

Towards Better Symbol Resolution for C/C++ Programs: A Cluster-based Solution

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Abstract—Resolving symbol references is an important part of many application areas from development environments to various static analyser tools, especially when it is used for code comprehension purposes. Different occurrences of the same program elements, like function definitions and their call sites, variable declarations and their usage, or type definitions and their applications should be connected. In case of the C++ programming language, the most current tools use mangled names to correlate symbols, e.g. when implementing actions like “go to definition” or “list all references”. However, for large projects, where multiple binaries are created, symbol resolution based on mangled names can be, and usually is, ambiguous. This leads to inaccurate behaviour even in major development tools. In this paper we explore the reason of this ambiguity, and propose our clustering algorithm based on essential build information to improve the accuracy of symbol resolution. We implemented our method as part of the CodeCompass open source code comprehension tool and measured its efficiency.

I. MOTIVATION

The size and scale of software systems have grown rapidly over the course of the recent years. Large-scale projects amounting up to million lines of code are not uncommon along with the usage of different build configurations across hardware architectures – the source code of the Linux kernel, with drivers, is around 17 million lines of code. This presents a challenge when it comes to understanding and navigability of the project. It is always essential to understand the precise behaviour of a software system when we are fixing a bug, or extending the system with a new functionality, and the importance of this understanding is preminent when a major refactoring task is being undertaken.

One of the most important parts of such a task is identifying the impact the changes have: when we are about to modify, e.g. a function, we are interested in the call sites of that function; for variables, we are looking for the read and write locations of that variable. These occurrences change as the project is built with different settings: behind a function of a given name, multiple implementations are present, depending on the environment of the build.

To enhance understanding of the project, we have to correlate the occurrences of symbols in the source code and how these symbols are present in the built binaries. This helps developers to better understand the project they are working on, while helping automated defect detection via static analysis tools. Consider, though, that this correlation usually can not be

discovered using simple name identity: in most programming languages, the same name could mean different symbols based on the occurrence’s context, e.g. attributes or methods with the same name in different classes, overloaded versions of functions, or functions with the same name in different namespaces/packages or build configurations.

Modern software tools, like various development frameworks [1], [2], [3], [4] and code comprehension tools [5], [6] provide discovery functionality: the user of the tool can jump to the place of the definition or can iterate all places of reference of a given symbol. Naturally, we expect such tools to work not on simple name identity, but on exact symbol correlation. Unfortunately, we found that current development and comprehension tools fall behind and into ambiguity with the increase of the code base’s size. The reason is that *mangled names* are allowed to be ambiguous when multiple executables are produced to form the released product.

A. Contributions of this Paper

To alleviate this issue, we describe a new method to *form clusters* of the mangled names found in the project into distinct groups, based on the information available about how the project is built, which translation units are used and in what exact build configuration and environment they used to form the resulting binaries. Mangled names belonging to the same cluster should refer to the same symbol; and they are distinct from symbols with identical mangled names classified to different clusters. This way, we were able to significantly reduce the possible ambiguity in symbol resolution.

We implemented the method as part of CodeCompass [7] – an open source software comprehension tool – where symbol correlation is used in a number of functionalities. We evaluated our method using CodeCompass to parse various open source C++ projects and measured different implementation variants on the run-time and storage expense. Our final solution has a minimal overhead on the discovery process, therefore it is applicable for various development and code comprehension tools.

Although some uncertainty remains in the rare cases when a symbol is used dynamically, e.g. when a shared library opened via `dlopen` and a symbol is retrieved with API functions [8], our method can dramatically increase the quality of C and C++ symbol resolution for large systems. This may further improve

essential functionalities of development frameworks and code comprehension tools.

This paper is organised as follows: In Section II we describe the basics of building C/C++ applications, and in Section III we describe the problem in detail using examples. Current well-known tools and their approach to the problem are evaluated in Section IV. Symbol resolution and queries are given a formal definition in Section V, where we outline the concepts needed for our solution and then define our precise, linkage-safe symbol reference resolution method. We discuss the implementation options and the evolution of the algorithm in Section VI. An efficient solution is presented in Section VI-D. Possible extensions for our solution is discussed in Section IX. Our paper concludes in Section X, where we reflect on the accomplishments discussed in this paper.

II. C/C++ BUILDING PIPELINE

Software products written in C or C++ language take multiple steps to be built. First, a translation unit, usually a source file is handled by the preprocessor which, amongst other things, includes header files containing more symbols (usually declarations and inlinable definitions) to the to-be-compiled code. The preprocessor can add and remove blocks of the source code (conditional compilation) and textually change tokens, rewrite text to use different code (preprocessor macros). This preprocessed code, which is still a simple text file, is then *compiled* into an object file. Thus, multiple object files could be created from the same initial source file, albeit with possibly different contents based on build configuration parameters, such as using different include paths for the headers, or defining different macros – the most trivial example would be enabling log emission from certain functions in a debug build.

A set of object files is then *linked* together by the linker to form a binary executable or a library. The linker takes object files and other libraries to form this output binary. Built libraries, which are results of a linking command, can also be used in the creation of other binaries. Thus, the potentially vast number of different object files could be used for multiple binaries, e.g. using 32-bit and 64-bit architectures or built for different system libraries (such as different versions of networking stacks or databases).

Various tools exist which allow the instrumentation of the pipeline in a way that the actual executed commands are available for other software to read and understand, such as the JSON compilation database format [9].

In the case of the C++ programming language, usually the *mangled name* [10], [11] is used to distinguish between different symbols of the same name. The mangled name is constructed using (possibly multiple) namespace and class information by concatenation, but its exact form is compiler-specific. Compilers use mangled names to enable *function overloading* [12], i.e. they generate different mangled names for functions with the same name but different parameter lists. Linkers use these mangled names to resolve symbols [13].

In the case of the C language, there is no such thing as namespace, class, or function overloading [14]. Still, in certain cases, such as specific optimisations on how a method is called, *name decoration* occurs [15]. In this paper we will refer to the name visible to the linker as *mangled name*, both in the context of C and C++ for the sake of simplicity.

While mangled names must be unique for all translation units linked into a single executable, this does not stand for large-scale projects where multiple executables are typical.

III. DESCRIPTION OF THE PROBLEM

In a software development and comprehension activity, one of the most frequent questions users ask are “Where is this method called, or type referenced?” and “What does the declaration or definition of this looks like?” [16]. A software development tool should be able to answer these questions as precisely as possible, as accuracy ensures more optimised usage of the developers’ time spent working. Both questions lead to the fundamental problem of correctly resolving references to the definition and usages of a type, a function, or variable, and other language components.

According to the *One Definition Rule* (ODR) of C++ [17], only one definition of any variable, function, class type, enumeration type, or template is allowed in any one translation unit. When resolving references to ordinary C functions, static and non-virtual C++ member functions, type names or non-polymorphic variables, the unique definition within a single translation unit can be found based on static information. Specifically, the function definition of non-virtual functions or ordinary C functions can be looked up based on function signature, which – according to [18] – contains the name of the function, the enclosing namespace, class of which the function is member of (in the context of C++), the type of the parameters, template parameter list (in case of function templates in C++), *cv*- and *ref*-qualifiers, unique type names (qualified with namespace) and scope-correct variable names.

Since the translation unit containing the reference and the set of translation units linked together is known for the linker, it is possible for the linker to look up the correct, unique definition for any given reference.

There can be, however, more than one definition belonging to the same unique-name or signature, but defined in different translation units that are not linked together. This is a typical scenario in large-scale programs consisting of multiple separate executables and build configurations, e.g. every executable having a *main()* function as entry point.

For a software development or comprehension tool, while the user is browsing a source file, the linkage context (the set of translation units linked together) where the definitions should be resolved is usually unknown [19]. This leads to ambiguous type, function or variable references. In some cases this ambiguity can be resolved automatically, by taking into consideration the linkage information. For example in Figure 1, the reference *f()* in *entry.cpp* can be resolved to the definition in *other.cpp*, since it is known that

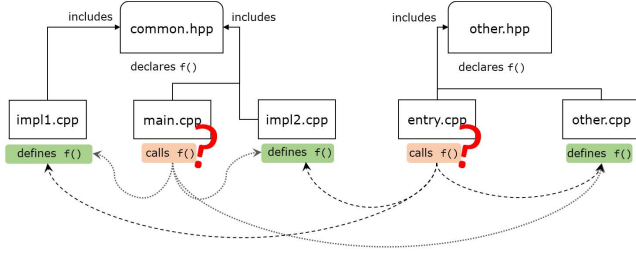


Fig. 1. Jumping to the definition of $f()$ from either call is ambiguous without knowing how translation units are linked together, the name identity-based resolution is not accurate enough.

`entry.cpp` is only linked with `other.cpp` in any target binary.

However, this is particularly problematic if the same source file is compiled into several binaries, such as `main.cpp`, which is compiled into `impl1.out` and `impl2.out`. When, for example the user queries the definition of $f()$ in `main.cpp`, it is impossible to decide whether to present $f()$ in `impl1.cpp` or `impl2.cpp`. In these cases the ambiguity can only be resolved by asking the user to specify the linking context, but asking the linking context should only be done when it is absolutely necessary, to avoid superfluous user interaction that causes disorientation in the comprehension process [20].

The prevalence of the problem was tested on a group of projects with measurement results presented in Table III. It appears that, statistically, a considerable ratio of symbols (0.5 – 10%) are affected – thus the problem is not negligible for its impact on development and code comprehension time when developers have to resolve symbol references using their internal and external knowledge instead of a proper tool solving the problem for them.

IV. STATE OF THE ART

Current well-known development, engineering, and code comprehension tools rarely provide good support for this problem. We have analysed some common tools in terms of their reaction to a “jump to definition” query:

- *Microsoft Visual Studio* [1] shows a disambiguation page when encountering the problem described in this paper. If the entire *solution* (a group of projects handled together) is configured for a certain dependency (i.e. only one of the ambiguous definitions is compiled when the solution is built) and the user changes the internal settings of the solution, Visual Studio decides which symbol a “jump to definition” query jumps to. This fine-tuning on the users’ end seemingly does not affect “get calls”/“get usage”-like queries, which still show results with every possible option present, including those which are clearly not valid in the solution’s current state.
- *JetBrains CLion* [2] analyses and builds symbol information when a project is configured, and one project having multiple separately configured executable targets

misleads the IDE. A certain file is designated as location where function $f()$ is defined – our understanding currently reveals that the file whose appears later in lexicographical order. The ambiguity is present even when a certain executable is being debugged by the IDE with “Step Into” showing the proper implementation being executed while “Jump to Definition” may open an entirely distinct source file.

- *NetBeans* [3] does not show a disambiguation page at all, seemingly jumping to a file first detected for a certain symbol after the last build – this can be overridden by manually setting certain files to “Exclude from Build” after which the file’s symbols won’t contribute to the set of potential results. The file to which NetBeans jumps for a definition varies between client restarts, seemingly in a non-deterministic fashion; the only exception is when the symbol is *defined* in the same file where it is *used*: in this case **all** queries jump to this location in particular.
- *Eclipse* [4] properly prioritises symbols explicitly defined in the same source file. However, if the definition is not found in the file where a query is issued (see examples in Figure 1 and 2), a disambiguation page is shown. Putting different builds into entirely different projects with their own `Makefile` solves this issue, but search queries do not traverse project boundaries.
- *Woboq Code Browser* [5] shows the locations where a symbol is defined when viewing information about a particular symbol, but the problem of Section III is present. Jumping to definition by clicking on a usage location jumps the user to the definition that has been first (in the order of build commands) discovered by the `codebrowser_generator` tool of *Woboq*. It binds usages and definitions in the same source file together, but further “clustering” capabilities are not present.
- *OpenGrok* [6] uses Apache Lucene to index source code and it considers source files as pure textual input with no knowledge of build relationships. This prevents the recognition of “clusters”.

The lack of accuracy seen in the tools means that developers need to invest their own knowledge – which may or may not exist, e.g. when venturing into a different module of a large system – to investigate how symbols affect each other in the code. This imposes a cost on time spent with understanding and developing software.

V. FORMALISATION OF THE PROBLEM

Software engineering and comprehension tools help their users by providing a platform which can be used to execute queries. Such queries include but are not limited to: finding a symbol’s (e.g. a function’s) definition or listing where a symbol is used (e.g. a function is being called). Conceptually these queries involve filtering the set of symbols S until a deemed answer is reached.

The first step in such filtering is to consider an equivalence relation which selects the equivalence set $\mathcal{O}$ of symbol set S which contain only symbols that are related to each other

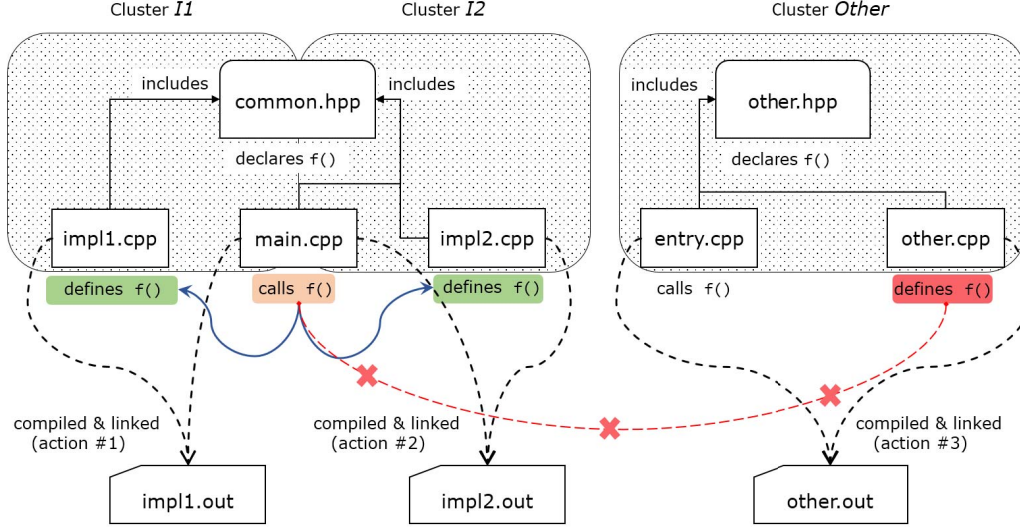


Fig. 2. Developers searching for the definition referenced by the `f()` call in `main.cpp` should be presented with an indication that the definition of a function with this signature in `other.cpp` has no static linkage connection to `main.cpp` – thus it is highly unlikely that the call in `main()` actually refers to this function.

in terms of meaning, such as all `f()` functions. It generally involves maintaining a symbol table (in a database or in the tool’s memory) and using *qualified* names and type information that are more descriptive about a symbol’s nature than verbatim source text. For example, in LLVM/Clang, a function `f()` has a mangled name `_Z1fv`.

The mentioned *jump to definition* and *get function calls* queries from this point involves further filtering this $\mathcal{O}$ set for a certain *definition* symbol or a set of symbols which are of *function call* kind.

Searching based on a symbol’s **mangled name** is usually considered “good enough” because of how the Language Specification lays out rules for symbol interaction in the compilation and linkage process. E.g. a function may only have strictly one definition and every call of this function is bound to that certain definition.

However, the aforementioned queries produce ambiguous results when executed on large-scale projects. This stems from the fact that these tools were developed with the language rules in mind, considering the entire project as a single ultimate binary. E.g. if a symbol is defined multiple times for a binary, – a clear violation of the language rules – the compilation toolchain issues an error for the programmer. Software engineering and comprehension tools could, at most, show a disambiguation page and put weight on the developer’s shoulders to make out which is the “real” definition said call is using.

Consider our example in Figure 1. If we contemplate that all files are sources for exactly one binary, the `f()` calls become ambiguous between the three definitions, while in reality, the programs are well-formed and each call is properly bound to executing the implementation of a single definition, which source has been compiled together with the usage. The func-

tion *defined* in either `impl1.cpp` or `impl2.cpp` is called at one location, while the *declaration* of `f()` in `common.hpp` is part of two binaries: from the declaration’s point of view, considering the entire project, multiple definitions exist.

A. Build sources and targets

We can view build actions as the propagation of symbols from one file to another. A build action always has one or more sources and one or more targets. We can express a program’s or a whole project’s build chain by chaining the usage of the “file is source of” and “file is target of” relations. The source file of a build action in this relation is the direct source file (`.c` or `.cpp`), from which the headers can be inferred by the compiler. The target file is the result of the build action, which is usually an object or a linked binary.

Consider the example depicted in Figure 2. We have `impl1.cpp` and `impl2.cpp` as our source translation units along with `main.cpp`, which are *compiled* and *linked* into `impl1.out` and `impl2.out` (action #1 and #2), respectively. A second binary is created by compiling and linking (action #3) `entry.cpp` and `other.cpp`. In this example, the build commands have a “two source–one target” layout.

B. Clusters

A *cluster* is a set of symbol occurrences which are referable by each other. It is deducible from the language rules (most importantly ODR) that every built binary well-defines its own cluster: every symbol which has been compiled and linked into a given binary is available to each other (in context of “physical” availability and not considering the concept of visibility), and thus part of the cluster formed by the given binary itself. Thus, we can identify the cluster by the ID of the build action that generated the binary which defines a

particular cluster. A symbol occurrence can be part of multiple clusters (just as how the declaration of function $f()$ in Figure 1 is), and in almost every case a cluster contains multiple symbol occurrences.

Symbols are propagated from one file to another via subsequent build actions, forming a chain. The intermediate files in this chain do not carry extra information in terms of symbol availability: if $a.o$ and $b.o$ is linked into $a.out$, the target will contain the symbols from every source. Thus these intermediate files can be omitted without the loss of generality. The solution to the problem described in this paper requires the consideration of *ultimate clusters*, a set of clusters into which symbols are propagated, and from where they are not propagated any further – the leaf nodes of the graph formed from the aforementioned build relations. For our examples in Figure 1 and 2 we consider two ultimate clusters.

C. Calculating a cluster

Assuming that we know the build actions that were used in the compilation of a given project, we can calculate the ultimate clusters for each build action by using the following algorithm. This algorithm takes a single build action B' – usually a *compile* command of a translation unit/source file – and it calculates a set of build actions that represent the ultimate clusters for the symbols found in the input build action’s sources.

In Figure 3, we present an example of output clusters for some inputs on a small project: we had a common object file which is used in both binaries, and executed our algorithm to calculate where symbols of this “common object” are present.

```

Input:  $B'$  build action
let  $C$  be a set of build actions
 $C \leftarrow \{B'\}$ 
expand  $\leftarrow$  true
while expand is true do
  expand  $\leftarrow$  false
   $C' \leftarrow C$ 
  for all  $\beta$  in  $C$  do
    for all  $T$  such that  $T$  is a target of build action  $\beta$  do
      if exists a build action for which  $T$  is a source file
      then {the build chain can be continued}
         $C' \leftarrow \{x \in C' \mid x \neq \beta\}$ 
         $\cup \{x \mid x \text{ build action for which } T \text{ is source}\}$ 
        expand  $\leftarrow$  true
      else {the build chain reached its end, no further
        expansion can happen for  $\beta$ }
        noop
      end if
    end for
  end for
   $C \leftarrow C'$ 
end while
Output:  $C$  ultimate clusters

```

The clusters into which a symbol s is propagated are the collection of all C sets calculated by calling the algorithm on every build action B for which the file containing s is a source.

In the case of symbols found in header files, the previous sentence considers “files containing s ” as the files which include – via any number of hops in the header inclusion chain – the header file where s is found.

In this paper, we propose a way of *enhancing* currently existent search queries by taking advantage of build information and relations described in Section V-A. By calculating the clusters for each symbol, we can walk in the footsteps of the compiler and recreate how the compiler bound and linked symbols together using the record of an executed build.

D. Weighing symbol matches

Consider a set of symbols σ which has been appropriately pre-filtered by a “good-enough” filtering method, e.g. based on *mangled names* described in Section V. For each of these symbols, we calculate the clusters in which a symbol is found, and if two symbols have at least one common cluster, i.e. they appeared in the same binary at least once, the relation between them is considered a **strong match**. A strong match definitely indicates that the compiler – in accordance with the language rules – did emplace a relation between the two symbols, e.g. a function call was linked to use the definition which was found in the same cluster.

On the contrary, if the two symbols never appear in a common cluster, the relation is considered a **weak match**. A weak match indicates that no *discovered* relationships enforce strength to the match, but the symbols could still be related to each other. A weak match could, e.g., indicate a function which is called from a dynamically loaded library.

We also define a third category called **indefinite match** for matches that are indefinite in their strength – no extra information could have been retrieved from calculating the clusters or the clusters do not exist at all. This could happen from the fact that certain translation units were not compiled or we have no build information (see Section V-A) available. We will see in Section VI-D that certain matches will deliberately fall into the latter category due to optimisation reasons. The fact that a match does not have any strength indication does not decrease search efficiency and accuracy any further, because in this case, the query results are unambiguous based on previously available properties, such as mangled name equivalence, and thus the clusters need not be investigated.

The algorithm which categorises symbol references based on the aforementioned “weights” is as follows:

- 0) A query (e.g. a “definition search”) is based on an input parameter (ξ), a particular occurrence of a symbol, e.g. a single function call in some translation unit.
- 1) The query is executed, and produces a set of symbols, which are *candidate results* – this process usually encompasses a mangled-name-based search. In the context of the previous “definition search” example, candidate results are definitions which match the call symbol’s mangled name.
- 2) **If and only if** the query results are ambiguous (based on language rules and the context of the query), we take clustering information into consideration for each

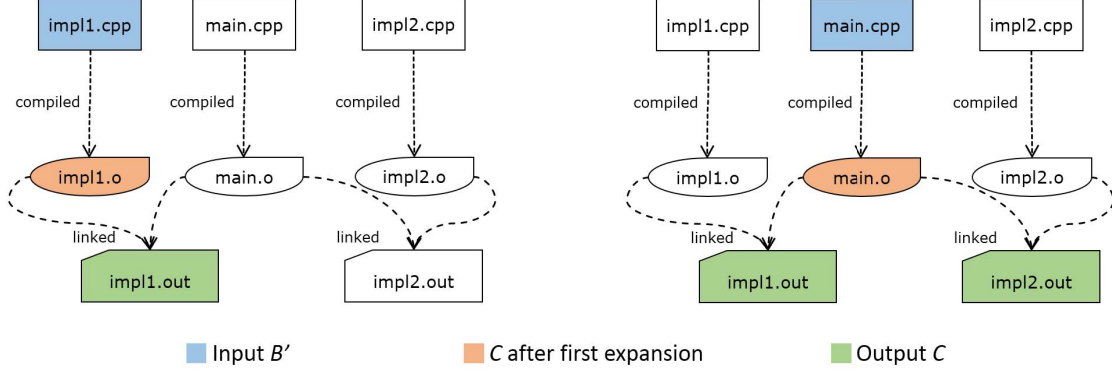


Fig. 3. An example of the clustering algorithm started from two inputs. Arrows indicate build (compile and link) actions. A common object file's content is propagated into multiple binaries, thus the symbols of its source file is assigned to multiple clusters.

candidate s and define *match strength* based on the relation below. (Note that this relation is symmetrical and is applicable between every pair of symbols.)

Let C_ξ be the set of clusters in which ξ is found, and C_s the set of clusters for a particular candidate result s .

$$\mathcal{R}(\xi, s) = \begin{cases} \text{strong,} & C_\xi \neq \emptyset \wedge C_s \neq \emptyset \wedge C_\xi \cap C_s \neq \emptyset \\ \text{weak,} & C_\xi \neq \emptyset \wedge C_s \neq \emptyset \wedge C_\xi \cap C_s = \emptyset \\ \text{indefinite,} & C_\xi = \emptyset \vee C_s = \emptyset \end{cases}$$

Consider the example depicted in Figure 2. For this project, assume that a user searched for the definition of $F::f()$ from a function call in `main.cpp`. Having the symbols in the project filtered by the mangled name, there are three *candidate* functions, from which two are *strong matches* and one is a *weak match*.

VI. IMPLEMENTATION

To test our algorithm in an industrial setting, we implemented the solutions in the CodeCompass tool. CodeCompass [7] is an open source web-based comprehension tool that helps in understanding large-scale software systems written in C/C++, Java or Python. CodeCompass utilises the LLVM/Clang [21] compiler infrastructure to analyse C and C++ source code and build an Abstract Syntax Tree (AST). It gives exact information about complex C/C++ language elements like overloading, inheritance, read or write locations of variables, possible calls on function pointers, virtual functions, or automatically generated methods – features that various existing tools support only partially. This information is saved into a database, and on a web interface, queries can be executed and visualisations – such as component diagrams, or class diagrams – can be rendered.

A. Store clusters information for every AST node

Our first approach was to store which AST node is found in which cluster for every AST node visited by the parser. Parsing a project involves registering the build actions (see Section V-A) and then visiting the AST and storing information for every source file in the project. We calculated the

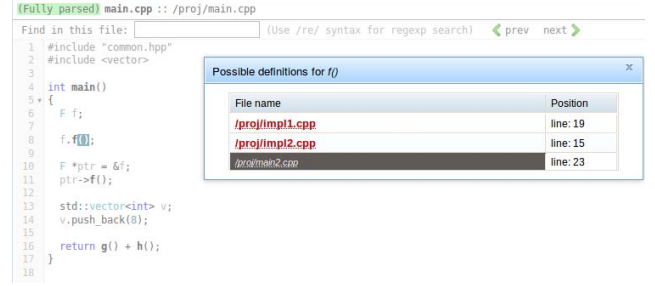


Fig. 4. Query results are shown by CodeCompass indicating their weight in a disambiguation page – *strong matches* are shown with a bold font while *weak matches* have a background colour attached.

clusters for each parsed source file and saved this set for each and every node in a new database table.

This made the previously described search enhancement very straightforward as we could instantly read the cluster information for the candidate nodes, but the time it took for a project to be parsed increased drastically, and so did the database's size.

Apache Xerces [23] has 123 882 AST nodes discovered by the parser which are related to function and type usage. The total count of different symbols appearing in different built binaries is 2 934 570, which is the number of new rows in the database. Calculating this information took 7 minutes (an increase of 100% compared to parse time without this new feature) and storing this extra data increased the database size from 190 MiB to 403 MiB, a 112% increase – this was considered to put an enormous strain on the process for larger projects by wasting processor time and thus we decided to discard this idea.

B. Store clusters for select AST nodes only

We have attempted to lessen the size requirement of storing this data by performing a cleanup routine after a project was parsed. To this end, we defined certain ambiguity criteria (see Section VII) for symbols of a certain type and our cleanup procedure only kept information about AST nodes where the

TABLE I
PARSING PERFORMANCE OF FILE-BASED CLUSTERING (SECTION VI-C)

	LLVM/Clang	LLVM/Linux	Xerces
Build time	18.5m	1m 36s	37.5s
Parse time w/o clusters	267m 20s	118m 17s	3m 53s
~ w/ clusters	350m	124m	4m
DB size w/o clusters	14 120 MiB	1 706 MiB	193 MiB
# of files	47 931	54 213	3 336
# of build actions	2 274	2 017	648
# of cluster info rows	734 332	835 724	46 273
Database overhead	40 MiB (.0028%)	43 MiB (.025%)	2.5 MiB (.013%)

calculated information could *actually* contribute to enhancing the accuracy of queries.

For Xerces, we found that from the almost 3 million extra rows in the database, only 31 949 rows had the aforementioned property. This post-processing step decreased the final, persistent database size to a 35% increase (compared to the size without using this feature), however, this post-processing step incurred an extra 2 hours – after a 7 minute parse of Xerces – of time increase whilst it also institutionalised the fact that 99% of the rows were calculated only to be deleted in the end.

It was obvious to us that such increase in either space usage and time requirement would not scale well at all for any software project beyond a few mebibytes, like CodeCompass [7] itself or LLVM/Clang [21] or LLVM/Linux kernel [24].

C. Store clusters for every file

Utilising the fact that the compiler treats source code as a set of interconnected files instead of a set of AST nodes we have decided to encompass this view. The containing file for every AST node is stored in the database. This change reduced the time it took to persist information about one translation unit greatly as there were only one set of cluster-information rows for each file instead of *num of nodes * num of clusters calculated*. Calculating a file’s cluster information in the context of a build action from which it is visited (see Section V-C) stayed the same and there were no impacts on query performance either.

However, this granularity shift introduced a problem with duplication, because a file can appear multiple times in the build actions of the project, and these appearances may lead to different binaries, thus, map the same file to different clusters. This was a very prominent issue with header files which are used almost everywhere in the codebase. We solved this by carefully deduplicating the entries.

We present the measurements of this process in Table I. The runtime increase is clearly visible as we consider larger projects, with LLVM/Clang showing a 33% increase in parse times. We have profiled our implementation and discovered that even comparing only integers, the deduplication contributes to large amounts of the time increase. Our measurement tests were run in a 24-core environment (with ~ 40 GiB of RAM, and database stored on enterprise-grade solid-state drives) so there were a maximum of 24 parsing threads allowed to run at any given time. We had to carefully make

the implementation thread-safe as the information of clusters is a project-level one. Due to locking, on many occasions in the process of parsing LLVM/Clang as much as half of the threads were waiting for one thread to persist its calculated data.

D. Store clusters for only certain files calculated heuristically

Drawing the conclusions from our previous approaches’ efficiency, we developed our final solution which combines the ideas described in Section VI-B and VI-C. We decided to keep the clusters’ on file-level scale, but instead of calculating and storing the cluster information of every file we stored information for files which contain certain symbols.

Taking into account that certain queries cannot benefit from clustering information for certain inputs – using a set of criteria (see Section VII) we established in Section VI-B – files that only contain references to such non-ambiguous nodes need not have their clusters calculated and persisted. We have decided not to modify the currently implemented parsing process at all, but instead implement a project-level post-process routine which could be expressed with the algorithm as follows:

```

1:  $\Sigma \leftarrow \emptyset$ 
2:  $\mathcal{S} \leftarrow$  set of ambiguous mangled names
3: for all  $s$  in  $\mathcal{S}$  do
4:    $\Sigma \leftarrow \Sigma \cup \{f \text{ file} \mid f \text{ contains a symbol with mangled name } s\}$ 
5: end for
6: for all  $f$  in  $\Sigma$  do
7:    $\mathcal{B} \leftarrow \{\beta \text{ build action} \mid f \text{ is a "source-of" } \beta\}$ 
8:    $\mathcal{B}' \leftarrow \text{calc\_cluster}(\mathcal{B})$ 
9:    $\text{persist}(f, \mathcal{B}')$ 
10: end for

```

The algorithm takes the following steps to calculate the clustering information:

- 1) (Line 2) A database query is executed which generates a set of mangled names which are definitely ambiguous by certain criteria (see Section VII) – we need the entire project to have been successfully parsed to discriminate on this property.
- 2) (Line 4) We create the list of files which contain references to symbols having mangled names generated in Step 1.
- 3) (Line 7) The *entry build action* set $\mathcal{B}$ is calculated for every marked file f . The entry build action set for a file is the set of build actions for which the file was first discovered by the parser: it was either a “source-of” or a header included into a “source-of” file (see Section V-A).
- 4) (Lines 8,9) These sets are formed into clusters with the procedure described in Section V-C, and the resulting clusters are persisted in the database.

Calculating clusters for multiple build actions one-by-one and then taking the union of the result is the same – in terms of the result – as starting with a $\mathcal{C}$ containing all entry build actions, so we modified the `calc_cluster` algorithm (see

TABLE 2-A
PARSING PERFORMANCE OF HEURISTIC FILE-BASED CLUSTERING
(SECTION VI-D) – “SMALLER” PROJECTS

	Xerces	CodeCompass
Source size	26 MiB	103 MiB
Build time	37.5s	3m 7s
Parse time w/o clusters	1m 48s	25m 16s
~ w/ clusters	1m 50s	25m 38s
# of files	1 753	4 451
~ involved in clustering	45 (2.57%)	82 (1.84%)
# of build actions	648	663
# of cluster info rows	445	6 425
Database overhead	64 KiB (.0004%)	448 KiB (.000204%)

Section V-C) to accept a set of build actions instead of exactly one build action and initialise its inner $\mathcal{C}$ with this input set, which increased the efficiency of our solution.

The calculations of Σ , $\mathcal{S}$ and $\mathcal{B}$ (for each file) were joined together into a single SQL query which returns (FileID, ClusterID) pairs. Queries of this magnitude (containing multiple Common Table Expressions [26]) can be heavily optimised by database engines which gave our solution another improvement in efficiency. Executing the equivalent algorithm written natively in C++ took CodeCompass 2 hours for Xerces (see Section VI-B) while a single query produced the results in under 10 seconds. The `calc_cluster` algorithm is then executed for every $\mathcal{B}$ in an independent, multi-threaded setup which further increased efficiency.

We measured the parse time increase compared to without this feature on some sample projects and were satisfied with the results: the impact our feature has on parse time is virtually nonexistent despite the increase in the project’s complexity. The amount of files that needed the calculations described in this paper were considerable, but – as seen in Tables 2-A and 2-B – the number correlates with the inner layout and complexity of the source code. The measurements are depicted in the form a diagram in Figure 5. Our measurements were

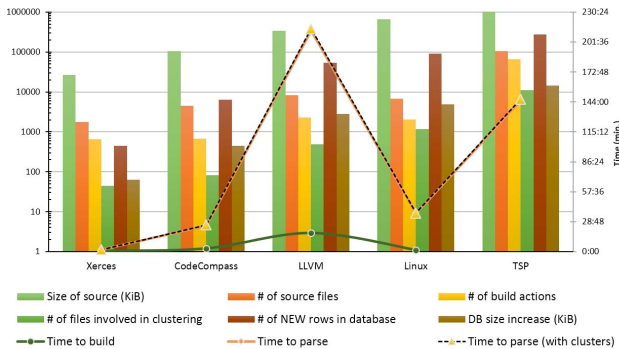


Fig. 5. Project measures and parsing performance of the solution described in Section VI-D. The most important result is that the solid and dashed lines representing time taken overlap each other – showing that calculating the clusters virtually does not impact performance at all.

TABLE 2-B
PARSING PERFORMANCE OF HEURISTIC FILE-BASED CLUSTERING
(SECTION VI-D) – “LARGER” PROJECTS

	LLVM	Linux	TSP [25]
Source size	328 MiB	642 MiB	1 109 MiB
Build time	18.5 m	1m 36s	—
Parse time w/o clusters	3h 32m 24s	36m 56s	2h 25m 17s
Parse time w/ clusters	3h 34m 16s	37m 9s	2h 26m 45s
# of files	8 346	6 676	103 601
~ involved in clustering	486 (5.82%)	1 163 (17.42%)	11 072 (10.69%)
# of build actions	2 262	2 017	65 558
# of cluster info rows	54 053	92 014	276 174
Database overhead	2 816 KiB (.000205%)	4 824 KiB (.00321%)	13 670 KiB (.00263%)

run focusing on the impact of the implementation described in this paper and we purposefully disabled other orthogonal capabilities (e.g. metrics calculation, Python parser, etc.) of CodeCompass.

Due to the efficient clusterisation algorithm, the parsing time increase only by $\sim 2\%$ even for large (over 10 million lines) software projects – see Table 2-B for measurements. The run-time performance of definition and reference (e.g. function callers, a type reference) lookup did not deteriorate in any noticeable extent. This means that this new symbol reference disambiguation feature could be introduced without any performance penalty which could hinder development and code comprehension.

As discussed previously in Section V-D, certain information is lost in this solution compared to previous ones. Files which only contain symbols which are unique across the entire project (see Section VII) are not considered at all for clustering as the *mangled-name*-based search is enough to produce accurate results. This is the reason behind the *indefinite match* category defined in the aforementioned section: a function call to $f()$ – assuming that $f()$ is a uniquely defined function in the entire project – is most definitely linked with the only definition, any other combination would be considered a violation of the Language Specification and produce a compile/link error. Storing this information would be superfluous and we have thoroughly discussed and reviewed our criteria and decided that this loss is negligible compared with the efficiency gain.

VII. AMBIGUITY CRITERIA

The solution described in Section VI-D requires well-formed criteria by which it considers a mangled name ambiguous. We have researched the following criteria to be sufficient in our C++ context of large projects for enhancing search accuracy.

In Table III, we show our measurements on how many of such problematic symbols were found for our test projects.

A. Functions

A function symbol $f()$ (mangled name in LLVM/Clang: `_Z1fv`) is considered ambiguous if neither of the following

TABLE III
NUMBER OF FUNCTIONS AND TYPES DISCOVERED AND FOUND AMBIGUOUS IN OUR TESTS PROJECTS (IN PARENTHESES FOR **NAMES** AND **NODES** THE NUMBER OF AMBIGUOUS NAMES AND NODES; FOR *Decl.*, *Def.*, AND *Usage*, THE RATIO OF SUCH NODES AMONGST ALL NODES)

	Functions					Types				
	Names	Nodes	<i>Decl.</i>	<i>Def.</i>	<i>Usage</i>	Names	Nodes	<i>Decl.</i>	<i>Def.</i>	<i>Usage</i>
Xerces [23]	18 547 (19, 0.1%)	63 167 (348, 0.5%)	14 933 (23%)	11 123 (18%)	37 111 (59%)	2 849 (9, 0.3%)	60 715 (329, 0.5%)	2 248 (4%)	1 402 (2%)	57 065 (94%)
CodeCompass [7]	337 833 (143, 0.04%)	622 220 (473, 0.07%)	229 737 (37%)	127 864 (20%)	264 619 (43%)	346 387 (1 315, 0.4%)	779 523 (9 461, 1.2%)	182 413 (23%)	169 124 (22%)	427 986 (55%)
LLVM [21]	1 793 978 (334, 0.02%)	4 545 086 (16 469, 0.4%)	1 213 123 (27%)	708 156 (16%)	2 623 807 (57%)	1 628 232 (7 192, 0.5%)	4 206 743 (73 375, 1.8%)	860 245 (20%)	789 886 (19%)	2 556 612 (61%)
Linux [24]	70 579 (503, 0.7%)	411 691 (11 074, 2.7%)	33 746 (8%)	66 228 (16%)	311 717 (76%)	19 883 (188, 1%)	159 581 (579, 0.3%)	1 990 (1%)	20 029 (13%)	137 562 (86%)
TSP [25]	410 946 (9 721, 2.3%)	2 091 578 (194 118, 9.3%)	377 393 (18%)	321 964 (15%)	1 392 221 (67%)	196 374 (2 478, 1.2%)	2 108 217 (74 511, 3.5%)	62 914 (3%)	162 226 (8%)	1 883 077 (89%)

conditions hold true for all symbols having this particular mangled name in the entire project:

- The function has exactly one *definition* node – in this case, this definition would be *the* definition
- The function does not have a *definition* node, but has exactly one *declaration* node – in this case, the “definition” becomes this single declaration node
- The function has neither a *definition* node nor a *declaration* node – in this case, we do not present a “definition” to the user as none were discovered

B. Types

A type T (mangled name in LLVM/Clang: T) is considered ambiguous if it is *defined* more than once in the entire project. Types can be *declared* as many times as needed.

A header discovered to be included multiple times in the same translation unit does not constitute as multiple definitions in CodeCompass – however, without a *header guard*, it would constitute as such and violate the language rules in a single compile/link action.

VIII. RELATED WORK

Producing clusters by decomposing large-scale software and observing the build toolchain of a project is not unknown. Richard C. Holt emphasises on the importance of linkage information when it comes to extracting software models in [27]. Their approach uses the information retrieved from the linker to resolve dangling references in software models created by extractors, such as Columbus [28]. Our research was centered on the code comprehension of large-scale systems with a well-scaling algorithm on the source code level, using hard facts retrieved from the toolchain.

Hou and Hoover discussed a way of using Abstract Syntax Graphs (ASGs) to further the accuracy of fact extracting tools used on source code. This method, called *source-level linking* [29], uses the ASG to retrieve a broader variety of information, as most extractors consider information on a per-translation unit level, where information useful for the software engineer can be lost.

Van der Burg *et al.* implemented a way of checking the license compliance of software products that use a variety of open-source software components by recording the steps taken when the product was built [30]. Our approach is similar to

theirs in terms of using exact build information, however, our goal was to show the connection between symbols in the built components.

IX. FUTURE WORK

Language Server Protocol [22], a JSON-RPC based protocol was announced by Microsoft and RedHat in Summer 2016. Its aim is to provide a common interface (already implemented for some languages, such as JavaScript and C#, and in some development tools, such as *Visual Studio Code*) between development environments, code navigation tools, and “language servers” providing services for features of a particular language, such as the aforementioned queries, or refactorings.

The interface provided by LSP offers an easy way of adding the enhancement described in this paper to the development tool infrastructure, which would alleviate the need of having to implement the algorithm in the most common IDEs and code navigators (see Section IV) individually. Providing support for LSP in CodeCompass is an undergoing effort as of now. We would like to increase our data by testing our solution on more projects. In terms of further developing our solution, a few routes are available and yet to be taken by us.

The clustering approach we have taken in our current implementation has proven robust enough to effectively be used in CodeCompass. We aim to consider the development of methods which aid in the discovery and modelling of dynamic type information and polymorphic reference bindings, which will further enhance the accuracy of our clustering method. The consideration of dynamically referenced symbols goes further than dynamic polymorphism in the project, we also aim for increasing the accuracy by discovering symbols in shared libraries and pure dynamically loaded objects, e.g. those referenced through *dlopen()*.

We would like to reduce the size of the data stored by excluding code with known semantics and easily resolvable duplication, e.g. parts of the Standard Template Library, from the ambiguity check process.

The development of further heuristics to ensure a finer-grained way of weighing matches (see Section V-D) is expected to decrease the number of false positive *weak matches*.

A problem similar to that described in Section III can be applied to other programming languages, e.g. in *Java*, different

classpaths could be considered as “linkage” information and the question of “How symbols reference each other?” is applicable for packages built with different configuration in a large-scale project.

X. CONCLUSION

Resolving symbol references is the base of many essential functionalities implemented in software development tools, code comprehension, and static analysis systems. These actions include finding the exact definition of a function call, listing all the call sites of a given function or the place of usage of a given variable, or where we used a certain type.

Most of the available tools implement these features for C/C++ based on mangled names. Unfortunately, using mangled names only may lead to ambiguity when different symbols with the same mangled name are defined in different translation units and assembled to different binary executables. In this paper we investigated this ambiguity in large C/C++ systems. We found, that this problematic scenario happens quite often for large systems compiled into different platforms (e.g. both 32 and 64 bit) as well as systems with extensive binary set of examples and test cases. Current state of the art tools are ignoring this problem which we found to affect a considerable ratio (0.5 – 10%) of symbols.

As this phenomenon may negatively affect code comprehension we suggest a clustering algorithm based on build actions to reason whether symbols with the same mangled name are identical or (likely) different. Although the method leaves some uncertainty for cases where symbols are resolved dynamically – e.g. via `dlopen` – in practice, it dramatically increases the accuracy of the symbol resolution.

We implemented our method as part of the open source CodeCompass code comprehension framework. CodeCompass utilises the LLVM/Clang compiler infrastructure to analyse systems in the gigabyte scale, and present quickly navigable source code to the user. Existing development environments can utilise our results to increase the quality of symbol resolution in two ways. They can either implement our clustering method as it requires only information which is already available for those tools, or – implementing Language Server Protocol – they can use CodeCompass as a symbol resolution server.

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