishes the uniqueness of identifiers in the studied PyPI corpus (RQ1), Section 5 measures how many identifiers are needed to narrow down the set of candidate product origins (RQ2), and Section 6 validates the approach by identifying the PyPI origin of Debian Python packages. We discuss obtained empirical results in Section 7, including threats to their validity. We conclude in Section 8, where we also suggest directions for future work.

2 Related work

Several bodies of work in the literature use identifier-based approaches to determine software provenance. In this section we compare and contrast them with the approach proposed in this paper.

2.1 Software provenance

The term *provenance* denotes a body of evidence used to establish what is the origin and the history of a development of an artifact of any kind. In the specific context of software development, stakeholders often wish to know how a (software) artifact came to occur, where it originated from, its evolution, and where it moves to over time [19, 41]. The exponential increase of available free and open source software (FOSS) has led to the prevalence of code reuse which in turn has made software provenance an increasingly relevant concern in software development. However, provenance recovery has received relatively little attention in software engineering research, with few exceptions that we discuss below.

In its most basic definition, the provenance of a software artifact is the location, within a reference corpus, where the artifact can be found. Godfrey [19] enumerates three common challenges that have to be faced to fully address this problem: definition of the scope and type of artifacts one wants to track, the gap between identified provenance and ground truth, and the need of scaling up provenance identification algorithms to large data sets. With respect to this checklist, in the present study we identify the provenance of (Python) source code entities at various granularities (package, version, file), sampling identifiers (class and function names) contained in the entity itself and matching them against a large-scale identifier-to-entity corpus. Our base lookup runtime complexity is logarithmic ($O(\log(n))$)—using standard database indexing technology—allowing to scale to large corpora. Also, to the best of our knowledge, this is the first study of software provenance recovery that uses a small subset of identifiers extracted from the software under audit.

Our approach is a practical instantiation of the Bertillonage framework introduced by Davies et al. [12, 13] and Godfrey [19]. The principle of Bertillonage is using computationally inexpensive techniques to narrow down the provenance search space and then applying more expensive approaches like manual determination or clone detection algorithms. With the present work we establish empirically that identifier-based search is a viable approach, both in terms of correctness and efficiency, for the first part (narrowing down) of Bertillonage, without restricting the design space for the second part.

For software artifacts implemented in Java, Davies et al. [12, 13] also adopted the Bertillonage framework to identify the origin of `.jar` bundles within a large Java source code corpus, Maven2. As indexing keys they used anchored class signatures, consisting of the class and method names in a class file. By searching for all signatures of a given package in a signature corpus, they recovered

the set of packages with the highest similarity with the queried one. We show in this paper that comparable results can be obtained using significantly less information (a few identifiers only, instead of all signatures in the package). Moreover, our approach is more flexible as it can match at different artifact granularities (packages, versions, files).

Other linked problems in the area of software provenance are addressed in the literature. For example, Godfrey et al. [20] proposed to use identifiers as a way to identify functions that have been either merged or split across different versions of the same software. Di Penta et al. [15] proposed a code-search approach, using filenames and class names, to identify software licenses. Ossher et al. [36] analyzed file-level clones in open source Java projects using several trivial methods: exact file matching, filename matching, identifier name fingerprint matching, and directory matching.

Rousseau et al. [41] introduced a compact storage model that allows to capture the provenance information of source code files in commits, and commits in software repositories, at the scale of the Software Heritage archive [10, 39], which is the largest public archive of software source code (≈ 10 billion files). Their approach is at much larger scale than what we experimented with for this paper, but the supported granularity is different. Also, identifier-based search is robust against file changes (as long as identifiers remain unmodified), whereas any file change makes files no longer recognizable within Software Heritage due to the use of strong cryptographic hashes as artifact identifiers.

Data model, ontologies, and document standards for capturing provenance in a broader context than software (but with applications *to* software artifacts) have also been developed [33, 32, 6, 31], together with accompanying tools [11], and techniques [30, 52]. For software, Bose [4] recently proposed a blockchain-enabled framework based on a standard model to manage provenance data at granularities ranging from releases to individual source files.

2.2 Code clone detection

In the architectural view advocated by this paper, code clone detection is useful to *precisely* pinpoint the origin of an artifact, *after* a small set of candidates has been obtained using identifier-based narrowing down. Since applicable code clone detection techniques abound, rather than detailing all possibilities we refer the reader to consolidated surveys in the field [21, 17, 46, 42].

The most relevant code clone detection approaches for our work are token-based approaches, since we also rely on source code lexical tokens (identifiers). In these approaches source code is first tokenized, then tokens are scanned to identify code clones [25], e.g., by relying on sub-sequence similarity. One of the major challenges of using these clone detection techniques for provenance identification is that they are prone to false positives.

CCFinder [24] is a multilingual token-based code clone detection system. The lexical analyzer processes a source file producing a stream of token, in which all identifiers are normalized to a special token. Then, a suffix tree

matching algorithm is used to find similar token sub-sequences. CP-Miner [27] is CCFinder successor and searches for copy-pasted code blocks and copy-paste-related bugs. To that end CP-Miner uses a threshold to detect code similarity as a percentage of unchanged identifiers. Yang et al. [53] created Boreas, an accurate and scalable token-based code clone detection tool, which introduced a metric-based system to capture identifiable characteristics of program segments.

Gabel et al. [16] conducted one of the first studies on source code uniqueness. They used a token-based approach for finding cloned fragments within a corpus. They defined the uniqueness of a unit of source code within the corpus as the degree to which each project can be “assembled” solely from portions of the corpus. They asked research questions similar to ours including: “at which granularity is software unique?” and “at a given granularity, how unique is software?”. In their study, the possible granularities are defined in terms of the length of considered token sequences rather than logical units (package, version, file, snippet) as we do. Perez et al. [37] proposed tree-based machine learning approach to detect cross-language clones, preserving identifier names in their abstract syntax trees.

A particularly relevant approach (and accompanying tool) for detecting code clones is SourcererCC [44], which was introduced to scale code clone detection to large code repositories—25 K projects for a total of 250 MLOC in the original experimental evaluation. On the one hand, SourcererCC follows an approach similar to ours, in particular it relies on an external code index based on tokens extracted from code, but it addresses a different (and more complex) problem than ours: identifying all code clone *pairs*, in the code base under analysis, e.g., to inform and support large-scale code refactoring. On the other hand we consider our code index to be a trusted knowledge base or preexisting open source code and use it to find where (if at all) code in the code base under audit comes from. At the code clone detection problem SourcererCC outperforms, in terms of scalability, all competitors at the time, losing in accuracy only to NiCad [9]. We did not conduct a comparative benchmark to any of those tools, because we solve a different problem. We observe that in terms of ballpark lookup times we outperform SourcererCC—our lookups are almost instantaneous and building the index takes hours rather than days—but that is not a fair benchmark due to the difference in the addressed problem.

Other differences w.r.t. our approach and SourcererCC are worth noting. First, SourcererCC uses as tokens almost all code lexemes, including language keywords, whereas we only considered identifiers. Given the effectiveness we notice in our experiments it would be worth trying to use only identifiers also in the case of SourcererCC, to further speed up clone detection. It is unclear however how doing so would impact accuracy. Relying only on identifiers could also make SourcererCC more robust and language-agnostic, because identifier extraction is something that could be performed without having to fully parse (or even just lex) source code, as developer tools like Ctags² do.

² <http://ctags.sourceforge.net/>, retrieved 2022-09-22

Second, SourcererCC relies on a bag-of-words (multiset) representation, whereas we limit ourselves to the single presence/absence of identifier tokens (set), not *counting* how many of each of them are encountered. Furthermore, SourcererCC use token frequency as a natural ordering of tokens as the basis for its heuristic for reducing the number of clone pair candidates to consider. Having to solve a simpler problem we did not need to resort to multiset representations to achieve good accuracy results. Exploring whether they could become even better using a bag-of-words representation remains to be explored as future work.

SourcererCC stands out w.r.t. most of its competitors due to its ability to handle Type-3 clones, where cloned fragments might have been modified upon reuse. By construction our approach deals well with detecting the provenance of code reused and subjected to Type-3 changes, as long as the modifications do not affect function and class identifiers (this is generally the case, due to the fact that those identifiers constitute APIs/ABIs which could induce breakages on unrelated software components, and renaming identifiers in a system is an expensive and potentially buggy operation); there are, however, exceptions (e.g., in the case of plagiarism where malicious actors actively try to avoid provenance/clone detection).

Finally, we would like to stress that SourcererCC (and other clone detection methods) and our approach are complementary. Once the corpus has been created, our approach can be used to find a small set of potential candidates (true origin or copies of the subject system being analyzed) in a matter of seconds; at this point, a clone detector can be used between the potential candidates and the subject to properly identify the origin of the subject, thus reducing the computational requirements of the clone detection analysis.

2.3 Identifier names

Finally, we review research findings on identifier names, independently from their use in connection with software provenance. Although not strictly relevant for our use case, this body of work sheds light on certain characteristics of identifiers, such as their distinctiveness, that can inform the design of identifier-based solutions for software provenance.

Deissenboeck and Pizka [14] observed that identifier tokens account for approximately 33% of the tokens and 72% of the characters in the source code of Eclipse, making identifiers a quantitatively relevant part of the informative code of source code. Caprile and Tonella agree [8], further claiming that identifier names are one of the most important sources of information about program entities. Interestingly, back in the 90's Sneed [47] conversely found that “in many legacy systems, procedures and data are named arbitrarily [...] programmers often choose to name procedures after their girlfriends or favorite sportsmen”.

A more convincing explanation for the distinctiveness of identifiers comes from the fact that, with a very high probability, different programmers would

name the same entity differently, as Butler et al. [5]: “the probability of having two people apply the same name to an object (in general not just in code) is between 7 and 18%, depending on the object”.

It is also commonly believed that the quality of identifier names has high correlation with software quality. For example, Binkley et al. [3] stated that identifier names are at the core of program comprehension, and the style of identifiers (e.g., abbreviation and camelCase) has a tremendous impact on program understanding, quality, and development cost. Similarly, Lawrie et al. [26] showed that both actual words and abbreviations in identifiers lead to better program comprehension, while excessively long identifiers overload short-term memory and negatively impact program comprehension, therefore a balance between information content and recall ability in identifiers is required. Yet, Hofmeister et al. [23] found that shorter identifier names take longer to comprehend, and that using words as identifier names helps to improve software quality and save costs.

Deissenboeck and Pizka [14] also proposed rules for consistent and concise identifier naming by curating an identifier dictionary during software development. Along similar lines, recent studies have shown how to manage identifier naming with automatic approaches. For example, Arnaoudova et al. [1] conducted empirical research on the programmer activity of renaming identifiers and developed a tool to automatically document, detect and apply renames in source code. Similarly, Warintarawej et al. [51] proposed an approach to automatically classify software identifiers.

Nguyen et al. [34] proposed MNire, a machine learning approach to check the consistency between the name of a given Java method and its implementation. They also looked into the distinctiveness of method names, discovering that in a selected set of high-quality Java open source projects 62.9% of method names are unique, 35.9% of them can be tokenized into separate words, and 78.1% of obtained tokens are shared among method names. We conjecture that the difference between the distinctiveness of Java method names and Python function names is due to primarily the size difference of the corpora (their Java dataset includes only 14K products, while our PyPI dataset includes 244K) since the probability of a collision of names is significantly impacted by the size of the population.

Identifiers, and specifically *public* identifiers that appear in exported functions and classes like the ones we use in the present work, can also be leveraged to improve code search results. Exemplar [29] is a seminal approach on this, translating developer searches expressed in natural language into API documentation searches (e.g., docstrings) and then searching a code corpus indexed by public identifiers. The indexing approach is analogous to what we use in this paper, but the problem solved very different: we aim at detecting where code at hand comes from and we do not use as input natural language queries, but directly the source code under audit instead.

In previous work by two of the authors [7], a large open dataset of identifiers was produced, by mining using Ctags (the same tool used in this paper) the entire source code of historical releases of the Debian distribution. It is a

larger and more diverse dataset of the one produced in this paper, but no distinctiveness analyses were conducted at the time.

3 Conceptual model

We briefly describe our provenance recovery approach as: given a source code entity whose provenance one wants to identify (the *subject*), we sample some of the global identifiers contained in the entity, match them against a *corpus* (a curated collection of software artifacts), and return a small set of entities that also contain all of the sampled identifiers. Common types of source code entities that we will consider in the following are: individual source code files, entire source code products (or “packages”, e.g., Apache Spark, which is released multiple times over time), and product releases (e.g., Apache Spark 3.0, containing several source code files). We will refer to the set of source code entities returned by a provenance recovery mechanism as the *candidates*. Ideally the *subject* should be in the set of *candidates*, (and this set be of size of one, ie. containing the subject and the candidate be the same).

3.1 Uniqueness of global identifiers

Any provenance discovery requires a reference *corpus*. A *corpus* is a collection of software entities that is curated (harvested, preprocessed and cleaned-up) to serve as a reference for provenance discovery. Finding the origin of a software entity (the *subject*) means finding the entity in the *corpus* from which the *subject* was copied from.³

A *corpus* can be created by scanning and downloading the source code of products from any repository from which there is some confidence that the product comes from its true creator/maintainer. For example, a *corpus* can be created from version control repositories (such as GitHub and GitLab), or from repositories of components used for dependency management (as long as they include source code, such as Maven Central, NPM, PyPI, CRAN, etc). Ideally a repository should be as comprehensive as possible.

To be able to precisely assert that a *subject* entity is a copy of a specific *candidate* entity in the *corpus* would require having information that documents how the *subject* entity was copied from the corresponding *candidate* entity in the *corpus*. Even if this was possible, there will still be instances where identical entities might have been created independently of each other (for example, the identifier `main` is created in every single C program, sometimes it might be a copy from another program, sometimes it will be typed in—created from scratch—by the programmer). Thus a given *subject* entity might have different potential matches (*candidates* entities).

³ Note that this copy might not have been done directly from the corpus; it is, however, a copy of the same entity that exists in the corpus.

Another aspect to consider when designing the *corpus* is how the location of the *candidate* is reported. Software entities exist in a hierarchical structure (recursively, an entity is composed of other entities). If there is a match for a given *subject* entity in the *corpus*, this result can be reported at any level of containment. For example, if the *corpus* was built from releases of products, the *candidates*' location can be reported as: the product (e.g., Apache Spark), a release of the component (Apache Spark 3.0) a file in a specific release, and even the specific location in the source code file where entity is defined. If the *corpus* was built from version control systems, it can be reported as a URL of the GitHub repository, as a revision/tag in this repository and a specific file in a specific revision.

In the context of this research, we are concerned with matching source code global identifiers defined inside an entity (e.g., software product, one of its releases, or one of the files in one of its releases). We use the notation $Defs(e)$ to denote the set of identifiers defined in the entity e , where e can be a product P , a release R or a file F . This function is computed taking into consideration the containment relationship of the entities. For instance, the identifiers defined in a product are the union of the identifiers in its releases:

$$Defs(P) = \bigcup_{R_i \in P} Defs(R_i)$$

and the identifiers in a release are the union of the identifiers of its files:

$$Defs(R) = \bigcup_{F_i \in R} Defs(F_i)$$

A *corpus* is created by defining the entity of interest (in particular, for the purpose of this research, an entity is the set of all releases of a software product). Such entity corresponds to a *document* in the information retrieval nomenclature[28], thus, an identifier id is in a document e (entity e) iff $id \in Defs(e)$. Thus, in this research, the document frequency of an identifier in the *corpus* is the number of software products in the *corpus* in which the identifier is defined.

For the sake of readability, in the rest of this document, we will refer to the document frequency of an identifier as the frequency of such identifier (within a given *corpus*).

4 On the uniqueness of identifiers

The first research question we address is:

RQ1 How frequent are global identifiers among open source Python packages?

For the purpose of provenance and origin analysis, we only consider global identifiers. That is, identifiers that can either be referenced from other programs, or that identify entities that could potentially be copy-pasted to other software.

We have chosen Python for our empirical experiments, and more specifically PyPI (the Python Package Index) for several reasons. First, Python is one of the most popular programming languages today with an active and vibrant ecosystem. Second, PyPI is an authoritative index of Python products and as such, it can be considered the canonical directory of most Python projects.⁴ And third, it is comprehensive: as of Sept. 2021, PyPI lists 331 K Python projects and 2.9 M releases of them.

The Python language does not have access modifiers; all identifiers defined at the top-level are publicly available (this is in contrast to languages like Java and C where the programmer can decide if an identifier is public, private or protected). We build our corpus with global functions and global classes (and their methods) as they are the most likely types of identifiers that are referenced (both internally within a product, and across products). For the rest of this paper, we will use the term *function* to refer to both functions or methods. We use identifiers that are *not qualified* by the class (in the case of methods) or module they belong to. In Python filenames correspond to names in the module hierarchy—e.g., a file named `foo.py` can be imported as `import foo`—the (path-less) name of a source code file is another identifier that can be used for provenance discovery.

Most Python products have many releases, and most of their identifiers will appear in multiple releases. For the purpose of answering RQ1, we will focus on identifying the *product* where identifiers are defined in, rather than the specific *releases* of such products. With respect to the conceptual model of Section 3, the scope of an entity will be a product, a document is a product, and the document frequency of an identifier corresponds to the number of PyPI products in which such identifier is defined (in at least one release).

4.1 Methodology

Our methodology for answering RQ1 consists of three main steps:

1. **Source code retrieval:** Crawling and downloading each release of every package in PyPI
2. **Identifier extraction:** For each package: extract all the identifiers defined in all its releases
3. **Frequency measurement:** Measure the frequency of every identifier found, at product granularity

We further detail each step below.

4.1.1 Source code retrieval

We performed the source code retrieval on August 20, 2020, using the following method:

⁴ Projects do not reside in PyPI, but PyPI links to their actual location.

Table 1 Descriptive statistics of PyPI products and their releases

# products:	244 084
# releases:	1 831 172
# products with only 1 release:	69 306 (28.4%)
# products with more than 100 releases:	1 451 (0.6%)
# products without Python source files:	13 739 (5.6%)
	Median / Mean / Stdev
# releases per product:	3 / 7.5 / 13.0
# files per release:	6 / 24.9 / 137.7
# files:	45 239 359
# different base filenames:	1 117 588

First, we retrieved the list of products with PyPI-simple (the official PyPI API).⁵ PyPI-simple returned 244 084 products (same as the number displayed on <https://pypi.org>) with a total of 1.83 million releases.

Next, for each product we downloaded its metadata and list of releases (using PyPI JSON’s API⁶). Some products had been retired and had no further information available on PyPI, other were not associated to any downloadable files; in total 13 379 products did not contribute any downloaded release to our corpus for these reasons.

The next step was to download, for each of the products, their releases. We observed that most products had few releases (the median number of releases per product was 7.5, with a standard deviation of 13). However, few products had an unusually high number of releases (for example, *CCXT*, a real-time cryptocurrency trading library, had over 7400 releases in 3 years). For this reason we decided to only download the 100 most recent releases of a product. Only 0.6% of products had more than 100 releases.

To download a release we retrieved one of its source distribution archive files (PyPI `package_type = "sdist"`). These types of files contain the complete source code of the release. A release can be offered in several formats, all with the same contents (such as `.zip`, `.bz2`, `.tgz`, etc.); therefore, we downloaded the first one that was listed. If the release did not provide a source distribution, we downloaded one of the binary distribution files (`package_type = "bdist_wheel"` or `"bdist_egg"`). Being Python an interpreted languages, “binary” distributions can still contain Python source code files, but only those source files necessary to run the software; it is likely that they do not contain certain types of files, such as those used during testing or building. We ignored 132 releases that did not have source distributions nor binary distributions, but only installer files such as `.exe` and `.rpm`. 17 products did not include any files for download. Table 1 summarizes results of this step.

The downloaded compressed releases occupied 1.6 TBytes of disk space.

⁵ <https://pypi.org/project/pypi-simple/>, accessed 2021-10-25

⁶ <https://warehouse.pypa.io/api-reference/json.html>, accessed 2021-10-25

Table 2 Descriptive statistics for the identifier corpus. All numbers correspond to unique names.

# class names:	2 665 927
# function names:	8 598 979
# filenames:	1 117 588
	Median / Mean / Stdev
# function names per product:	21 / 92.0 / 471.8
# function names per release:	40 / 155.0 / 629.5
# class names per product:	6 / 29.1 / 184.3
# class names per release:	10 / 46.3 / 210.6
# filenames per product:	4 / 12.81 / 65.6

4.1.2 Identifier extraction

We used `Universal Ctags`⁷ to extract class and function identifiers from Python source code. We did not transform the identifiers in any way (we did not normalize capitalization, nor split compound tokens in `CamelCase` or `snake_case` conventions).

For each release, we uncompressed its files into a temporary directory and ran `ctags` recursively on all files of the release with extension `.py` (case insensitive). We discarded all identifiers except classes (type `class` in `ctags` results) and functions (types `function` and `member`). For filenames, we discarded their path. For each identifier we recorded a tuple $\langle \text{product name}, \text{identifier name}, \text{identifier type} \rangle$ in a `sqlite3` database. Our database is 66 Gbytes (including indexes).

We identified that 13 739 products (5.6%) did not include any Python files, and therefore did not contribute any identifiers to our corpus. Many of these products were written in languages other than Python.

Table 2 summarizes the main statistics of the extracted identifiers. We found 2.6 million different class names, 8.6 million function names, and 1.1 million different filenames in the PyPI corpus. As it can be seen, most products have very few filenames (median 4 different filenames), and define a relatively small number of identifiers (median: 6 different class names and 21 different functions names).

Using a SQLite database, for each identifier (function, class or filename), we computed its distinctiveness (the number of different products where it was found).

4.2 Results

4.2.1 Frequency measurement

Table 3 summarizes the results for each type of identifier. 75.8% of class names, 76.7% of function names, and 79.3% of filenames exist in only one product.

⁷ <https://ctags.io/>, accessed 2021-10-25. Universal Ctags 0.0.0 (2015) derived from Exuberant Ctags 5.8.

Table 3 Distribution of frequency of identifiers at product level

frequency	Class names			Function names			Filenames		
	# Idents	Prop (%)	Cum (%)	# Idents	Prop (%)	Cum (%)	# Filenames	Prop (%)	Cum (%)
1	2 020 027	75.8	75.8	6 595 770	76.7	76.7	886 236	79.3	79.3
2	343 195	12.8	88.6	1 048 985	12.2	88.9	122 929	11.0	90.3
3	117 016	4.4	93.0	335 572	3.9	92.8	43 064	3.9	94.2
4	52 326	2.0	95.0	164 056	1.9	94.7	17 234	1.5	95.7
5	30 224	1.1	96.1	101 079	1.2	95.9	10 038	0.9	96.6
6	20 528	0.8	96.9	60 735	0.7	96.6	6 458	0.6	97.2
7	12 829	0.5	97.4	44 863	0.5	97.1	4 638	0.4	97.6
8	9 786	0.3	97.7	35 849	0.4	97.5	3 273	0.3	97.9
9	8 622	0.4	98.1	28 282	0.2	97.9	3 004	0.3	98.1
10	6 623	0.3	98.3	22 702	0.2	98.1	2 886	0.3	98.4
11-100	42 241	1.6	99.9	150 015	1.7	99.9	15 885	1.4	99.8
101-1000	2 385	0.1	100	10 308	0.1	100	1 795	0.2	100
1001-	125	0.0	100	763	0.0	100	148	0.0	100

Table 4 Distribution of frequency at product level of source code identifiers combined

Source code identifiers classes and methods combined			
frequency	# Idents	(%)	Cum (%)
1	8 561 214	76.4	76.4
2	1 385 535	12.4	88.8
3	451 270	4.0	92.8
4	215 288	1.9	94.8
5	130 731	1.2	95.9
6	81 036	0.7	96.7
7	57 359	0.5	97.2
8	45 546	0.4	97.6
9	36 750	0.3	97.9
10	221 186	0.3	98.2
10-100	191 844	1.7	99.9
101-1000	12 778	0.1	100.0
1001 -	902	0.01	100.0

Class and function identifiers have almost identical distributions: in both cases, 93% of identifiers have a frequency of at most 3. The distribution for filenames is very similar but with two notable differences: it has slightly more unique filenames, and almost twice as many very common filenames (frequency >100) than both class and function names.

4.2.2 Identifiers used for both: classes and function names

The intersection between the names of classes and names of functions is very small: only 65 982 identifiers (out of 11.2 million identifiers, 0.59%) are used for both classes and functions. In other words, in 99.41% cases, the name of the identifier is sufficient to know if it is a class name or a function name.

Table 4 shows the frequency of the combined source code identifiers. While comparing this table to Table 3, note how the distributions of class names, functions names, and the combined identifiers (both class names and function names) are virtually identical.

These results allow to conclude that we do not need to use the type of identifier to determine the product where it is declared. Thus, for the rest of the paper we will use the term identifier to refer to both a function or class name identifier.

Filenames have a significantly larger intersection with other types of identifiers: 12% of filenames are also a class name, and 17% a function name.

4.2.3 Probability of sampling a unique identifier or filename

The results of the previous section indicate that more than 75% of identifiers and filenames are unique. However, some identifiers are very common. Frequent identifiers might be much more common than all the unique identifiers combined. For this reason, it is important to calculate the proportion of instances corresponding to each frequency. This is similar to conducting the following experiment: if we had a set of all instances of all identifiers defined in the corpus (name of product, identifier), and were to randomly choose an identifier from this set, how many products would have the same identifier? (i.e. what would be the frequency of this identifier). We repeat this experiment for filenames too.

In the PyPI corpus there are 26.8 Million instances of identifiers, but only 11.2 M different ones (e.g., the identifier *main* was declared in 53 413 products). For filenames there are 2.9 M instances, 1.1 M different ones. Table 5 shows the proportion of total instances of identifiers that have a given frequency. For instance, at frequency 2 (i.e., identifiers that occur in two different products), there are 1 390 971 different identifiers that occur in 2 781 942 products, which correspond to 10.4% of all identifier instances in the corpus.

Even though the frequency of files and identifiers is not that different, those differences compound. As shown in table 5 only 32.1% of identifier instances are unique, and 50% of identifiers instances have a frequency of 4 or less. If we were to randomly choose an identifier within a randomly chosen product, the probability that this identifier is unique is 32.1%; and in 50% of the cases, its frequency would be 4 or less. For filenames, the probability of randomly choosing a unique one is 30%; and in 50% of the cases, it would have a frequency of 8 or less. The most common identifiers (frequency > 1000), even though only 888, account for 10.9% of all instances. In the case of files, 148 filenames account for 18.4% of all instances.

4.2.4 Frequent identifiers

The last row of Table 5 shows that there are only 888 identifiers (0.01%) with frequency larger than 1000, but they are very frequent and correspond to 10.9% of all instances. For filenames, there are 148 files that account for 18.4%

Table 5 Distribution of distinctiveness of instances of identifiers and filenames at product level. For example, identifiers of distinctiveness equal to 4 correspond to 3.2% of all identifier instances, and 50.8% of instances have a distinctiveness of at most 4.

Frequency	Source code identifiers (classes and methods)				Filenames			
	# Ids	Instances			# Ids	Instances		
		#	Prop (%)	Cum (%)		#	Prop (%)	Cum (%)
1	8 600 252	8 600 252	32.1	32.1	886 236	886 236	30.0	30.0
2	1 390 971	2 781 942	10.4	42.5	122 929	245 858	8.3	38.3
3	452 285	1 356 855	5.1	47.6	43 064	129 192	4.4	42.7
4	216 279	865 116	3.2	50.8	17 234	68 936	2.3	45.1
5	131 248	656 240	2.5	53.3	10 038	50 190	1.7	46.8
6	81 232	487 392	1.8	55.1	6458	38 748	1.3	48.1
7	57 686	403 802	1.5	56.6	4638	32 466	1.1	49.2
8	45 620	364 960	1.4	58.0	3273	26 184	0.9	50.1
9	36 885	331 965	1.2	59.2	3004	27 036	0.9	51.0
10	29 308	293 080	1.1	60.3	2886	28 860	1.0	51.9
11-100	192 252	4 682 191	17.5	77.8	15 885	421 320	14.3	66.2
101-1000	12 695	3 030 540	11.3	89.1	1795	453 591	15.4	81.6
1001-	888	2 913 499	10.9	100.0	148	543 811	18.4	100.0

Table 6 The 10 most frequent identifier names in functions and classes. #Prs is the number of products where that identifier is defined (its distinctiveness).

Name	Classes		Functions		Filenames	
	Products Freq	%	Products Freq	%	Name	Products Freq %
Meta	9771	4.0	__init__	159 528 65.3	__init__	60 482 26.3
Command	6246	2.6	main	53 368 21.9	setup	54 462 23.6
Config	6113	2.5	run	46 158 18.9	utils	31 149 13.5
Migration	6062	2.5	__str__	44 664 18.3	cli	15 600 6.8
Client	5520	2.3	__repr__	41 796 17.1	exceptions	14 888 6.5
PostInstallCommand	5100	2.1	get	33 024 13.5	models	13 816 6.0
PostDevelopCommand	4737	1.9	__call__	31 053 12.7	base	13 048 5.7
EggInfoCommand	4598	1.9	setUp	30 205 12.3	config	9925 4.3
User	4291	1.8	read	25 981 10.6	main	9658 4.2
Error	4094	1.7	__getitem__	25 714 10.5	util	9317 4.0

of all instances. This result suggests the possibility of creating a small list of most frequent identifiers that can be excluded from any method to determine their origin (similar to stop words in natural language processing).

The top 10 of each identifier type are presented in Table 6. As it can be seen, most of class identifiers are installation- and configuration-related. They are required to be defined by a product that uses Python distribution mechanism (used by *setuptools*). Regarding the most common functions, many are prefixed and suffixed with `__` (e.g. `__getitem__`). Python uses such identifiers—called “dunders” or “magic methods”—to modify its run-time behaviour (e.g., the method `__getitem__` of a class is used to redefine the behaviour of `[]` indexing).

Regarding files, they also correspond to common naming conventions (e.g., `setup`, `main`, `config`, and `exceptions`).

To summarize: in PyPI 75.8% of class identifiers, 76.7% of function identifiers and 79.3% of filenames are defined in only one product. The set of identifiers for functions and the set of identifiers for classes are almost mutually exclusive (0.59% of identifiers are used for both). While 95% of identifiers (and 96% of filenames) are defined in at most 4 products, these identifiers correspond to only 50.8% of all instances of identifiers (45.1% for filenames).

5 Using identifiers to determine software provenance

We have determined that most of the identifiers in PyPI are very distinct at product level. This fact makes identifiers a promising building block for a lightweight approach to determine the provenance of a file or set of files within a software corpus (like PyPI). In order to move from this potential to a working approach, however, we need to turn this intuition into a practical heuristic.

Consider the following scenario: we have a set of files (we will refer to them as the subject files) from a release of an unknown product, and we would like to determine which product they belong to. This problem can be answered with many different methods. For example, one can create a database of hashes of every file of every release of every product in the database. If the subject files have not been modified, their hashes can be quickly compared to this database. However, if the files have been modified (even by a single byte), this method would not work. Alternatively, we can use *diff* tools or clone detection tools; these methods will be more expensive methods.

Answering RQ1 we established that the identifiers defined in products in the PyPI corpus are relatively unique. We can use this information to create a “fingerprint” that can be used to reduce the search space of potential products from which the subject files might have originated. If this set is small, other time-consuming methods can then be used to match the subject files to the products in this set.

This *fingerprint* is a set of N globally declared identifiers in the subject files; if we randomly extract N globally declared identifiers from subject files, we expect that very few projects (potentially only one) will have declared *all* these identifiers. Thus, we can quantify the effectiveness of this method by answering RQ2:

RQ2 How many global identifiers are needed to *narrow down* the origin of a given source code artifact to a small set of candidates, within the open source Python ecosystem?

5.1 Methodology

For this experiment we used the PyPI corpus described in Section 4. The main parameter to this experiment is the number of distinct identifiers extracted from the subject files (the size of the *fingerprint*). We use N to refer to this parameter. We want to find the minimum number of identifiers needed. As we observed in the previous section, most identifiers are unique, but there are more instances of non-unique identifiers than instances of unique identifiers. If we randomly choose one identifier from a package, we have a 32% chance of finding a unique identifier (and 50% that it has a frequency of at most 4 packages). Thus, we are likely to need to sample more than one identifier from the subject package to increase this probability. Our goal is to identify the ideal number of identifiers we need. Thus, we repeat the experiment for $N \in [1, \dots, 5]$ and compare the results. The methodology for each value of N consists of 3 parts: sampling, fingerprinting, and matching.

Sampling. We start by randomly selecting a sample of 1000 different product releases from the corpus, making sure they all belong to difference products. From each chosen release we extract a *fingerprint* (discussed below) composed of N distinct identifiers. Note that it is not always possible to do so (e.g., in extreme cases a release might contain less than N distinct identifiers); in those cases the release will be discarded and another one will be chosen at random until success.

Fingerprinting. We tested two different strategies to create the *fingerprint* that depend on how many different files the identifiers are sampled from. Intuitively, extracting the identifiers from a single file will result in more candidates than extracting them from different files. Nonetheless, we are interesting to quantify how much better one method is that the other.

Single-file strategy: this method requires that all N fingerprint identifiers come from a single file. To that end we randomly select one source code file from the input release and then randomly select from it N distinct identifiers. If the file does not contain enough distinct identifiers we backtrack and pick another file. If no files allow to satisfy the criteria the release is discarded and another one chosen at random until success.

Disjoint-files strategy: this method requires that the N fingerprint identifiers be different and come from N different *files* in the input release (i.e., one per file). To achieve this we randomly sample N files without replacement and randomly select from each file one identifier that has not been selected yet. In case a file does not contain any (new) identifier, we backtrack and select another file at random until success. As before, if the release does not have enough files or enough identifiers to create the *fingerprint*, it is discarded and another one is chosen at random until success.

In term of fingerprint sizes we make N vary in the $n \in [1, \dots, 5]$ closed interval; while even the maximum size allowed by this choice (5 identifiers)

appears small, our results show that it is more than enough in practice in most cases.

Note that there is no need to redo the sampling step for each possible value of N . One can perform a single sampling with $n = 5$ and then use fingerprint *prefixes* of length $n \in [1, \dots, 5]$ for the matching phase. Similarly, in order to speed up sampling, we have excluded all releases that do not have either enough identifiers or enough files as a whole to potentially permit sampling 5 identifiers. This introduced some bias in the experiment, but we believe that a useful real-world Python product will contain at least 5 identifiers.

Matching. For matching input releases to the corpus, the approach is straightforward: given a fingerprint of N identifiers find the set of all PyPI products that contain *all* identifiers in the fingerprint. These products constitute the candidate products from where the input release originate from and it is very efficient to determine. We will analyze and discuss the number of products returned using different fingerprint sizes and sampling techniques.

Dealing with stop words. As discussed in Section 4.2.4, some identifiers are very common and correspond to a large proportion of the occurrences (e.g., the top 888 most frequent identifiers account for 10.9% of all occurrences, and the top 148 filenames for 18.4%). Very common identifiers will not be very useful for provenance discovery. Examples of such identifiers for Python are `__init__` (the prescribed name of class constructor methods) or `main` (a common name for the entry point function in an executable). As it is common practice in language-based searches, we establish a *blocklist*: a list of the most frequent stop “words” (identifiers in this case) that are excluded from sampling, and therefore cannot appear in fingerprints. An important question is how large should the *blocklist* be. Intuitively, the larger the list the better (e.g., if our *blocklist* is composed of any identifier that exists in two or more products, then any identifier not in the *blocklist* would uniquely identify a product in PyPI—assuming the identifier exists in the corpus). However, a large list has two disadvantages: a) the larger the list the more expensive it is to use it; and, more importantly b) if the list is too big, it might not be possible to extract sufficient identifiers from the subject file to create the *fingerprint*.

Figure 1 shows the impact of the size blocklist with respect to the proportion of identifiers removed from the corpus (for example, the identifiers in a blocklist of size 100 account for 5.2% of the occurrences of identifiers; for filenames, a size of 100 corresponds to 17% of occurrences). We empirically verified the impact of the blocklist by running the following experiment: we randomly sampled 5000 products from the corpus, using the single file strategy, with a fingerprint size of 3—that is, an eligible product must have at least one file with at least 3 different identifiers not in the blocklist being tested; we then counted the number of products that match such fingerprint. As for the blocklist itself, we experimented with different sizes of it, each time corresponding to the top- N identifiers in the entire corpus. We made N (the size of the blocklist) vary from 0 to 10000.

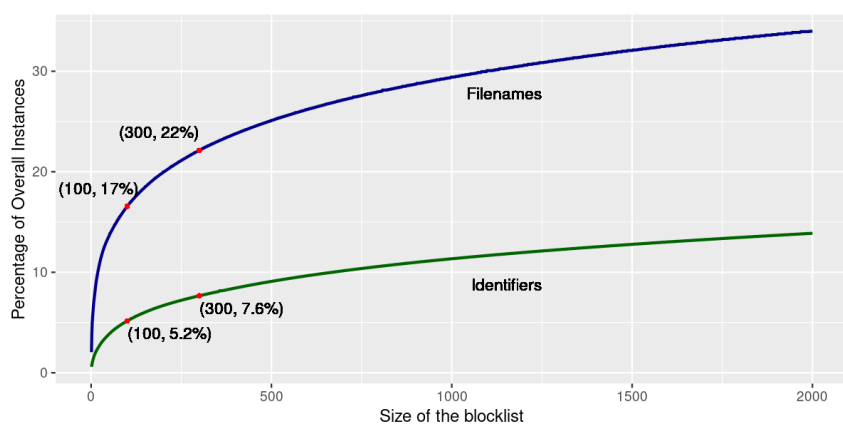


Fig. 1 Impact of the size of the blocklist in the proportion of occurrences that would be removed from the corpus.

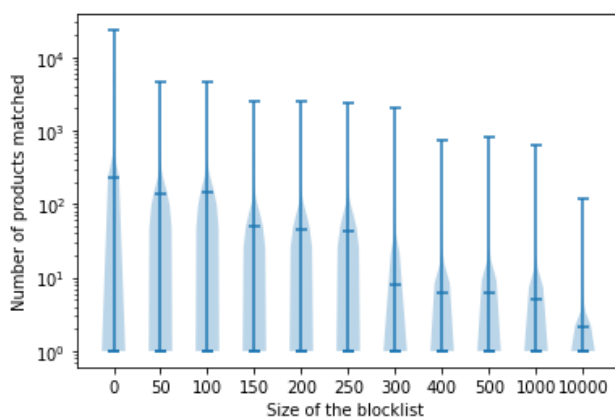


Fig. 2 For each size of the blocklist, 5000 random fingerprints were matched. Thus, each column represents a violin-plot of the number of products match. We chose a size of 300 because it shows the last significant drop in the median number of matched products.

Results are shown in Figure 2. As expected, increasing the size of the blocklist reduces the number of candidates. There is a significant drop at 300, which is also observable in Figure 1. For these reasons we decided to use a blocklist of 300 for the following experiments. It is worth noting that by removing the top-300 identifiers, only 0.27% of all unique identifiers are removed; yet, this list removes 7.6% of all identifier occurrences in the PyPI corpus. For filenames, 300 correspond to 0.27% of distinct filenames, and removes 22% of all filename occurrences.

Note that a blocklist can be implemented by keeping the frequency of each identifier (or its inverse document frequency *idf*) in the corpus database. An identifier will be part of the blocklist if its frequency is above a certain thresh-

old. In this corpus, that threshold is at least 2230 (*idf* 2.039) for identifiers and 551 for files (*idf* 2.645).

To summarize, we performed the experiments described using:

- two sampling strategies: single-file v. disjoint-files;
- fingerprint size varying from 1 to 5;
- a *blocklist* size composed of the 300 most popular identifiers.

5.2 Results

Our goal is to understand how the size of the *fingerprint* impacts the number of products matched in the corpus. In terms of information retrieval metrics, this experiment will always have a recall of 100% since the project from where the identifiers are extracted is always in the result. The precision would be the inverse of the number of matched projects.

In Figures 3 and 4 we show the cumulative distributions of the number of candidates selected, respectively, by the single file and disjoint files fingerprinting strategies. Results are shown for varying *fingerprint* size from 1 to 5. To account for randomness in fingerprint selection, each experiment was run 5 times. For each *fingerprint* size the figures show a box plot of 5 points. Each box plot value shows the accumulated proportion of searches in which the number of products matched was less or equal to a certain number of different products (from 1 to 5). For example, in the 5 experiments using single-file sampling and *fingerprint* size equal to 1, the proportion of times that the *fingerprint* matched three or less product was 44.1%, 46.7%, 46.9%, 47.2%, and 47.5%; in other words in a median of 46.9% cases, the number of products matched was less or equal to 3 (34.6% returned 1, 7.8% returned 2, and 4.5% returned 3). As it can be seen, in all cases the 5 runs returned very similar results—suggesting that the method is very stable.

For both strategies, there is a significant reduction in number of matches from a *fingerprint* of size 1 to 3. After 3 we reach a point of diminishing returns. For a fingerprint of size 3, the single file strategy finds 5 or less matched products in a median of 93.1% of cases, while the disjoint file strategy finds 5 or less matches in a median of 96.7% of cases. Equally important is that with a *fingerprint* of size 3, 76.7% of cases returned exactly one match for the single file strategy, and 81.3% for the disjoint file one. The disjoint files sampling strategy performs best, likely because sampling from different files provides more information regarding the project the identifiers belong to.

When three non-common (after blocklist exclusion) identifiers are sampled from different files of a project, the number of projects with those identifiers is 1 in 80% of cases (precision 100%), and at most 5 in 98% of cases (precision 20%). For the single-file method, the number of results of size 1 is in 74% of cases, and at most 5 in 89.2% (the recall is always 100%).

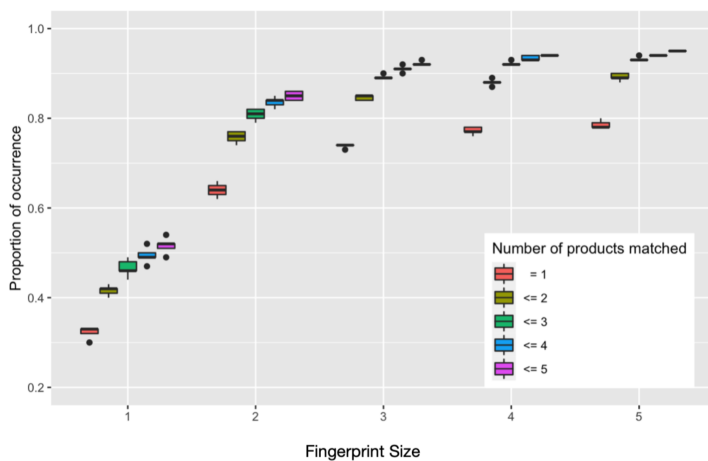


Fig. 3 Distribution of the number of candidates: single file strategy

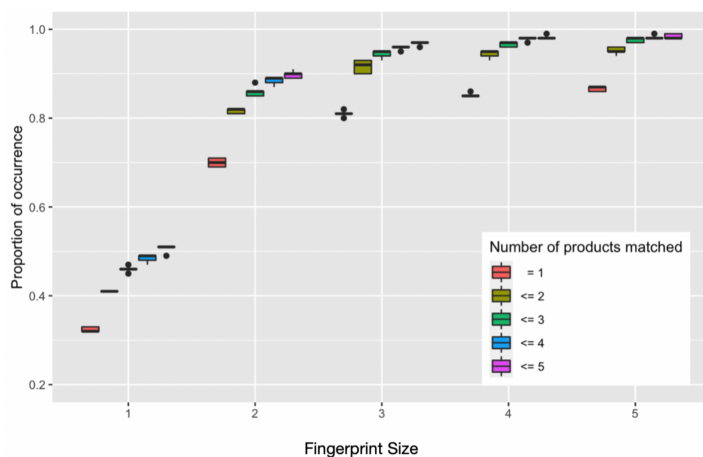


Fig. 4 Distribution of the number of candidates: disjoint files strategy

6 Evaluation

In this section we empirically evaluate the effectiveness of our approach for software provenance identification based on identifiers. To that end, we use as subjects a set of software packages that were not extracted directly from our PyPI corpus (compared to what we did in Section 5), but that we expect to be present in this corpus. Specifically, we consider version 10 “Buster” of the Debian GNU/Linux distribution and assume that Python software shipped by Debian is also present in PyPI. This is a reasonable assumption, because Debian is fairly selective in what it ships in its stable releases and PyPI is the most comprehensive listing of Python packages. Thus, we expect PyPI to be a

superset of the Python packages shipped in Debian stable release like Buster and, conversely, Debian Python packages to be a “*golden (sub)set*” of PyPI.

6.1 Creating a golden set from Debian

We started by listing all Debian source packages shipped by Debian Buster as of August 2020,⁸ at the same time we built our PyPI corpus (see Section 4.1). The initial list includes over 28 000 Debian source packages. We first determined the list of Python packages using a coarse heuristic based on package names: we selected the source packages that contain any of the following substrings in either their name or in the name of any of the binary packages they generate: “`py`” and “`python`”. We identified 3155 Debian source packages related to Python this way. We downloaded the full source code of each package running the command `apt-get source PACKAGE_NAME` on a Debian Buster machine.

One major challenge to create a ground truth is to match a package in Debian to its corresponding package in PyPI, as they might have different names. PyPI requires packages to include a `setup.py` file which, in its implementation, should eventually call the `distutils.setup()` function passing a `name` parameter that matches the PyPI package name. We used two best-effort methods to identify PyPI product names based on this.

First, we ran `python setup.py --name`, with both versions 2 and 3 of the Python interpreter (because Debian source packages can be implemented in either version of the language, and there are subtle syntactic differences between the two language versions). If this script failed, we inspected manually the package to find its PyPI origin. We were able to match 2221 Debian package names to PyPI projects in our corpus. 40 packages did not have any identifiers and were ignored (e.g., the Debian package `python-xstatic-ds3` originates from the PyPI package `xstatic-ds3`, but it only contains `__init__.py` and `setup.py` files that do not declare any global identifier).

In the end, our golden dataset was composed of 2181 pairs. Each pair was a Debian source package and its corresponding PyPI project.

6.2 Ranking candidates

Our provenance detection method returns a set of candidates for further inspection. Ideally we would like this set to be a singleton. However, we expect that more than one package will be returned in the general case. Thus, it will be beneficial to rank the candidates in such a manner that the most likely candidates appear first. This way candidates with a higher probability of being the correct answer will be examined sooner.

⁸ At that time Debian Buster was already shipped as a “stable” release, so while it is possible that its content has changed since, modifications are expected to be minimal according to Debian release processes.

Document term frequency is used in several methods for ranking result candidates (such as tf-idf-weighting). Unfortunately it is not applicable for this purpose because if an identifier is declared two or more times in package A more than in package B, A is still equally relevant as a source of the identifier than package B. Other methods rely on partial matches to rank the results; these methods cannot be used in our experiments because we are interested only in documents that match all identifiers in the fingerprint.

Instead, for ranking results we leverage SourceRank [43], a well-established ranking metric for open source software packages developed by the Libraries.io project.⁹ Roughly speaking, SourceRank is a compound metric that takes into account both package *popularity* (based on GitHub “stars”, for example) and several *quality* metrics such as the presence of metadata, license information, README, etc.

We conjecture that if a package is popular (as SourceRank indicates), it is more likely to be the origin of an entity than one that is less popular. In these evaluation experiments, when a set of N candidate PyPI packages is returned, we then order them by their SourceRank in descending order, thus returning a list (where position 1 is the package with the highest Source Rank, i.e., the most relevant package).

6.3 Methodology

In this experiment we want to evaluate the *single-file* and *disjoint-files* strategies for provenance identification with a *fingerprint* of size 3 and a *blocklist* of 300. Because these methods are randomized, we perform 5 trials for each of the strategies.

For the single-file strategy, one file is sampled per trial. From this file, 3 identifiers (not in the blocklist) are randomly sampled.

For the disjoint-files strategy, in each trial 3 different files are randomly sampled (without replacement), and from each file one identifier (not in the blocklist) is randomly sampled. At each trial level, all source code files are considered (thus, it is possible that two or more trials use the same files).

Except for the randomly extracted identifiers, no other information is used in these trials. To evaluate the effectiveness of the proposed method we computed the following metrics:

- The size of the candidate set C obtained with each sampling strategy. The smaller, the better: a size of 1 is ideal.
- Given that our results are ranked, we computed the recall and precision for the top k -results. In general, as k increases, precision is expected to drop and recall to increase. For this method to be successful we expect that, for small values of k both precision and recall to be high.

⁹ <https://docs.libraries.io/overview.html#sourcerank>, accessed 2021-12-07

Table 7 Overall results when matching Debian python packages to the PyPI corpus.

	Single-file	Disjoint-files
Subjects	2147	1631
Outcomes	10 735	8155
Empty (no candidates)	619 (5.8%)	900 (11.0%)
Non-empty candidates		
Successful (i.e. overall recall)	9982 (93.0%)	7145 (87.6%)
Failed	134 (1.2%)	110 (1.3%)
Size of result per outcome		
Median	1	1
Avg	14.5	2.4
Max	2104	175

6.4 Results

Table 7 summarizes the obtained evaluation results for the single-file and disjoint-files strategies. As it can be seen, a number of outcomes did not yield any candidate (no file was found in our corpus): 5.8% for single-file method, and 11.0% for the disjoint method; we will revisit this result in Section 6.5.

The overall recall of the experiments (i.e. the number of outcomes that included the correct origin of the product) was 93% for single-file and 87.6% for disjoint-files. The proportion of outcomes that yielded at least one candidate, but none was the true origin of the package, was 1.2% and 1.3% for each method, respectively.

We computed the precision, recall and F-score of the top k-results. This method of using precision and recall is widely used to evaluate the quality of search results. For a specific search, its precision at k is defined as number of relevant items in the first k-results; while recall is defined (as usual) as the number of retrieved items in the first k-results divided by the number of all possible relevant items.

In our experiment there is only one relevant item for any search, therefore the search has a binary outcome: either the correct product is part of the results or not. The recall at k is either 1 if the correct product is found in the first k-results, or zero otherwise. Therefore, the average recall at k is equal to the proportion of successful outcomes when the subject is found in the first k results of each search.

For a given search, the precision at k is $1/\min(k, n)$ if the correct product is in the first k-results and zero otherwise (where n is the overall number of items in the result of the search). Because there is only one potential correct item, the precision at k drops rapidly as k increases and the query returns at least k elements. We compute the average precision at k over all outcomes ignoring the cases where the result returns zero results (precision is undefined; approximately 10% of results fell into this category).

For the sake of readability, for the rest of this paper we will refer to average recall at k and average precision at k simply as recall at k and precision at k.

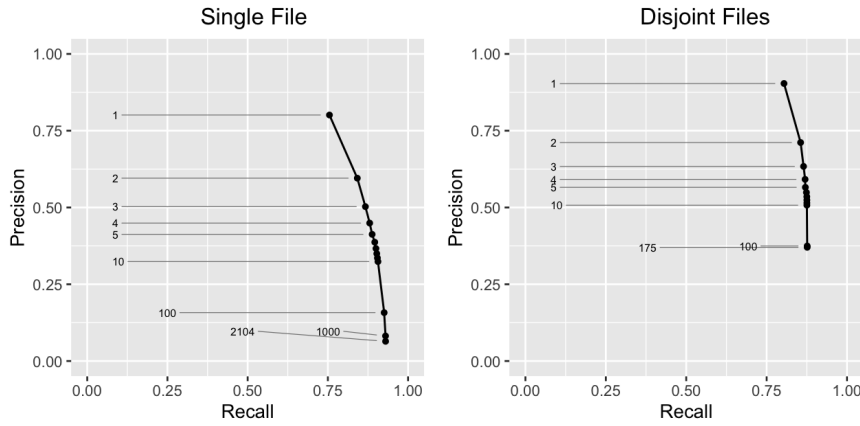


Fig. 5 Average recall and precision at k for both strategies. The small numbers to the left correspond to k . For example, for the single-file strategy, the top result ($k=1$) has a recall of 75%, and a precision of 80%.

Figure 5 shows these values for the single-file strategy, which are also shown in Table 8. As it can be seen, for $k = 1$, the precision is 80% and the recall is 75% (this is because 7.6% of outcomes did not return any result). With $k > 5$, the gains in recall are very marginal; yet, at $k = 10$, the precision is almost $\frac{1}{3}$. The table also includes the number and proportion of outcomes that yielded a result of size k or larger; for example 89.0% of outcomes returned one or more candidates (31.1% returned exactly one candidate), and 16.4% returned more than 6 or more candidates.

Table 8 Average recall, precision and F-score at k for single-file strategy. The number and proportion of relevant outcomes corresponds to those that had at least k candidates; e.g. only 31% of outcomes had 3 or more candidates.

k	Relevant Outcomes Count	Prop.	Recall	Precision	F-score
1	10116	94.2%	0.75	0.80	0.78
2	5059	47.1%	0.84	0.60	0.70
3	3337	31.1%	0.87	0.50	0.64
4	2523	23.5%	0.88	0.45	0.59
5	2069	19.2%	0.89	0.41	0.56
6	1756	16.4%	0.90	0.39	0.54
7	1504	14.0%	0.90	0.37	0.52
8	1334	12.4%	0.90	0.35	0.50
9	1228	11.4%	0.90	0.34	0.49
10	1111	10.3%	0.91	0.32	0.48
100	169	1.6%	0.93	0.16	0.27
1000	34	0.3%	0.93	0.08	0.15
2104	2	0.0%	0.93	0.06	0.12

For the disjoint-files strategy, the precision and recall at k is shown in Figure 5 and Table 9. For this strategy 11% of outcomes did not generate any

Table 9 Average recall, precision and F-score at k for disjoint-files strategy.

k	Relevant Outcomes		Recall	Precision	F-score
	Count	Prop.			
1	7255	89.0%	0.80	0.90	0.85
2	2552	31.3%	0.86	0.71	0.78
3	1322	16.2%	0.86	0.63	0.73
4	858	10.5%	0.87	0.59	0.70
5	563	6.9%	0.87	0.57	0.69
6	428	5.3%	0.87	0.55	0.67
7	353	4.3%	0.87	0.54	0.66
8	282	3.5%	0.88	0.52	0.66
9	245	3.0%	0.88	0.52	0.65
10	207	2.5%	0.88	0.51	0.64
100	11	0.1%	0.88	0.37	0.52
175	1	0.0%	0.88	0.37	0.52

result. As it can be seen, the recall and precision is very high for $k = 1$ (0.8 and 0.9 respectively), and for $k > 2$ there is no significant gain in recall. Thus, in most cases, it suffices to inspect only the top 2 results, with a recall of 86% and a precision of 71%. Inspecting results beyond the second candidate only yielded a successful result in 2% of the outcomes. Also, only 16.2% of all searches return more than 2 candidates, and 5.3% more than 6 or more candidates.

Comparing the two methods we observe that:

- For $k = 1$, the disjoint strategy has better recall (0.80 vs 0.75).
- The single-file strategy returned larger lists of candidates than the disjoint one. As a consequence, the precision of the single-file strategy drops much more as k increases,
- For $k \geq 4$, the single-file strategy has better recall than the disjoint strategy.

While the precision of the disjoint-files strategy is higher than the single-file one, not all packages had 3 files and after $k > 2$ the recall of the single-file strategy is higher.

Both strategies (single-file and disjoint-files) are effective at finding the origin of a Debian Python package in PyPI without the need to inspect many candidates. At $k=1$, the recall and precision of the single-file strategy were 0.75 and 0.8; while for the disjoint-files strategy, they were 0.8 and 0.9, respectively.

6.5 False negatives

Since we manually curated the dataset we expected to have no false negatives (i.e. we know the Debian package exist in PyPI), yet the proposed method is unable to identify the origin of several packages. As shown in table Table 7,

the single-file strategy did not return any results in 5.8% of the outcomes and in 1.2% of the outcomes the results did not include its true origin. For the disjoint-files strategy, the number of outcomes with empty results was almost twice (11.0%) and the number of outcomes that did not include its true origin was almost the same (1.3%).

There were 21 packages that were never matched to a package in PyPI by either strategy. We manually inspected each of them. We observed that the reason these packages resulted in false negatives was that their corresponding packages in PyPI did not contain all the original source files of the packages (which the Debian package included). We observed two cases:

- Some PyPI packages did not include testing or examples source code. 19 of the 21 packages did not include Python files located in the `test`, `examples`, or `documentation` folders. Many packages in PyPI were *binary* distributions (called distribution archives by the Python Packaging Authority). These distribution packages were a subset of the original source code and contain the files necessary to use the package, not to build it [2]. Some of these 19 packages had very few source files in PyPI and many more test source files in Debian. For example, *pyfaidx* had 3 Python files (`setup.py`, `__init__`, `cli.py`) in PyPI, and 21 in Debian (the other 18 files were inside the test folder).
- Some PyPI packages contained only installation scripts. The remaining two packages (*egenix-mx-base* and *QuantLib*) only included installation scripts in PyPI without most of its source code. For example, *egenix-mx-base* had 85 files in Debian and only 2 in PyPI. In the case of *QuantLib*, the numbers were 23 and 1 respectively.

Given the first point above, we hypothesized that false positive outcomes would include files in `test` or `example` paths and that Debian packages would be more likely to include files in `test` or `example` folders. We checked each of the false negatives outcomes to see if the sample file had `test` or `example` in the name of a folder in the path of the file (checking if the full filename matched the regular expression `(text|example).*/`); for disjoint-files strategy we check if at least one file in the outcome satisfied this condition). The results are presented in Table 10. As it can be seen, for outcomes that had an empty result (no candidates), 75% of files were in `test` or `example` folders for the single-file strategy; for the disjoint-files strategy it was 89.2%. In total, 70% of the false negative outcomes in the single-file strategy were in folders named `test` or `example`, and for the disjoint-files strategy they were 87%.

We checked the number of packages with tests or example files in our experiment. Out of the 2147 Debian packages used in our experiment, 1461 had at least one of these types of files. In contrast, of the corresponding 2147 PyPI packages, 1461 had one or more test or example files. Therefore, the problem of missing test files seems to be restricted to a small proportion of packages. In fact, in the single-file strategy experiment, 3,198 trials that used a test or example file were successful (out of 3,709, 86.2%). Thus test and example files contain identifiers that are useful for provenance discovery.

Table 10 Most of the false negatives used one or more files placed in folders called `test` or `example`. We manually inspected 19 out of 21 that only had false positives and discovered that such files were present in the Debian package and its source code repository, but not in the PyPI packages.

	Single-file		Disjoint-files	
Outcomes	753		1010	
Had file(s) in test or example folder	525	69.8%	880	87.1%
No candidates	619		900	
Had file(s) in test or example folder	456	73.7%	803	89.2%
Non-empty candidates	134		110	
Had file(s) in test or example folder	69	51.5%	77	70.0%

Table 11 Results for best outcome (out of 5 trials per project) for the *single-file* sampling strategy: 2147 subjects; and for disjoint-files: 1631 subjects.

	Single-file	Disjoint-files
Subjects	2147	1631
Outcomes	2147	1631
Empty (no candidates)	38 (1.8%)	116 (7.1%)
Non-empty candidates		
Successful (overall recall)	2099 (97.8%)	1501 (92.0%)
Failed	10 (0.5%)	14 (0.9%)
Size of result per outcome		
Median	1	1
Avg	4.5	2.2
Max	2031	175

These results imply that our experiments yielded false positives and empty results because, when a file is picked at random, the chosen file is not included in the PyPI package (such as the files in `test` and `example` folders as described above). In the design of our experiment we took into account some of the effects of this randomness, and repeated the search 5 times per project. Table 11 shows the summary of the results when we pick the best outcome per project. When these results are compared with Table 7 we can observe that the overall recall jumps from 93.0% to 97.8% for the single-file strategy, and from 87.6% to 92.0% for the disjoint-files strategy; the best outcome did not find the origin of a package in 2.2% (48) projects for the single-file strategy and 8% (130) for the disjoint-strategy.

Table 12 shows the recall and precision at k for best outcome for single-file strategy; and Table 13 for best outcome for disjoint-files strategy (out of 5 trials in both cases). As it can be seen, for $k=1$, the F-score of single-file strategy is 0.91, and 0.92 for the disjoint-files strategy. Note that the numbers for disjoint-files strategy are (with the exception of precision and F-score at $k=1$) worse than the single-file strategy, implying that, when we take the best of various trials, it is best to use the single-file strategy.

Table 12 Best outcome (out of 5 trials per project), single-file strategy.

k	Relevant Outcomes		Recall	Precision	F-score
	Count	Prop.			
1	2109	98.23	0.90	0.92	0.91
2	924	43.04	0.95	0.67	0.79
3	559	26.04	0.96	0.57	0.72
4	388	18.07	0.96	0.52	0.68
5	290	13.51	0.97	0.49	0.65
6	218	10.15	0.97	0.46	0.63
7	177	8.24	0.97	0.45	0.61
8	140	6.52	0.97	0.43	0.60
9	123	5.73	0.97	0.42	0.59
10	101	4.70	0.97	0.41	0.58
100	5	0.23	0.98	0.30	0.46
1000	1	0.05	0.98	0.25	0.39
2031	1	0.05	0.98	0.22	0.36

Table 13 Best outcome (out of 5), disjoint-files strategy.

k	Relevant Outcomes		Recall	Precision	F-score
	Count	Prop.			
1	1515	92.89	0.88	0.95	0.92
2	494	30.29	0.91	0.74	0.82
3	245	15.02	0.91	0.66	0.77
4	150	9.20	0.92	0.62	0.74
5	94	5.76	0.92	0.60	0.72
6	66	4.05	0.92	0.59	0.72
7	56	3.43	0.92	0.57	0.71
8	40	2.45	0.92	0.56	0.70
9	38	2.33	0.92	0.56	0.69
10	32	1.96	0.92	0.55	0.69
100	1	0.06	0.92	0.41	0.57
123	1	0.06	0.92	0.41	0.57

Manual inspection of the false positives appears to indicate that several packages in PyPI do not have all the source code of their corresponding packages. This problem can be alleviated by repeating the search several times. In our experiments, when using the best of 5 trials result, the average precision and recall at k=1 of the single-file method improves to 0.90 and 0.92, and to 0.88 and 0.95 for the disjoint-files method (i.e. when only inspecting the top result).

6.6 An improved algorithm for provenance discovery using identifiers

Overall, these results suggest the following algorithm that will only inspect 5 candidates at most, and uses the single-file strategy:

- Repeat at most 5 times:
 1. Pick one file at random with replacement.
 2. From this file, extract 3 random identifiers not in the blocklist.
 3. Search the corpus for candidates.
 4. Inspect only the top-candidate:
 - If it is the origin of the package stop.

In our experiments, this algorithm has a recall of 0.90 and precision of 0.77 (it would have required to inspect 2731 candidates, of which 2099 were correct). Equally important, it would have been applicable to 30% more packages than the disjoint method. The processing time of querying an identifier is negligible, thus most of the CPU time will be consumed extracting the random identifiers from a given file. The inspection of each top candidate can be assisted with a clone detector that compares the subject against the candidate.

Using the single-file strategy and repeating the search at most 5 times and only inspecting the top result has a recall of 0.90 and precision of 0.77.

6.7 Low precision in few outcomes

Most outcomes had a very small set of candidates (the median was 1). However, in some cases the number of candidates was very large. We manually inspected the results of outcomes with the most candidates. What we observed is that there is a significant amount of cloning in PyPI packages. We queried the PyPI corpus to identify packages that had a large number of common identifiers and manually inspected several of them (further research should conduct a proper study of the existence and frequency of these common identifiers in PyPI). We identified the following reasons why some identifiers are used in different packages:

1. Commonly used identifiers. This case corresponds to functions/classes that are frequently used, yet have very different source code. We have already discussed them in the creation of the blocklist (see Section 4.2.4).
2. Different variants of the same package. Some packages are specialized versions of others. These packages appear to be different binary distributions of the same source code, yet each appears as a different PyPI package. For example, the following packages share the majority of their code with *tensorflow*: *tensorflow-cpu*, *tensorflow-directml*, *tensorflow-fedora20*, *tensorflow-gpu*, *tensorflow-gpu-macos*, *tensorflow-rocm*, *tensorflow-rocm-enhanced*, *tensorflow-tflex*; these packages share between 3801 and 11,802 functions with *tensorflow*.
3. Embedding dependencies. We found that a significant number of packages embed their dependencies. Usually this is done during the build process,

where the dependencies are located in a folder named `thirparty`. We identified 131 packages that have python files in the folder `thirparty` and 112 in `third_party`. For example, *sqlmap* had twenty different packages under `thirparty`; these dependencies did not have any information that documented the version or origin of each of them.

4. Embedding a dependency into its own source code. In this case, the dependency is copied inside the source code tree of the package (usually inside the folder `src`) and becomes part of the source code of the package. For example, *nplab* embedded the project *lucam* (a single Python file).
5. Copied functions. Sometimes code is cloned among different projects. For example, we found one common class (`ColorizingStreamHandler`) in *sqlmap* and *Mopidy* that originated from a gist in github. Both packages properly attributed the origin of this class. In another case, the packages *imgserve* and *Amara* shared only one identical function (`get_filename_parts_from_url`) with no attribution.
6. Same package, different names. We found one package that was uploaded under different names by different maintainers (*hd-llz* and *hand-detector-test*). Furthermore, the source code of the packages was slightly different (one had 940 files, the other 895).
7. Subclassing. Some libraries expect to be reused via subclassing and dynamic dispatch. In this case, the new code will reuse the same identifiers for some of the method's functions. For example, the *meta-blocks* defines a class `MetaBlocksExperimentSearchPathPlugin` derived from the class `SearchPathPlugin` in package *hydra-core*. In this class, *meta-blocks* redefines the method `manipulate_search_path`, that is originally defined in *hydra-core*.
8. Code generation. Some packages shared names of classes and functions that had been generated by the same tool. For example, *yuuki-core*, *AsyncLine* and *LineService* had several classes in common, all in files that included the header `Autogenerated by Thrift Compiler`.

These points emphasize the difficulties of curating a corpus for provenance discovery. During the creation of the corpus, provenance analysis of each package could be done in order to identify cases such as the ones above towards the goal of improving the quality of the corpus.

7 Discussion

Developers of PyPI products seem to, consciously or not, choose identifiers that are either unique or very distinctive throughout the entire PyPI ecosystem. Out of 11.2 million different identifiers for classes and functions/methods (in 244k different products), 76% are unique (and 95% appear in at most 4 different products). Equally remarkable is that the intersection of the names of classes and functions was negligible (less than 0.6%).

Python has a strict module namespace mechanism. By default, the user of a library should prefix any of its identifiers with the name of the library

What should I add? please help me :(

Some code:

```

for i in range(from_page, num_page):
    print(f'halaman ke-{i+1}')

# default tripadvisor website

url = f"https://www.tripadvisor.co.id/Attraction_Review-g3177248-d2314079-Revie

# if you pass the inputs in the command line
if (len(sys.argv) == 4):
    path_to_file = sys.argv[1]
    num_page = int(sys.argv[2])
    url = sys.argv[3]

# Import the webdriver
driver.get(url)
# expand the review
time.sleep(5)
element = driver.find_element_by_xpath("//span[contains(@class, 'DrjyGw-P _1l
driver.execute_script("arguments[0].click();", element)

first_container = driver.find_element_by_xpath("//div[@class='_1c8_1IT0']")
container = first_container.find_elements_by_xpath(".*")

print(len(container))

for j in range(len(container)-1):

    text_review = container[j].find_element_by_xpath("//div[@class='DrjyGw-P
    review_text = text_review.find_element_by_xpath("//span[@class='_2tsgCuqy

    csvwriter.writerow((review_text,))
    print('Selanjutnya -->')

driver.close()

```

Fig. 6 Example of a Stack Overflow question that does not indicate which Python library it is using. The identifiers used in it narrow it to 3 candidate: `selene`, `selene-kentastik` and `django-cloud-replay`, of which `selene` is the highest ranked by Libraries.io.

(e.g., `pandas.DataFrame`); this implies that identifiers only need to be unique within the project. At the same time there is an implicit expectation grounded in Python practices and coding guidelines that developers will import library identifiers in such a way that they do not require the full qualified name (e.g., `from pandas import DataFrame`) and this might be a motivating reason why identifiers tend to be unique. Nonetheless, universally unique identifiers seem to also naturally emerge in the corpus.

The median length of identifiers in PyPI is 16 characters for classes and 19 for function names. This means that developers of PyPI packages are willing to name their identifiers with descriptive names. Future research should look into the composition of identifiers in terms of its components (e.g., by splitting at underscores or case changes) and abbreviations used. Filenames, which correspond to module names in Python, are also quite long with a length of 15 characters.

The fact that most identifiers are unique to a package can be leveraged for applications other than software provenance identification. For instance, it

might be possible to scan a Python source code snippet and determine with little or no ambiguity the libraries it uses, even when `import` statements are omitted. Consider questions on the Stack Overflow Q&A website, where only very popular libraries (such as `pandas`, `numpy`, etc.) tend to have dedicated classification tags on the website; it is not trivial to identify postings that use other libraries, unless library names are explicitly mentioned in the question title. Identifiers can be automatically extracted from the code snippet and matched to the corresponding packages. Take for example Stack Overflow question n. 68878857¹⁰ depicted in Figure 6, which does not mention which library the snippet is using. The identifiers `find_element_by_xpath`, `get`, `execute_script`, and the filename `driver.py` only exist in 3 different packages (*django-cloud-deploy*, *selene*, and *selene-kentastik*), *selene* (Python bindings for selenium) being the highest ranked package among them according to SourceRank (*selene-kentastik* is a different set of selenium bindings for Python—thus using some identifiers with *selene*).

The Debian experiment demonstrated the effectiveness of a method of provenance discovery that uses identifiers. Specifically, that by simply conducting at most five trials, and only inspecting the first result returned, the single-file strategy can achieve a recall of 0.9 and precision of 0.77.

We must emphasize that the effectiveness of any method of software provenance identification depends primarily on how comprehensive the corpus is, and the corpus needs to be maintained current as time passes by. New product versions tend to keep most previous identifiers, can introduce new ones, but can also remove some. Thus using *only* global identifiers (and in particular with methods that rely on random sampling, as in our Debian experiment) is insufficient to correctly pinpoint the *release* of a product. However, once a product has been identified, it is possible to use set distance metrics (such as Jaccard) or clone detection methods to determine the best candidate release that matches the candidate.

There are also other potential uses for a corpus of identifiers. For example, it might be possible to identify products that have evolved from others (i.e., forks) or that have changed name. It might also be possible to identify functions and classes that are copied from one product to another. Finally, IDEs can benefit from such a corpus of identifiers to suggest (or automatically add) `include/import` statements.

The goal of the propose approach to provenance identification is not to replace clone detection tools. On the contrary, the goal is to narrow the potential search space such that more time consuming methods (including, but not limited to clone detection ones) can be applied more selectively.

¹⁰ Titled: “Scraping tripadvisor review, len container change, no such element Unable to locate element”, <https://stackoverflow.com/questions/68878857>, accessed 2022-01-16

7.1 Threats to validity

Construct validity. We have conducted several integrity tests to verify that our processing is accurate. We entirely relied on Universal Ctags for the extraction of classes and function names in Python, hence we depend on its reliability. At the same time it is the state-of-the-art open source tool for identifier indexing and is actively maintained, so we are confident in its quality.

We note that we only processed the most recent 100 releases of each PyPI product. However, the impact of this decision is probably negligible, since we expect any recent releases to have a large identifier overlap with older releases (we have observed that most releases are a superset of previous releases, only rarely identifiers are removed).

Internal validity. In our experiments we assume that PyPI is a trustworthy reference corpus for Python products. However, PyPI relies on the developers to make sure they upload correct code. We observed that in some cases, developers might upload releases with embedded dependencies, a phenomenon known as “dependency vendoring” [54]. This is often addressed in future releases by removing from them the source code of previously embedded dependencies, but the older bloated releases remain in PyPI. Since Python does not have a way to restrict the visibility of an identifier, any global identifier in a product is thus available outside it. It is very likely that developers use different naming mechanisms for identifiers that are expected to be used by others from those that they are only to be used locally.

External validity. Our results only apply to the ecosystem of packages in PyPI and written in Python. We do not claim that these results apply to other programming languages or ecosystems. In fact, we believe that an empirical evaluation similar to the one we have conducted in this work should be conducted on each major programming language ecosystems, to document and compare the level of uniqueness/distinctiveness across languages. It would also be interesting to analyze identifier distinctiveness when considering multiple programming languages *together*. While there are identifiers that will be expected to be shared across languages (such as the case of language bindings that we have identified and discussed) it is possible that identifiers will be fairly unique across languages, helping with software provenance tracking in contexts where the programming language of the code under audit has not been determined, for whatever reason.

8 Conclusions

In this paper we have determined that in the Python ecosystem of libraries approximately 75% of global identifiers are unique. Furthermore we have also identified a set of identifiers that are too common to use, and therefore, can be considered as “stop words” in identifier analyses.

We have then used this property to develop a randomized approach to identify the provenance of a Python library that uses a very small set of globally defined identifiers to identify the origin of a product. The approach is straightforward to implement, fast, and had a recall of 0.9 and precision of 0.77. experiments, when inspecting only the top result in each of the five trials for the single-file strategy. In spite of its high accuracy the proposed approach is not meant to be used in isolation, but rather as a preliminary filtering step before applying more expensive identification techniques (if and when multiple candidates are identified), such as code clone detection.

8.1 Future work

Several research directions, including several empirical studies, remain to be pursued as future work. A promising one is further increasing the granularity of detection, reaching down to the level of code snippets—such as individual functions or classes extracted from complete source code files, or snippets posted in isolation on social coding websites and platforms. In principle, the proposed approach is completely agnostic to granularity: it would work at the level of snippets as it does as that of products and releases. In practical terms, however, two challenges exist: 1) when an entity is duplicated in the corpus, which copy should be considered the canonical origin, and 2) accuracy would be different at the snippet level, although it is not clear if for the better or worse. A large-scale empirical experiment is needed, either by splitting up functions/classes from corpora like the one we have already investigated in this work (PyPI) or relying on snippet-first datasets such as GitHub gists or Stack Overflow snippets.

The proposed approach is also agnostic to programming languages. The only requirement being the ability to create a comprehensive corpus of identifiers for the desired programming language. Large-scale empirical experiments targeting different programming languages and/or package ecosystems are needed to verify if the language independence of the model translates to good accuracy in other contexts. It is possible that programming convention in different communities would result in different levels of identifier uniqueness that could in turn impact accuracy, for better or worse.

The potential synergies between the introduced method and traditional clone detection techniques also deserves further exploration. With few exceptions, scaling clone detection to large software repositories remains an open challenge. This is particularly true when one considers that, for provenance discovery, clones of a source code snippet are not necessarily copies, thus increasing—from the point of view of provenance discovery—the number of false positives. Future work should evaluate a hybrid approach, where identifiers are used to narrow the potential number of candidates, and then using clone detection tools to finally identify the provenance of source code. Also, future work should explore methods to improve the quality of a corpus (such as re-

moving instances of copies of dependencies or identifying variants of the same product). This is another area where such a hybrid approach can help.

Data availability

A replication package for this paper is available at <https://doi.org/10.5281/zenodo.7637703> [49]. This replication package contains all pairs (identifier, product) found in PyPI.

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