

Incremental clone detection for IDEs using dynamic suffix arrays

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Motivation

- Duplicated code is generally considered harmful to software quality
- Code clone detection, analysis and management is therefore important
- Incremental clone detection algorithms have not been thoroughly researched
- Incremental algorithms are useful in use-cases such as in IDEs

Our contribution

- CCDetect-LSP: An incremental clone detection tool for IDEs
- Uses a novel application of dynamic extended suffix arrays for clone detection
- Language- and IDE agnostic via Tree-sitter and LSP

Code clones

Definition (Code snippet)

A code snippet is a piece of contiguous source code in a larger software system.

Definition (Code clone)

A code clone is a code snippet which is equal or similar to another code snippet. The two code snippets are both code clones, and together they form a clone pair. Similarity is determined by some metric such as number of equal lines of code.

Clone types

- Code clones are classified into four types
 - Type-1: Syntactically identical
 - Type-2: Structurally identical
 - Type-3: Structurally similar
 - Type-4: Functionally similar (generally)

Clone type examples: type-1 and type-2

```
for (int i = 0; i < 10; i++) {  
    print(i);  
}
```

```
for (int i = 0; i < 10; i++) {  
    // A comment  
  
    print(i);  
}
```

Figure: Type-1 clone pair

```
for (int i = 0; i < 10; i++) {  
    print(i);  
}
```

```
for (int j = 5; j < 20; j++) {  
    print(j);  
}
```

Figure: Type-2 clone pair

Clone type examples: type-3 and type-4

```
for (int i = 0; i < 10; i++) {  
    print(i);  
}
```

```
for (int i = 0; i < 10; i++) {  
    print(i);  
    print(i*2);  
}
```

Figure: Type-3 clone pair

```
print((n*(n-1))/2)
```

```
int sum = 0;  
for (int i = 0; i < n; i++) {  
    for (int j = i+1; j < n; j++) {  
        sum++;  
    }  
}  
print(sum);
```

Figure: Type-4 clone pair

Clone detection

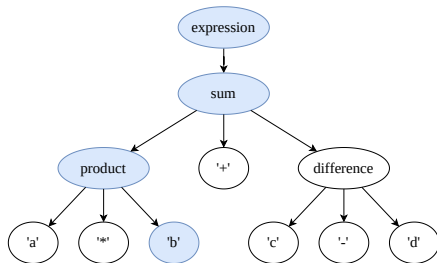


Clone matching techniques

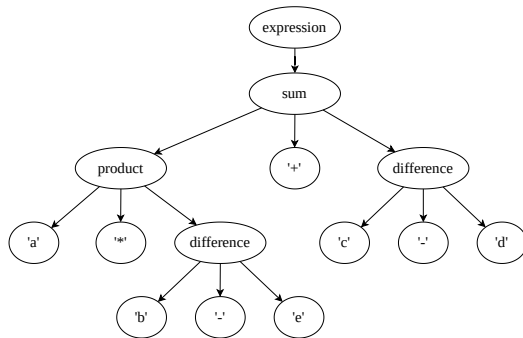
- Text-based detection
 - Match based on raw source code
- Token-based detection
 - Match based on tokens
- Syntactic detection
 - Match based on AST
- Hybrid detection
 - Combine multiple approaches

Parsing and incremental parsing

$a * b + (c - d)$



$a * (b - e) + (c - d)$



Suffix tree

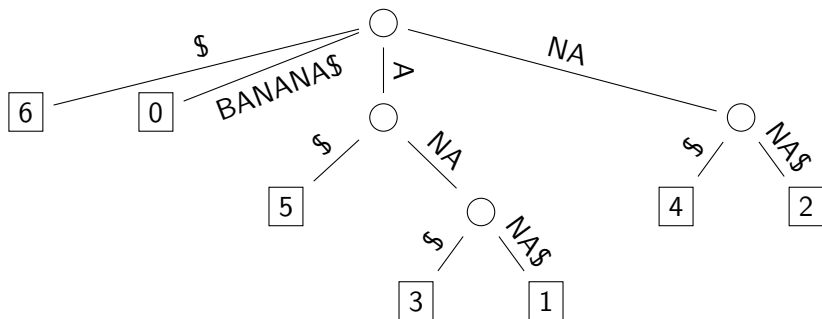


Figure: Suffix tree for $S = \text{BANANA\$}$

Suffix array

| Index | Suffix |
|-------|-----------|
| 0 | BANANAS\$ |
| 1 | ANANAS\$ |
| 2 | NANAS\$ |
| 3 | ANAS\$ |
| 4 | NAS\$ |
| 5 | AS\$ |
| 6 | \$ |

(a) Suffixes

| Index | Suffix |
|-------|-----------|
| 6 | \$ |
| 5 | AS\$ |
| 3 | ANAS\$ |
| 1 | ANANAS\$ |
| 0 | BANANAS\$ |
| 4 | NAS\$ |
| 2 | NANAS\$ |

(b) Sorted suffixes

| Index | SA | ISA | LCP |
|-------|----|-----|-----|
| 0 | 6 | 4 | 0 |
| 1 | 5 | 3 | 0 |
| 2 | 3 | 6 | 1 |
| 3 | 1 | 2 | 3 |
| 4 | 0 | 5 | 0 |
| 5 | 4 | 1 | 0 |
| 6 | 2 | 0 | 2 |

(c) SA, ISA and LCP

Burrows-Wheeler transform

| Index | CS | Index | CS | L | F |
|-------|----------|-------|----------|---|------------------------------------|
| 0 | BANANA\$ | 6 | \$BANANA | 0 | $Rank_A(0) + C[A] = 0 + 1 = 1$ |
| 1 | ANANA\$B | 5 | A\$BANAN | 1 | $Rank_N(1) + C[N] = 0 + 5 = 5$ |
| 2 | NANA\$BA | 3 | ANA\$BAN | 2 | $Rank_N(2) + C[N] = 1 + 5 = 6$ |
| 3 | ANA\$BAN | 1 | ANANA\$B | 3 | $Rank_B(3) + C[B] = 0 + 4 = 4$ |
| 4 | NA\$BANA | 0 | BANANA\$ | 4 | $Rank_{\$}(4) + C[\$] = 0 + 0 = 0$ |
| 5 | A\$BANAN | 4 | NA\$BANA | 5 | $Rank_A(5) + C[A] = 1 + 1 = 2$ |
| 6 | \$BANANA | 2 | NANA\$BA | 6 | $Rank_A(6) + C[A] = 2 + 1 = 3$ |

(d) Cyclic shifts

(e) Sorted cyclic shifts
and BWT

(f) LF function

Table: $S = \text{BANANA\$}$, $\text{BWT} = \text{ANNB\$AA}$

CCDetect-LSP features

■ CCDetect-LSP is implemented as an LSP server

- List clones
- Display clones inline with code
- Jump between matching clones
- Incremental updates on each edit

```

997     ... clone(s) detected
998     BufferedImageRaster.java(398, 25): Clone detected
999     ImageUtil.java(1002, 31): Clone detected
1000     (int bufferDataType)
1001     View Problem (Alt+F8) No quick fixes available
1002
1003     {
1004         case java.awt.image.DataBuffer.TYPE_BYTE:
1005             return (Byte.SIZE / 8);
1006         case java.awt.image.DataBuffer.TYPE_DOUBLE:
1007             return (Double.SIZE / 8);
1008         case java.awt.image.DataBuffer.TYPE_FLOAT:
1009             return (Float.SIZE / 8);
1010         case java.awt.image.DataBuffer.TYPE_INT:
1011             return (Integer.SIZE / 8);
1012         case java.awt.image.DataBuffer.TYPE_SHORT:
1013             return (Short.SIZE / 8);
1014         case java.awt.image.DataBuffer.TYPE_USHORT:
1015             return (Short.SIZE / 8);
1016         case java.awt.image.DataBuffer.TYPE_UNDEFINED:
1017             break;
1018     }
1019     return 0L;
1020
1021     /**
1022     * Opens a spatial image. Reprojects the image if it is in UTM projection.
1023     * @param imageFile source image
1024     * @param interpolation_mode the interpolation mode if the image is reprojected.
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```

Implementation: Initial clone detection

- Algorithm which initially detects type-1 and optionally type-2 clones
- Pipeline of 5 phases, returns a list of clones
- Uses an extended suffix array for match detection
- Starting point: Assume documents are indexed

Detection algorithm overview

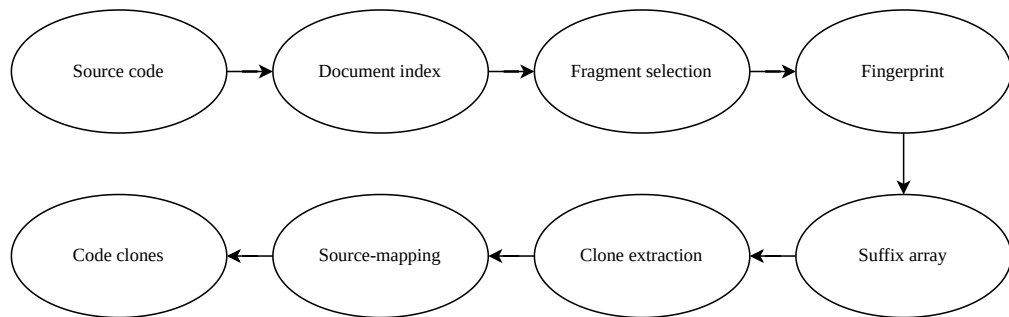


Figure: Overview of detection algorithm phases

Phase 1: Fragment selection

- Parse files using Tree-sitter
- Use a configurable Tree-sitter query to “capture” nodes
- Extract and store the tokens of captured nodes

```
(method_declaration) @method (constructor_declaration) @constructor
```

Phase 2: Fingerprinting

- Consistently hash each token value with an increasing integer counter
- Store the fingerprint of each fragment in the document index
- For type-2 detection, hash the token type instead

Phase 2: Fingerprinting

```
public class Math() {
    public int multiplyByTwo(int param) {
        return param * 2;
    }

    public int addTwo(int param) {
        return param + 2;
    }
}
```

| Token | Fingerprint |
|---------------|-------------|
| public | 2 |
| int | 3 |
| multiplyByTwo | 4 |
| (| 5 |
| param | 6 |
|) | 7 |
| { | 8 |
| return | 9 |
| * | 10 |
| 2 | 11 |
| ; | 12 |
| } | 13 |
| addTwo | 14 |
| + | 15 |

[2, 3, 4, 5, 3, 6, 7, 8, 9, 6, 10, 11, 1, 2, 3, 14, 5, 3, 6, 7, 8, 9, 6, 15, 11, 1, 0]

Figure: Example fingerprint of Java source-code

Phase 3: Suffix array construction

- Concatenate the fingerprints of each document in the index
- Construct SA, ISA and LCP array of the full fingerprint
- Uses “Induced sorting variable-length LMS-substrings” (SA-IS) algorithm
- LCP algorithm slightly modified

F: [2, 3, 4, 5, 3, 6, 7, 8, 9, 6, 10, 11, 1, 2, 3, 14, 5, 3, 6, 7, 8, 9, 6, 15, 11, 1, 0]
SA: [26, 25, 12, 0, 13, 1, 4, 17, 14, 2, 3, 16, 5, 18, 9, 22, 6, 19, 7, 20, 8, 21, 10, 24, 11, 15, 23]
ISA: [3, 5, 9, 10, 6, 12, 16, 18, 20, 14, 22, 24, 2, 4, 8, 25, 11, 7, 13, 17, 19, 21, 15, 26, 23, 1, 0]
LCP: [0, 0, 0, 0, 2, 0, 1, 6, 1, 0, 0, 7, 0, 5, 1, 1, 0, 4, 0, 3, 0, 2, 0, 0, 1, 0, 0]

Phase 4: Clone extraction

- Use SA, ISA and LCP to find clone positions
- Linear scan through the fingerprint
- Skip contained clones

Phase 5: Source-mapping

- Map the positions of clones back to the original source-code
- Find the correct file and position of an index in the fingerprint

Implementation: Incremental clone detection

- Convert the algorithm to an incremental one
- Input is now the file which has changed and potentially the range
- Dynamic suffix array with edit operations as input

Phase 1: Update document index and fragment selection

- Store the AST of the opened files
- If range available, incrementally parse the changed file
- Mark changed files
- Fragment selection unchanged

Phase 2: Fingerprinting

- Each document stores its fingerprint
- Only need to fingerprint (and fragment select) changed files

Phase 2.5: Edit operations

- Input to phase 3: Edit operations
- How to determine edit operations?
- Edit distance algorithm!
- “Batched” operations preferred

| | | D | E | M | O | C | R | A | T |
|---|----|----|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| R | 1 | 1 | 2 | 3 | 4 | 5 | 5 | 6 | 7 |
| E | 2 | 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| P | 3 | 3 | 2 | 2 | 3 | 4 | 5 | 6 | 7 |
| U | 4 | 4 | 3 | 3 | 3 | 4 | 5 | 6 | 7 |
| B | 5 | 5 | 4 | 4 | 4 | 4 | 5 | 6 | 7 |
| L | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 6 | 7 |
| I | 7 | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 7 |
| C | 8 | 8 | 7 | 7 | 7 | 6 | 7 | 7 | 7 |
| A | 9 | 9 | 8 | 8 | 8 | 7 | 7 | 7 | 8 |
| N | 10 | 10 | 9 | 9 | 9 | 8 | 8 | 8 | 8 |

Table: REPUBLICAN → DEMOCRAT

Optimize edit distance

- Standard algorithm memory usage is too high
- Need to optimize
 - Compare new/old fingerprint of changed document only
 - Remove trivial part at each end of matrix
 - Hirschberg's algorithm

| | | F | I | N | I | S | H | I | N | G |
|---|----|----|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| F | 1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| A | 2 | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| S | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 5 | 6 | 7 |
| C | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 6 | 7 |
| I | 5 | 4 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 6 |
| N | 6 | 5 | 4 | 3 | 4 | 4 | 5 | 5 | 4 | 5 |
| A | 7 | 6 | 5 | 4 | 4 | 5 | 5 | 6 | 5 | 5 |
| T | 8 | 7 | 6 | 5 | 5 | 5 | 6 | 6 | 6 | 6 |
| I | 9 | 8 | 7 | 6 | 5 | 6 | 6 | 6 | 7 | 7 |
| N | 10 | 9 | 8 | 7 | 6 | 6 | 7 | 7 | 6 | 7 |
| G | 11 | 10 | 9 | 8 | 7 | 7 | 7 | 8 | 7 | 6 |

Table: FASCINATING → FINISHING
ASCINAT → INISH

Phase 3: Dynamic suffix array

- Update suffix array based on edit operations
- “Four-stage algorithm for updating a Burrows-Wheeler transform”
- Updates to the BWT correlates with updates to the SA and ISA
- Inserting a single character leads to:
 - A new character in the BWT
 - A changed character in the BWT
 - 0 or more reordering of characters

Phase 3: Dynamic suffix array

| Order | F | L |
|-------|----|----|
| 6 | \$ | A |
| 5 | A | N |
| 3 | A | N |
| 1 | A | B |
| 0 | B | \$ |
| 4 | N | A |
| 2 | N | A |

(a) Original BWT

| Order | F | L |
|-------|----------|----------|
| 7 | \$ | A |
| 6 | A | N |
| 4 | A | N |
| 1 | A | B |
| 0 | B | \$ |
| 2 | B | A |
| 5 | B | A |
| 3 | N | B |

(b) After change and insert

| Order | F | L |
|-------|----------|----------|
| 7 | \$ | A |
| 6 | A | N |
| 1 | A | B |
| 4 | A | N |
| 0 | B | \$ |
| 2 | B | A |
| 5 | B | A |
| 3 | N | B |

(c) After reordering

Table: Updating BWT dynamically for the string BANANA\$ \rightarrow BABNANA\$

Dynamic extended suffix array

- Updating suffix array is slow
 - Inserting: $O(n)$
 - Incrementing: $O(n)$
- We therefore change the data structure which stores SA, ISA and LCP

Dynamic extended suffix array

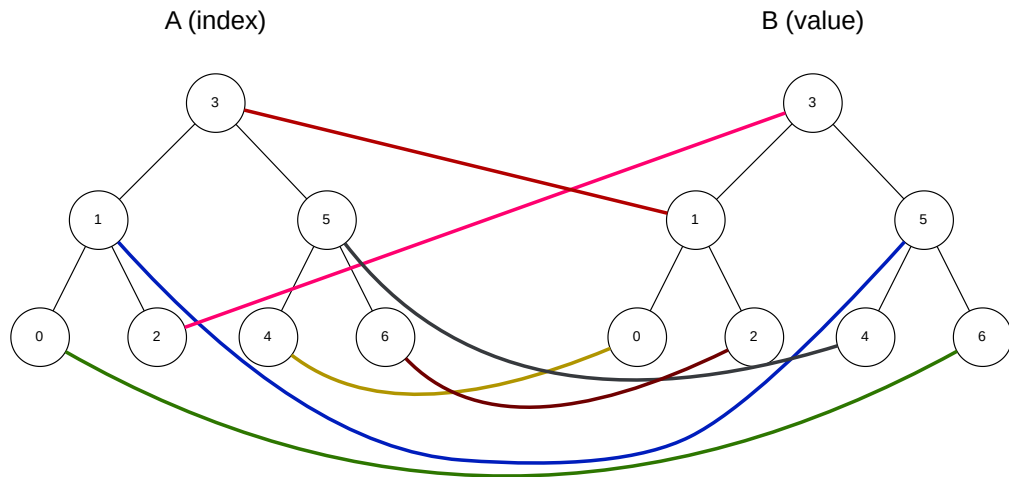


Figure: Dynamic permutation for the permutation $[6, 5, 3, 1, 0, 4, 2]$.

Updating LCP values

- SA updates correlate with LCP values which need to be updated

| | \leftrightarrow | | | | | INS | | |
|---------|-------------------|---|----------|----------|----------|----------|----------|---|
| BWT | A | N | B | N | \$ | A | A | B |
| SA | 7 | 6 | 4 | 1 | 0 | 2 | 5 | 3 |
| Old LCP | 0 | 0 | <u>1</u> | <u>3</u> | <u>0</u> | <u>N</u> | <u>0</u> | 2 |
| New LCP | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 2 |

Phase 4 and 5: Clone extraction and source-mapping

- Very similar to the initial detection
- Accessing SA, ISA and LCP is now a bit slower, but this is optimized

Evaluation

- CCDetect-LSP evaluation:
 - Verify correctness with BigCloneEval
 - Benchmark performance
 - Benchmark memory usage
 - Tested multiple languages and IDEs

BigCloneBench

- A large database of clones in a Java dataset
- BigCloneEval can evaluate detection tools on BigCloneBench

```
-- Recall Per Clone Type (type: numDetected / numClones = recall) --  
      Type-1: 23209 / 23210 = 0.999956915122792  
      Type-2: 3542 / 3547 = 0.9985903580490555  
      Type-2 (blind): 242 / 245 = 0.9877551020408163  
      Type-2 (consistent): 3300 / 3302 = 0.9993943064809206
```

Figure: BigCloneEval evaluation report for CCDetect-LSP

Performance evaluation

- CCDetect-LSP was evaluated on multiple codebases
- Performance compared against SACA detection and iClones
- Incremental updates were randomly generated
- 10×10 or 10×100 tokens inserted/deleted

| Code base | LOC | Clones detected | LCP_{avg} | $LCP_{\geq 100}$ |
|--------------------|---------|-----------------|-------------|------------------|
| WorldWind | 550KLOC | 1517 | 18 | 63967 |
| neo4j | 1MLOC | 1313 | 9 | 27557 |
| graal | 2.2MLOC | 2012 | 28 | 154452 |
| flink | 2.3MLOC | 4729 | 13 | 155754 |
| elasticsearch | 3.2MLOC | 9986 | 14 | 289511 |
| intellij-community | 5.8MLOC | 3585 | 19 | 336190 |

Table: Properties of code bases

WorldWind (550KLOC)

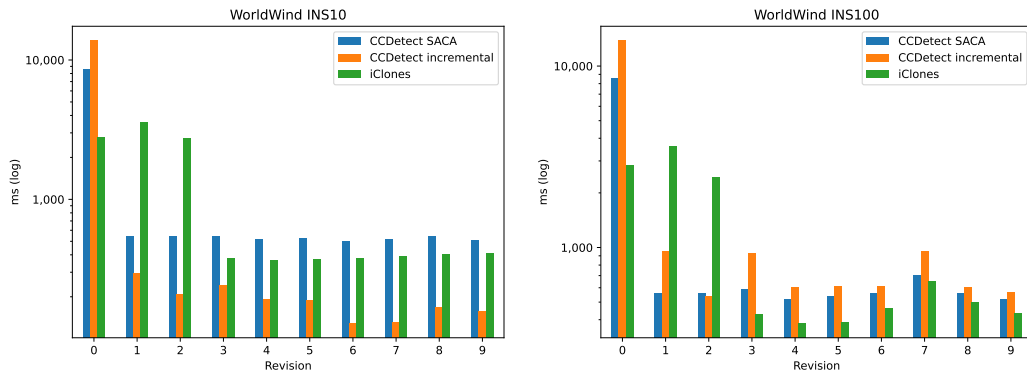


Figure: WorldWind performance benchmark

neo4j (1MLOC)

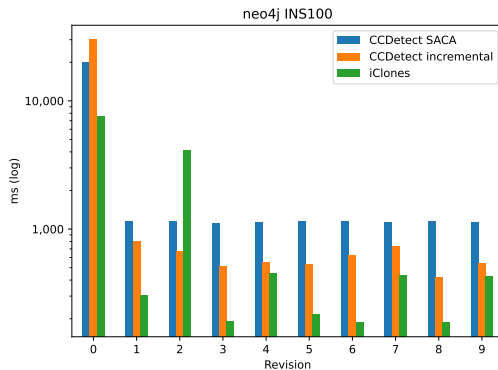
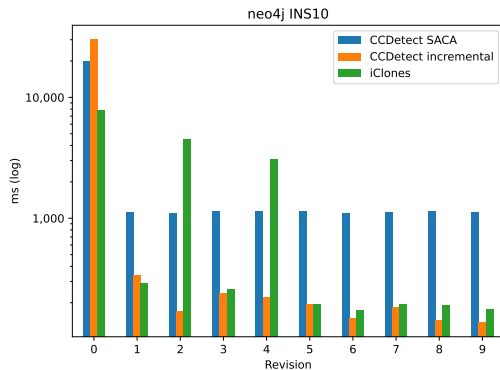


Figure: neo4j performance benchmark

graal (2.2MLOC)

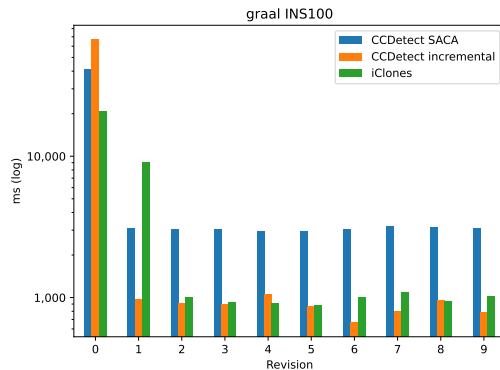
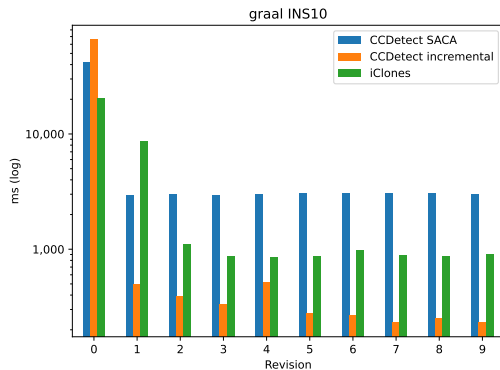


Figure: graal performance benchmark

flink (2.3MLOC)

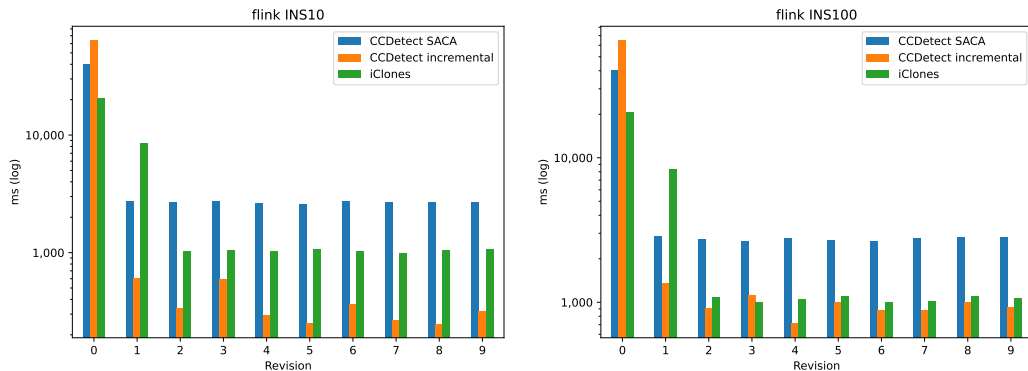


Figure: flink performance benchmark

elasticsearch (3.2MLOC)

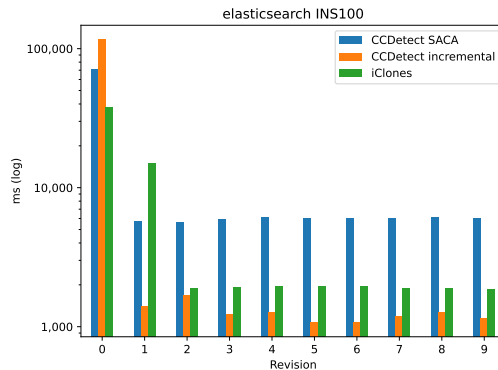
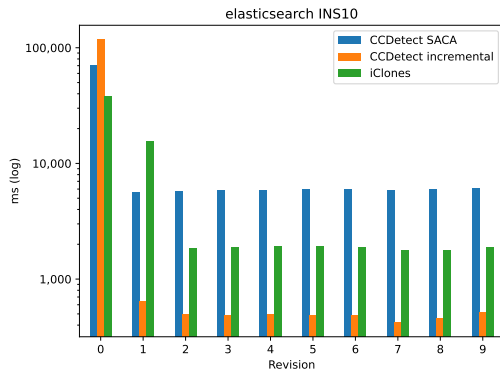


Figure: elasticsearch performance benchmark

intellij-community (5.8MLOC)

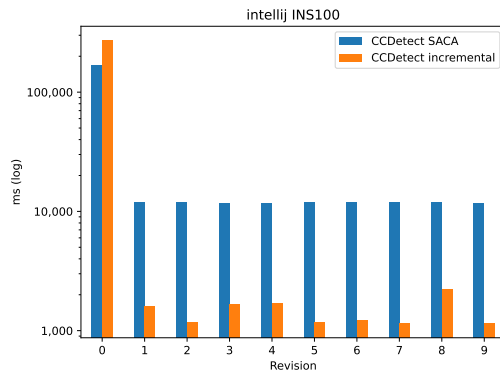
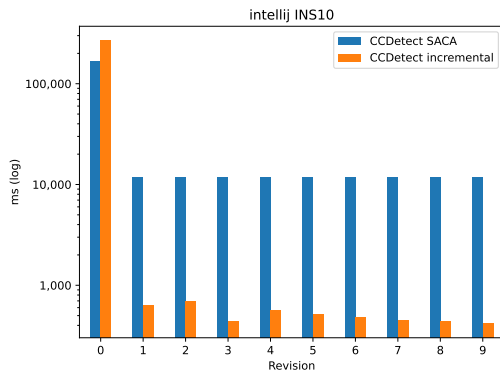


Figure: intellij-community performance benchmark

elasticsearch (3.2MLOC)

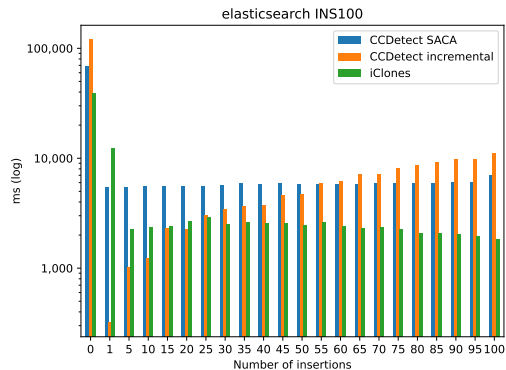
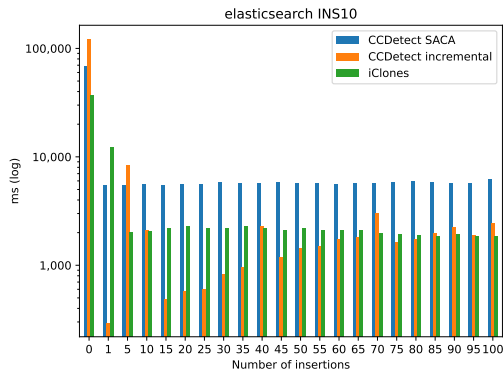


Figure: Elasticsearch performance benchmark with increasing number of edits

Memory usage

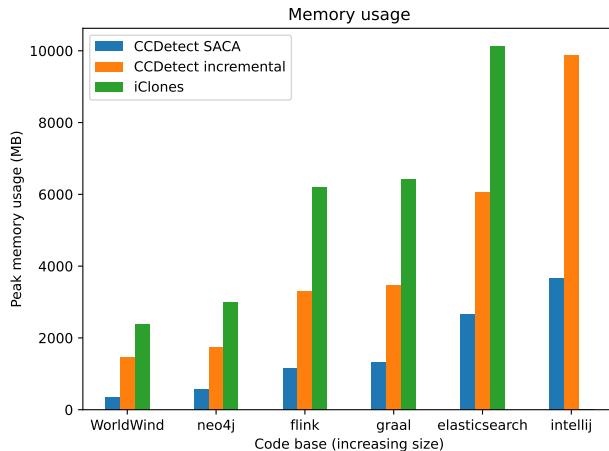


Figure: Peak memory usage of each tool when running the DEL10 test for each code base.

Language and IDE agnostic

- CCDetect tested on 6 languages
 - Java
 - Python
 - C
 - Rust
 - Javascript
 - Go
- And 2 IDEs
 - Neovim
 - VSCode
- Works well in our experience

Discussion

- Performance
 - Incremental detection has best performance if edits are small
- Memory usage
 - SACA detection best, incremental detection better than iClones
 - Memory usage is probably a bottle-neck for practical usage
- Language agnostic
 - Works well if grammar is correct
- IDE agnostic
 - Functionality should work in most IDEs
 - Setup and configuration depends on IDE

Conclusion

- CCDetect-LSP is a performant incremental clone detection tool
- Language- and IDE agnostic clone detection is achieved
- Practical usage?
 - Clone information used by other tools
 - Live manual refactoring of code clones
- Future work?
 - Type-3 clones
 - Refactoring clones
 - Compressing data structures
 - Optimal edit operations

Questions?

- Questions?
 - Demo?
 - LSP communication and architecture?
 - Anything else?

LSP

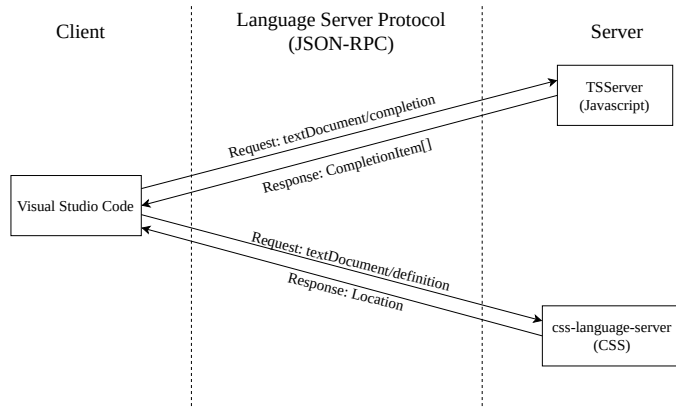


Figure: Example LSP server communication

LSP architecture

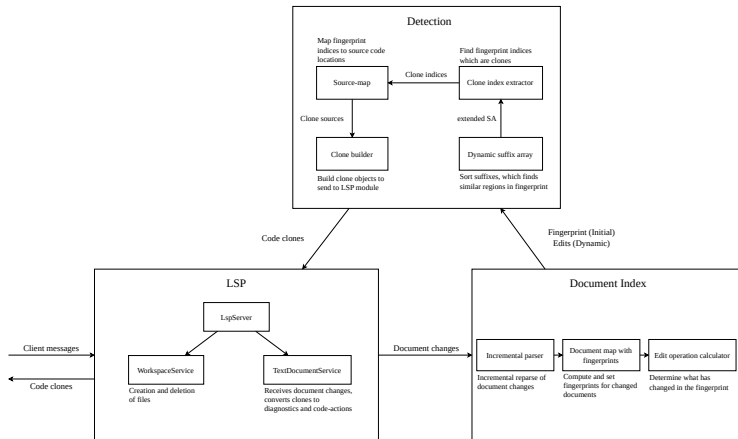


Figure: Architecture of CCDetect-LSP