Clone Detection Using Abstract Syntax Suffix Trees

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Abstract

Reusing software through copying and pasting is a continuous plague in software development despite the fact that it creates serious maintenance problems. Various techniques have been proposed to find duplicated redundant code (also known as software clones). A recent study has compared these techniques and shown that token-based clone detection based on suffix trees is extremely fast but yields clone candidates that are often no syntactic units. Current techniques based on abstract syntax trees—on the other hand—find syntactic clones but are considerably less efficient.

This paper describes how we can make use of suffix trees to find clones in abstract syntax trees. This new approach is able to find syntactic clones in linear time and space. The paper reports the results of several large case studies in which we empirically compare the new technique to other techniques using the Bellon benchmark for clone detectors.

1 Introduction

It is still a common habit of programmers to reuse code through copy&paste. Even though copy&paste is an obvious strategy of reuse and avoidance of unwanted side effects if a programmer does not oversee the consequences of a change to an existing piece of code, this strategy is only a short-term win. The interests of these strategies must be paid back later by increased maintenance through replicated changes in all copies if the original code must be corrected or adapted.

Although some researchers argue not to remove clones because of the associated risks, there is a consensus that clones need to be detected at least. Detection is necessary to find the place where a change must be replicated and also useful to monitor development in order to stop the increase of redundancy before it is too late.

Detecting duplicated code (also known as software clones) is an active research area. A recent study has compared these techniques and shown that token-based clone detection based on suffix trees is extremely fast but yields clone candidates that are often no syntactic units [6]. Current techniques based on abstract syntax trees (AST)—on the other hand—find syntactic clones but are considerably less efficient.

There are additional reasons for AST-based clone detection beyond better precision. Because most refactoring tools are based on ASTs, they need to access clones in terms of nodes in the AST if they support clone removal. Furthermore, ASTs offer syntactic knowledge which can be leveraged to filter certain types of clones. For instance, one could exclude clones in declarative code or strictly sequential assignments as in constructors, which are often unavoidable. From a research point of view, it would be also interesting to categorize and see where the redundancy occurs mostly in syntactic terms [14]. Such empirical studies could also help to identify programming language deficiencies.

Contributions. This paper describes how we can make use of suffix trees to find duplicates in abstract syntax trees. This new approach is able to find syntactic duplicates in linear time and space. The paper reports the results of several large case studies in which we empirically and quantitatively compare the new technique to nine other techniques using the Bellon benchmark for clone detectors. As a side effect of our case study, we extend the Bellon benchmark by additional reference clones.

Overview. The remainder of this paper is organized as follows. Section 2 summarizes related research. In particular, this section describes clone detection based on suffix trees and ASTs in detail as they form the foundation of our new technique. Section 3 introduces the new technique. In Section 4, we compare the new technique to other techniques based on the Bellon benchmark for clone detectors.

2 Related Research

The foremost question to answer is "What is a clone?" Generally speaking, two code fragments form a clone pair if they are similar enough according to a given definition of similarity. Different definitions of *similarity* and associated levels of tolerance allow for different kinds and degrees of clones.

Ideally, code is free of redundancy. A piece of code, A, is redundant if there is another piece of code, B, that subsumes the functionality of A, in other words, they have "similar" pre and post conditions. We call such a pair (A, B) a *semantic* clone. Unfortunately, detecting semantic clones is undecidable in general.

Another definition of similarity considers the program text: Two code fragments form a clone pair if their program text is similar. The two code fragments may or may not be equivalent semantically. These kinds of clones are most often the result of *copy&paste*; that is, the programmer selects a code fragment and copies it to another location.

Clones of this nature may be compared on the basis of the program text that has been copied. We can distinguish the following types of clones:

- **Type 1** is an exact copy without modifications (except for whitespace and comments).
- **Type 2** is a syntactically identical copy; only variable, type, or function identifiers have been changed.
- **Type 3** is a copy with further modifications; statements have been changed, added, or removed.

Several techniques have been proposed to find these types of clones.

Textual comparison: whole lines are compared to each other textually [12] using hashing for strings. The result may be visualized as a dotplot, where each dot indicates a pair of cloned lines. Consecutive duplicated lines can be spotted as uninterrupted diagonals or displaced diagonals in the dotplot [9].

Token comparison: Baker's technique is also a line-based comparison where the token sequences of lines are compared efficiently through a suffix tree. First, each token sequence for whole lines is summarized by a so called *functor* that abstracts of concrete values of identifiers and literals.

The functor characterizes this token sequence uniquely. Concrete values of identifiers and literals are captured as parameters to this functor. An encoding of these parameters abstracts from their concrete values but not from their order so that code fragments may be detected that differ only in systematic renaming of parameters. Two lines are clones if they match in their functors and parameter encoding.

The functors and their parameters are summarized in a trie[1] that represents all suffixes of the program in a compact fashion. Every branch in this trie represents program suffixes with common beginnings, hence, cloned sequences. A more detailed description follows in Section 2.1.

Kamiya et al. increase recall for superfluous different, yet equivalent sequences by normalizing the token sequences [13].

[1]A trie, or prefix tree, is an ordered tree data structure that is used to store an associative array where the keys are strings.

Because syntax is not taken into account, the found clones may overlap different syntactic units, which cannot be replaced through functional abstraction. Either in a preprocessing [7, 10] or post-processing [11, 13] step, clones that completely fall in syntactic blocks can be found if block delimiters are known.

Metric comparison: Merlo et al. gather different metrics for code fragments and compare these metric vectors instead of comparing code directly [19, 17, 8, 20]. An allowable distance (for instance, Euclidean distance) for these metric vectors can be used as a hint for similar code.

Comparison of abstract syntax trees (AST): Baxter et al. partition subtrees of the abstract syntax tree of a program based on a hash function and then compare subtrees in the same partition through tree matching (allowing for some divergences) [5]. A similar approach was proposed earlier by Yang [27] using dynamic programming to find differences between two versions of the same file.

Comparison of program dependency graphs: control and data flow dependencies of a function may be represented by a program dependency graph; clones may be identified as isomorphic subgraphs [18, 16].

Other techniques are based on latent semantic indexing [22], data mining [26], and combination of different techniques [21].

In the following section, we will go into details of token-based clone detection and AST-based clone detection as they build the foundation for our own algorithm.

2.1 Token-Suffix-Tree based Detection

Efficient token-based clone detection is based on suffix trees, originally used for efficient string search [23]. Brenda Baker has extended the original algorithm to parameterized strings for clone detection [2]. Baker's approach offers the advantage of finding cloned token sequences with consisting renaming of parameters (variables and literals can be treated as parameters). To simplify the description, however, we prefer to describe the original string-based approach as follows. For computer programs, we apply this kind of clone detection to the tokens of the program.

We will use the following string as an example (two concatenated titles of research papers on clone detection):

Clone Detection Using Abstract Syntax Trees Clone Detection Using Abstract Syntax Suffix Trees

A suffix tree is a representation of a string as a trie where every suffix is presented through a path from the root to a leaf. The edges are labeled with the substrings. Paths with common prefixes share an edge. Suffix trees are linear in space with respect to the string length (the edge labels are stored as indexes of start and end token of a substring) and there are linear algorithms to compute them [23, 25].

The suffix tree for our running example is shown in Figure 1 where we use the first letter as an abbreviation for

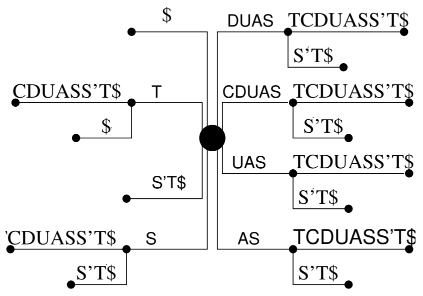


Figure 1. Suffix Tree for *CDUASTCDUASS'T$*; **the large dot is the root**

the words in the text (e.g., *A* for *Abstract*) and *S'* denotes *Suffix*. That is, we construct the suffix tree for the string *CDUASTCDUASS'T$*. The unique character *$* denotes the end of the string.

A clone can be identified in the suffix tree as an inner node. The length is the number of characters from the root to this inner node. The number of occurrences of the clone is the number of the leaves that can be reached from it. For instance, *CDUAS* occurs twice and has length 5 and *AS* occurs twice, too, but has length 2.

As shown in the suffix tree, there are six clones in the text, but we notice, too, that all of them except *T* are suffixes of the longest one, namely, *CDUAS*. Baker describes an algorithm to determine the maximal clone sequences in the tree efficiently [3] .

A filter on minimal length can be used to exclude irrelevant clones such as *T*. In summary, we detect that the string "Clone Detection Using Abstract Syntax" occurs twice.

2.2 AST-based Detection

Baxter et al. have proposed a clone detection technique based on AST. To find clones in the AST, we need – in principal – to compare each subtree to each other subtree in the AST. Because this approach would not scale, Baxter et al. use a hash function that first partitions the AST into similar subtrees. Because such a hash function cannot be perfect (there is an infinite number of possible combinations of AST nodes), it is necessary to compare all subtrees within the same partition in a second step. This comparison is a tree match, where Baxter et al. use an inexact match based on a similarity metric. The similarity metric measures the fraction of common nodes of two trees. Cloned subtrees that are themselves part of a complete cloned subtree are combined to larger clones. Special care is taken of chained nodes that represent sequences in order to find cloned subsequences.

2.3 Token based versus AST based

The analysis based token-suffix trees offers several advantages over other techniques. It scales very well because of its linear complexity in both time and space, which makes it very attractive for large systems. Moreover, no parsing is necessary and, hence, the code may be even incomplete and syntactically incorrect. Another advantage for a tool builder is that a token-based clone detector can be adjusted to a new language in very short time [24]. As opposed to text-based techniques, this token-based analysis is independent of layout (this argument is not quite true for Baker's technique, which is line based; however, if one uses the original string-based technique, line breaks do not have any effect). Also, token-based analysis may be more reliable than metrics because the latter are often very coarse-grained abstractions of a piece of code; furthermore, the level of granularity of metrics is typically whole functions rather than individual statements.

Two independent quantitative studies by Bellon/Koschke [6] and Bailey/Burd [1] have shown that token-based techniques have a high recall but suffer from many false positives, whereas Baxter's technique has a higher precision at the cost of a lower recall.

In both studies, a human analyst judged the clone candidates produced by various techniques. One of the criteria of the analysts was that the clone candidate should be something that is relatively complete, which is not true for token-based candidates as they often do not form syntactic units. For instance, the two program snippets left and right in Listing 1 are considered a clone by a token-based analysis because their token sequence is identical:

return id ; } int id ( ) { int id ;

Although from a lexical point of view, these are in fact rightful clones, a maintenance programmer would hardly consider this finding useful.

```
 return result;         return x; }
}
int foo() {            int bar () { int y;
  int a;
```

Listing 1. Spurious clones

Syntactic clones can be found to some extent by token-based techniques if the candidate sequences are split in a postprocessing step into ranges where opening and their corresponding closing tokens are completely contained in a sequence. For instance, by counting matching opening and closing brackets, we could exclude many spurious clones such as the one in Listing 1. However, programming languages do have many types of delimiting tokens beyond brackets. The `if`, `then`, `else`, and `end if` all constitute syntax delimiters in Ada. In particular, `end if` is an interesting example as two consecutive tokens form one delimiter, of which both can be each individual delimiters in other syntactic contexts. If one wants to handle these delimiters reliably, one is about to start imitating a parser by a lexer.

The AST-based technique, on the other hand, yields syntactic clones. And it was Baxter's AST-based technique with the highest precision in the cited experiment. Moreover, the AST-based clone detection offers many additional advantages as already mentioned in the introduction.

Unfortunately, Baxter's technique did not match up with the speed of token-based analysis. Even though partitioning the subtrees in the first stage helps a lot, the comparison of subtrees in the same partition is still pairwise and hence requires quadratic time. Moreover, the AST nodes are visited many times both in the comparison within a partition and across partitions because the same node could occur in a subtree subsumed by a larger clone contained in a different partition.

Another point is that the construction of the AST is more expensive than the generation of a token stream. And with a post processing step the token based approach will lead to similar results in the area of eliminating syntactic incomplete clones. We assume however that the clone detection is part of a larger system (a tool chain, a refactoring tool, or an IDE) and the AST is already available.

It would be valuable to have an AST-based technique at the speed of token-based techniques. In the next section, we show how a linear-time analysis can be achieved.

3 Approach

The algorithm consists of the following steps:

1. parse program and generate AST
2. serialize AST
3. apply suffix tree detection
4. decompose resulting type-1/type-2 token sequence into complete syntactic units

Subsequent type-1 and type-2 can be combined to larger type-3 clones with Baker's technique based on dynamic programming [4] (our implementation currently does not support that). Step (1) is a standard procedure which will not be discussed further. Step (3) has been described in Section 2.1. We will primarily explain step (4) step-by-step. We will first explain the serialization of the AST and then present the algorithm to cut the cloned token sequence into syntactic units.

3.1 Serializing the AST

We will use the example in Listing 2 as an example to illustrate the algorithm. The AST corresponding to Listing 2 is shown in Figure 2.

```
if x + y then a := i; else foo; end if;
if p     then a := j; else foo; end if;
if q     then z := k; else bar; end if;
```

Listing 2. Sequence of if statements in Ada

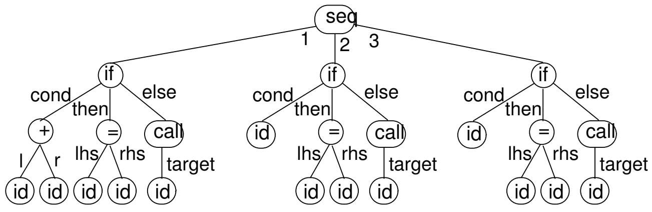


Figure 2. Example AST

Because the token-based clone detection is based on a token stream, we need to serialize the AST nodes. We serialize the AST by a preorder traversal. For each visited AST node N, we emit N as root and associate the number of arguments (number of AST nodes transitively derived from N) with it (in the following presented as subscript).

Note that we assume that we traverse the children of a node from left to right according to their corresponding source locations so that their order corresponds to the textual order.

The serialized AST nodes produced in step (2) for the example are shown in Listing 3.

```
seq_23
   if_8 +_2 id_0 id_0 =_2 id_0 id_0 call_1 id_0
   if_6 id_0 =_2 id_0 id_0 call_1 id_0
   if_6 id_0 =_2 id_0 id_0 call_1 id_0
```

Listing 3. Serialized AST nodes

The serialized form is isomorphic to the original AST. Hence, no clones are lost and no artificial syntactic clones are introduced.

3.2 Suffix Tree Detection

The original suffix tree clone detection is based on tokens. In our application of suffix trees, the AST node type plays the role of a token. Because we use the AST node type as distinguishing criterion, the actual value of identifiers and literals (their string representation) does not matter because they are treated as AST node attributes and hence are ignored. The actual value of identifiers and literals becomes relevant in a postprocessing step where we make the distinction between type-1 and type-2 clones.

Instead of Baker's algorithms for parameterized strings, we are using the simpler string-based algorithm by Ukkonen [25]. Consequently, the token-based clone detection returns equivalence classes of type-1 and type-2 clones as we do not distinguish type-1 and type-2 clones at this stage.

For our running example, the two representative cloned token sequences in Listing 4 and Listing 5, respectively, would be considered.

```
  if_6 id_0 =_2 id_0 id_0 call_1 id_0
-- in line 3 and 4
```

Listing 4. Cloned token sequence

```
id_0 =_2 id_0 id_0 call_1 id_0
-- in line 2 (token pos. 4-9), 3, and 4
```

Listing 5. Cloned token sequence

The token sequence in Listing 4 is a complete syntactic unit whereas the sequence in Listing 5 is not a single syntactic unit and, hence, needs to be decomposed into three syntactic subsequences as follows: <id$_0$>, <=$_2$ id$_0$ id$_0$>, and <call$_1$ id$_0$>.

3.3 Decomposing into Syntactic Clones

The previous step has produced a set of clone classes of maximally long equivalent AST node sequences. These sequences may or may not be syntactic clones. In the next step—described in this section—these sequences will be decomposed into syntactic clones. This step is the main difference between our algorithm and purely token-based approaches.

The main algorithm is shown in Listing 6 where `inset` is the input set of clone sequence partitions as determined in the previous step. For each class in `inset`, we select a representative and decompose it with algorithm `cut`, which we will explain shortly. The output is denoted by `outset` and incrementally produced by `cut`. The result is again a set of token sequence partitions, but the difference here is that each sequence in `outset` is a syntactic unit. Hence, `outset` is a refinement of `inset`.

Procedure `emit` is used to report clones based on the representative. It may filter clones based on various additional criteria such as length, type of clone, syntactic type (e.g., it may ignore clones in declarative code), differentiates the clone class elements into type-1 and type-2 clones, and finally reports all clones of a class to the user. We omit the details of `emit` here.

To ease the presentation, we will first ignore series of consecutive syntactic units that could be combined into one

```
procedure cut_all (inset) is
outset := ∅
for each class in inset loop
  cut (representative (class), outset)
end loop;
emit (outset);
```

Listing 6. Cutting out syntactic clones

clone subsequence. We will come back to this issue after the presentation of the basic algorithm.

Finding Syntactic Token Sequences (Basic) The underlying observation for our basic algorithm is as follows. Let `ts` be the clone token sequence returned by the token-based clone detection that we use as a representative. An AST subtree is a complete clone if all its tokens are completely contained in a cloned token sequence. The test whether the tokens of an AST subtree, rooted by N, are contained in the cloned token sequence `ts` is simple: its root N must be contained and the number of its arguments `tokens(N)` (number of transitive successor AST nodes reachable from N excluding N itself) must not exceed the end of `ts`. More precisely, let `ts'first` and `ts'last` denote the first and last index in this sequence, respectively; then the following condition must hold for a complete syntactic unit: `n + tokens (N)` $\leq$ `ts'last` where n is the index of N in `ts`.

Listing 7 shows the basic algorithm. It traverses the whole cloned token sequence `ts`. If a root is found to be complete (lines 7–9), the search continues after the last token of the rooted tree. The tokens up to the last token are part of the cloned rooted tree and we are interested only in maximal clones. For this reason, they may be skipped.

```
 1  procedure cut (ts, outset) is
 2  le := ts'first;
 3  while le ≤ ts'last loop
 4    if le + tokens(le) > ts'last then
 5      le := le + 1;
 6    else
 7      ri := le + tokens (le) + 1;
 8      outset := outset ∪ {ts (le..ri -1)};
 9      le := ri;
10    end if;
11  end loop
```

Listing 7. Cutting out syntactic clones

Variables `le` and `ri` indicate the currently handled range of tokens for the current syntactic clone (the representative). If the current rooted tree, indexed by `le`, is not completely contained in the cloned token sequence, we continue with its next child, which is the next token in the sequence (line 5 in Listing 7). This way, we descend into subtrees of a root to identify additional clones contained in an incomplete rooted tree. Descending into subtrees is necessary only at the end of a cloned token sequence, but it may be necessary to descend recursively. The recursion shows up in the traversal by increasingly smaller steps in the traversal.

Handling Sequences The basic algorithm finds syntactic units in the cloned token sequence. Yet, it misses subsequences of subtrees that together form a maximal clone. As an example consider Listing 8 and its corresponding AST in Figure 3. The example consists of a statement sequence rep-

```
    foo();                      goto l;
    x = a;                      x = a;
    y = b;                      y = b;
    { bar();                    { bar();
        foo(); }                    z = j; }
```

Listing 8. Example sequences in C

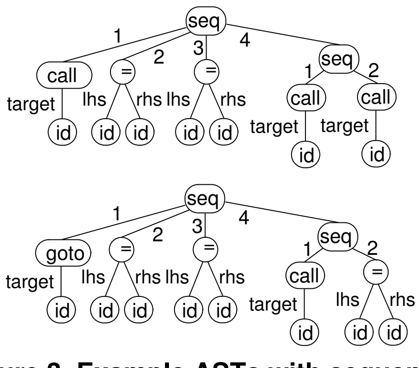


Figure 3. Example ASTs with sequences

```
1   procedure cut (ts, outset) is
2   le := ts'first;
3   while le ≤ ts'last loop
4     if le + tokens(le) > ts'last
5     then
6       le := le + 1;
7     else
8       if is_seq (parent (ts (le))) then
9         ri := le;
10        -- assert: ri + tokens(ri) ≤ ts'last
11        loop
12          ri := ri + tokens (ri) + 1;
13          exit when ri + tokens (ri) > ts'last
14                or else parent (ts(le))
15                        ≠ parent (ts(ri));
16        end loop;
17      else
18        ri := le + tokens (le) + 1;
19      end if;
20      outset := outset ∪ {ts (le..ri-1)};
21      le := ri;
22    end if;
23  end loop;
```

Listing 9. Cutting out syntactic sequence clones

resented by a node type *seq* with another nested sequence. The cloned token sequence representative for this example is as follows: $=_2$ id_0 id_0 $=_2$ id_0 id_0 seq_5 call_1 id_0

As you can see, the sequence runs into the nested sequence without covering it completely. The basic algorithm would, hence, find syntactic clone sequences as follows: $<=_2$ id_0 $\text{id}_0>$ (`x=a`), once more $<=_2$ id_0 $\text{id}_0>$ (`y=b`), and $<\text{call}_1$ $\text{id}_0>$ (`bar()`). However, the two consecutive assignments together form a maximal clone sequence. The basic algorithm misses this maximal clone sequence because only parts of the outer sequence are part of the cloned token sequence. Whereas other AST node types require that all parts are present to form a complete clone, consecutive parts of a sequence may together form a maximal clone.

The extended algorithm in Listing 9 considers sequences. The extension is found in lines 8–16. Predicate `if_seq` is true if an AST node represents a sequence. In that case, we collect all syntactic cloned token subsequences (line 12) as long as they are completely contained in the cloned token sequence (line 13) and have the same parent (lines 14–15). Function `parent(N)` returns the parent AST node of `N`.

4 Empirical Case Studies

In this section, we evaluate our new technique empirically by comparing it to alternative techniques. We first describe the experimental layout.

Bellon benchmark The basis for this comparison is the Bellon benchmark that has been developed and used for the most comprehensive quantitative comparison of software clone detectors to date [6]. In that study, six different research tools (cf. Fig. 4 above double line) have been compared based on several Java and C systems. For our study, we limit ourselves to the systems in Figure 5 because our prototype does not yet support Java. The Bellon study has not shown any significant difference in the performance of these tools for C and Java.

The tools report their findings as *clone pairs* uniformly; clone pairs are two code snippets identified by their filename, starting and ending line. Both code snippets need to be at least 6 lines long to be considered. Stefan Bellon has validated the clone pairs of the mentioned tools blindly and evenly; that is, an algorithm presented him clone pairs in about the same fraction of submitted clones without telling which tool has proposed the candidate.

Each clone pair suggested by a tool will be called *candidate* and each clone pair of the reference corpus will be called *reference* in the following. The candidates examined but rejected by Bellon are used to measure precision. Those accepted (possibly with slight modification in range) form the reference corpus and are used to measure recall.

At least two percents of each tool's clone pairs have been judged by him. Although 2% sounds like a small fraction, one should be aware that the validation took him 77 hours in total. Anticipating this problem in the design of the experiment, one evaluation was done after 1 % of the candidates had been "oracled". Then another percent was "oracled". The interesting observation was that the relative quantitative results are almost the same.

We oracled the candidates of our tools and added them to the benchmark. All three authors of this paper firstly oracled jointly to develop a comparable notion of what constitutes a clone and then split to oracle in parallel. We spent about 36 hours to oracle at least 2% of each new tool.

Metrics The Bellon benchmark comes with a set of tools to oracle and evaluate the clone detectors, which we reused. In order to compare candidates to references, a two-step process is used. First, the evaluation tools attempt to find a matching reference for each candidate. There are two types of matches. A *good match* is one in which reference and candidate overlap to at least 70% of their snippets. The snippets need not be exactly the same because there were some off-by-one differences in the way code lines are reported by the tools. An *OK match* is one in which a candidate is contained to at least 70% of its line in a reference or vice versa. In this evaluation, we will focus on good matches only due to reasons of space.

The match classifies candidates and references as follows. *True negatives* are references where no candidate of a particular tool has a good match. *Detected references* are those for which a good match exists. *Rejected candidates* are candidates for which no good match exists with any reference.

After matches are found, percentages as well as recall and precision are measured as follows where T is a variable denoting one of the participating tools, P is a variable denoting one of the analyzed programs, and τ is a variable denoting the clone type that is observed. All three variables have a special value “all” referring to all tools, programs, and clone types, respectively. τ furthermore has a special value “unknown” as some tools cannot categorize clone types.

$$\mathrm{Recall}(P,T,\tau) = \frac{|\mathrm{DetectedRefs}(P,T,\tau)|}{|\mathrm{Refs}(P,\tau)|}$$

$$\mathrm{Rejected}(P,T,\tau) = \frac{|\mathrm{RejectedCands}(P,T,\tau)|}{|\mathrm{SeenCands}(P,T,\tau)|}$$

$$\mathrm{TrueNegatives}(P,T,\tau) = \frac{|\mathrm{TrueNegativeRefs}(P,T,\tau)|}{|\mathrm{Refs}(P,\tau)|}$$

Additional Tools In order to compare the tools not only in terms of precision and recall but also in runtime, we implemented three additional variations of the evaluated tools (cf. Fig. 4 below double line). Because these tools are built on a common infrastructure of ours, written in the same programming language and were executed on the same hardware, the runtime comparison is more meaningful than the reports in the Bellon study [6].

`cpdetector` implements the technique that we describe in this paper. The closest techniques to our approach are the token-based and AST-based techniques. That is why we chose these techniques as a point of comparison. `ccdiml` is a variation of Baxter’s `CloneDR` also based on ASTs. The main differences are the avoidance of the similarity metric, the handling of sequences, the hashing, the fact that `CloneDR` works concurrently, and that `CloneDR` checks for consistent renaming while `ccdiml` currently does not do this. Yet, the overall approach is the same. `cpdetector` and `ccdiml` share the same AST as intermediate representation.

`clones` is a variation of Baker’s technique with the difference that it is not based on lines but solely on tokens and that it uses nonparameterized suffixes. The advantage of nonparameterized suffixes is that `clones` does not depend upon layout (line breaks); the disadvantage is that the distinction between type 1 and 2 must be made in a postprocessing step. Another main difference is that `clones` does currently not check whether identifiers in type-2 clones are renamed consistently.

As already discussed in Section 2.3, token-based techniques can be extended so that they attempt to find syntactic clones as well by splitting cloned token sequences into subsequences with a balanced set of opening and closing scope delimiters in a postprocessing step. For this reason, we compare our new techniques also to a token-based technique applying this strategy. `cscope` implements this postprocessing step. As a matter of fact, `cscope` is not a new tool but just an additional feature built into `clones` that can be turned on via a command line switch.

It is worth to note that our suffix tree implementation is generic and is used in `cpdetector`, `clones` and `cscope` identically.

All our tools find type-1 and type-2 clones except for `ccdiml`, which also finds type-3 clones; but type-3 detection has been disabled in this experiment.

Author	Tool	Comparison
Brenda S. Baker	`Dup`	Tokens
Ira D. Baxter	`CloneDR`	AST
Toshihiro Kamiya	`CCFinder`	Tokens
Jens Krinke	`Duplix`	PDG
Ettore Merlo	`CLAN`	Function Metrics /Tokens
Matthias Rieger	`Duploc`	Text
Rainer Koschke	`cpdetector`	AST/suffix tree
Stefan Bellon	`ccdiml`	AST/tree matching
Rainer Koschke	`clones`	Tokens
Pierre Frenzel	`cscope`	Tokens

Figure 4. Compared tools

Program	Domain	Size
bison 1.32	parser generator	19K
wget 1.5.3	network downloader	16K
SNNS 4.2	neural network simulator	105K
PostgreSQL 7.2	database	235K

Figure 5. Analyzed programs (size in SLOC)

Results Because of limited space, we present only one system. We chose SNNS because some tools of the earlier experiment had problems with the larger PostgreSQL system, so their results cannot be compared with the new tools we evaluate in this paper. The new tools ran successfully for all systems in Figure 5. The results of all tools including our and the earlier tools that did run successfully for PostgreSQL are comparable, however.

Figure 6(a) shows the number of candidates found by the various tools for SNNS. Here, clones found 71% more clones than CCFinder (the tool with the highest number in the earlier experiment), while the number for cscope is comparable to the numbers of other token-based tools. cpdetector yields a low number of candidates and ccdiml is similar to cscope. The number of candidates of token-based approaches almost doubles those found by AST-based tools.

The **rejected candidates** are shown in Figure 6(b). These candidates are very high for clones and cscope. Other token-based methods have a reject rate of 50% and 54% while clones and cscope have 90% and 82%. The reason is that clones and cscope do not check for consistent renaming of identifiers and literals.

Rejects for ccdiml and cpdetector are comparable to CCFinder, Dup, and Duploc with respect to type-2 clones. The reason is that neither ccdiml nor cpdetector check for consistent renaming. Given the fact that ccdiml and cpdetector have much lesser rejected type-1 clones, we conclude that they could perform better than token-based techniques provided that they check for consistent renaming.

Figure 6(c) contains the **true negatives**. The tools clones, cscope, and cpdetector find an average percentage of references of 30%, 33% and 26%, respectively. ccdiml has the second best result (53%) after CCFinder (61%). There is no substantial difference in the overall percentage of true negatives for token-based versus AST-based approaches.

Recall of clones (cf.Figure 6(d)), cscope, and cpdetector is with 30%, 33% and 26% at average. The recall of ccdiml, however, is with 53% the second best with quite a big advantage. The average recall of the token-based tools (clones, cscope, Dup, CCFinder) is higher (54%) than the AST-based tools (30%).

The percentages of rejected candidates of cpdetector for PostgreSQL are 68% (total), 50% (type-1), 68% (type-2), of true negatives 71/91/68%, and of recall 29/48/33%, respectively.

Runtime Comparison The runtime for each tool is given in Figure 7, determined on a 64bit Intel dual-processor architecture (3.0 GHz) with 16 GB RAM running Linux (Fedora Core 5), where only one CPU was used. The runtime for the AST-based tools contains loading the AST from disk; i.e., the time excludes parsing. The time for the token-based tools contains reading and tokenizing source text.

Comparing cpdetector to ccdiml, we notice a dramatic performance difference. The non-linear behavior of ccdiml is mainly caused by a quadratic tree comparison required to compare each pair of AST subtrees in the same bucket. ccdiml can be adjusted in various ways which affect both precision and scalability. We chose the setting of parameters which give the most precise results, but also require most resources. The figures for ccdiml are comparable to those of CloneDR, which required 10800 seconds for SNNS and 9780 seconds for PostgreSQL but on a weaker hardware (Pentium Pro/200 MHz running Windows NT 4.0) in the earlier experiment.

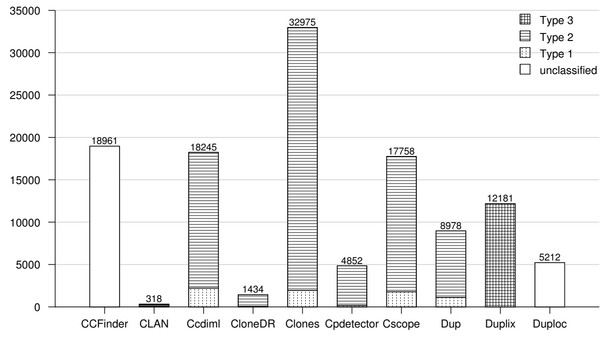
The extra effort of cscope compared to clones lies in the postprocessing step to split clones into syntactic units. As you can notice, this step is a considerable factor. The effort of cscope, which also finds syntactic clones, versus cpdetector is similar, in case of PostgreSQL even much lower. As the data for PostgreSQL suggest, splitting sequences into syntactic clones using ASTs is more efficient for larger systems. cpdetector skips all tokens subsumed by a rooted AST tree in one step, whereas cscope traverses through a sequence token by token because it does not have a notion of syntactic containment.

System	cpd	ccdiml	clones	cscope
bison	3.76	68,20	1.82	3.72
wget	3.46	81.12	2.83	4.55
SNNS	29.66	7009.45	11.63	25.73
PostgreSQL	62.61	16942.38	74.02	113.08

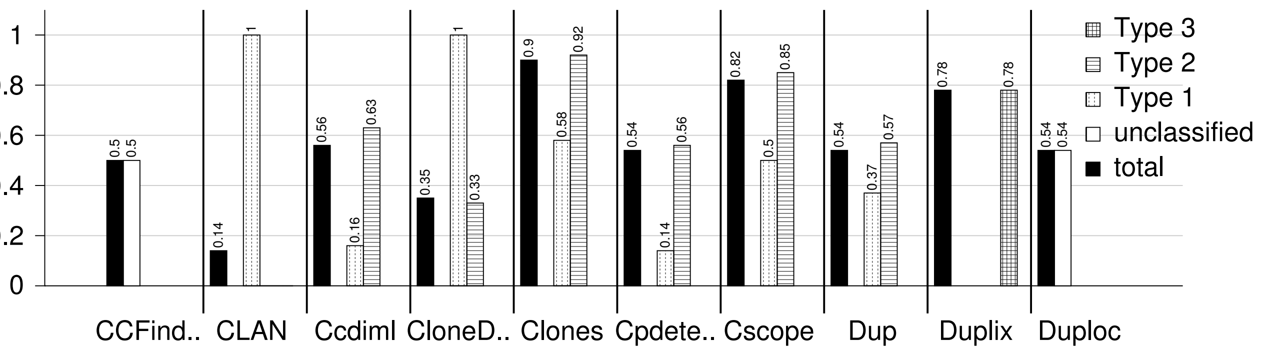
Figure 7. Runtime comparison [seconds]; cpd = cpdetector (for the other tools, see [6]).

5 Conclusion

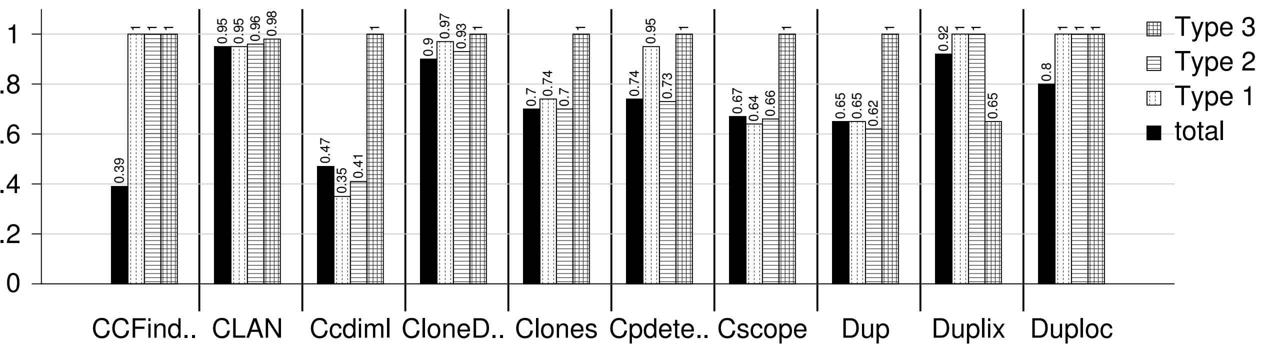
Our experiment has confirmed the earlier result that token-based techniques tend to have higher recall but also lower precision for type-1 clones. We noticed only after the case studies that checking for consistent renaming is an important feature of a clone detector. The results for token-based techniques that perform this check are much better than those that do not. As a consequence, we could have a better precision for type-2 clones for our AST-based tools if they also made this check.



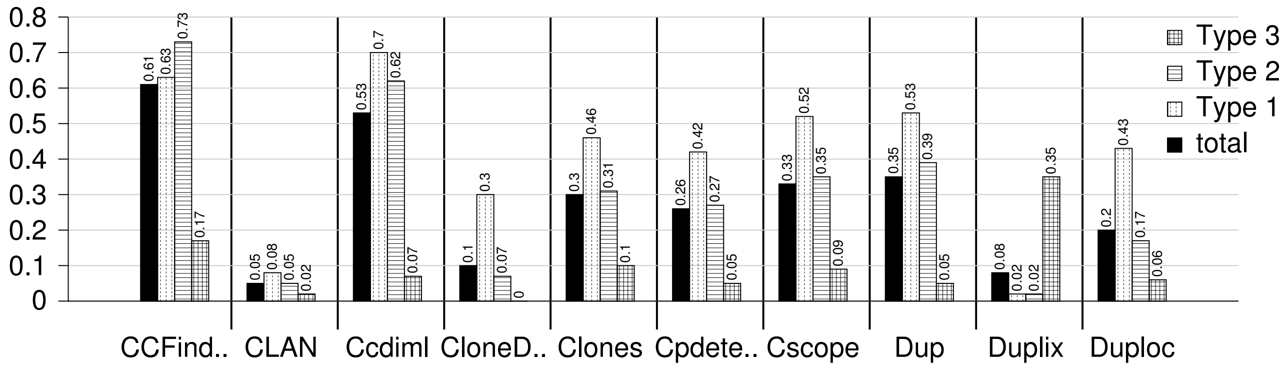
(a) Number of candidates



(b) Percentage of rejected candidates



(c) Percentage of true negatives



(d) Recall

Figure 6. Results for SNNS

	CloneDR	cpdetector	ccdiml
Rejection	+	○	○
Recall	–	○	+
True negatives	–	○	+
Runtime	–	+	–

Figure 8. Comparision of AST-based tools

Figure 8 shows a comparison for the AST-based tools. `cpdetector` is a compromise between recall and precision, but offers better scalability that compares to token-based techniques.

We made additional observations during oracling. Often, token-based tools proposed the end of one function plus the beginning of the lexically next function as a clone. Here our `cscope` tool helped to increase the quality of the results compared to `clones`. A second observation is that tools reported frequently occurring patterns such as sequences of assignments, very large initializer lists for arrays, and structurally equivalent code with totally different identifiers of record components. Such spurious clones could be filtered out by syntactic property checks. Such a post-processing is described by Kapser and Godfrey [15] using lightweight parsing. However, filtering in syntactic terms is more reliably following an AST-based approach.

Another point of improvement that relates to the benchmark is to use token counts instead of lines as a measure of clone size. We often found clones that contained two statements separated by several blank or commented lines. In addition, generated files (like parsers) should be excluded from the benchmark since such code tends to be regular and appears as spurious clone candidates.

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