Incremental clone detection for IDEs using dynamic suffix arrays

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Outline

Motivation

- Duplicated code is generally considered harmful to software quality
- Software often contains $10 - 15\%$ duplicated code
- 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.

Clone types: 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);
}
```

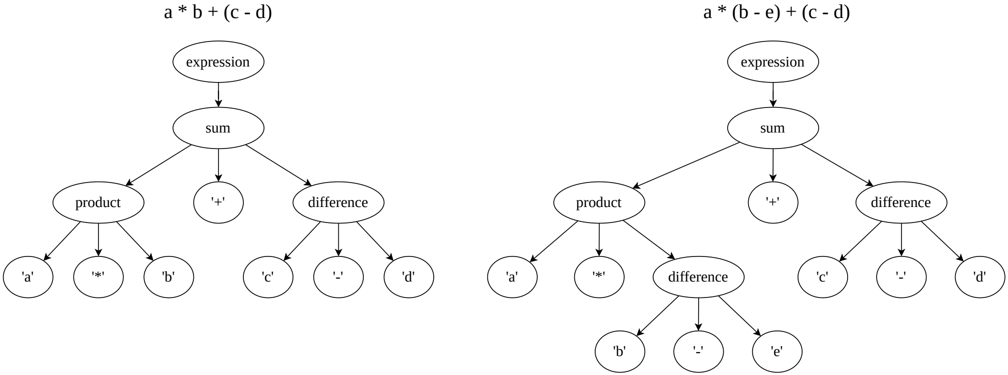
Figure: Type-1 clone pair

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

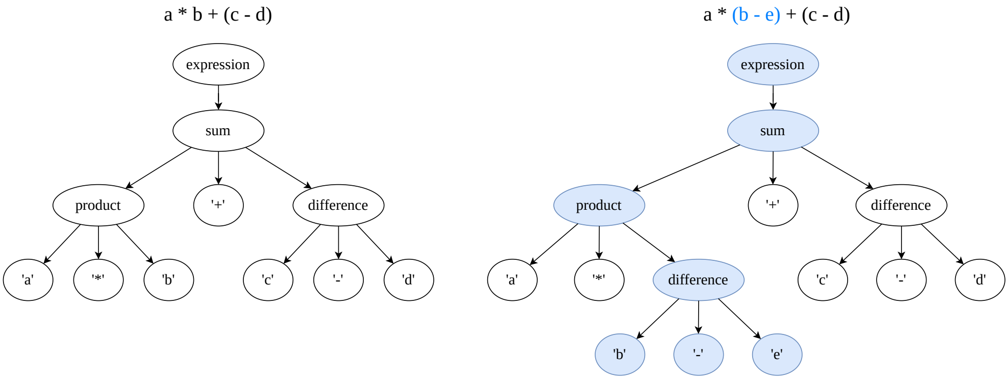
```
for (int j = 5; j < 20; j++) {
    print(j);
}
```

Figure: Type-2 clone pair

Parsing and incremental parsing



Parsing and incremental parsing



Suffix array

Index	Suffix
0	BANANA$
1	ANANA$
2	NANA$
3	ANA$
4	NA$
5	A$
6	$

(a) Suffixes

Index	Suffix
6	$
5	A$
3	ANA$
1	ANANA$
0	BANANA$
4	NA$
2	NANA$

(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
0	BANANA$
1	ANANA$B
2	NANA$BA
3	ANA$BAN
4	NA$BANA
5	A$BANAN
6	$BANANA

(d) Cyclic shifts

Index	CS
6	$BANAN**A**
5	A$BANA**N**
3	ANA$BA**N**
1	ANANA$**B**
0	BANANA**$**
4	NA$BAN**A**
2	NANA$B**A**

(e) Sorted cyclic shifts and BWT

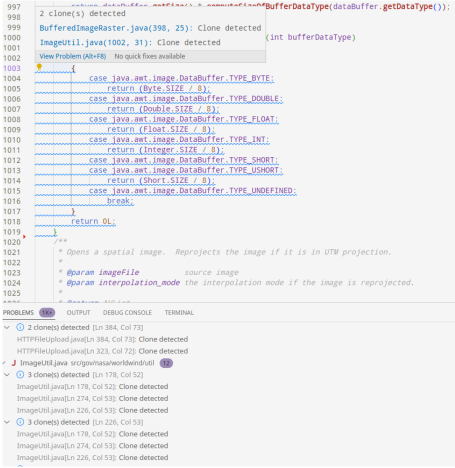
L	F
0	$Rank_A(0) + C[A] = 0 + 1 = 1$
1	$Rank_N(1) + C[N] = 0 + 5 = 5$
2	$Rank_N(2) + C[N] = 1 + 5 = 6$
3	$Rank_B(3) + C[B] = 0 + 4 = 4$
4	$Rank_\$(4) + C[\$] = 0 + 0 = 0$
5	$Rank_A(5) + C[A] = 1 + 1 = 2$
6	$Rank_A(6) + C[A] = 2 + 1 = 3$

(f) LF function

Table: S = BANANA$, BWT = ANNB$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



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

Detection algorithm overview

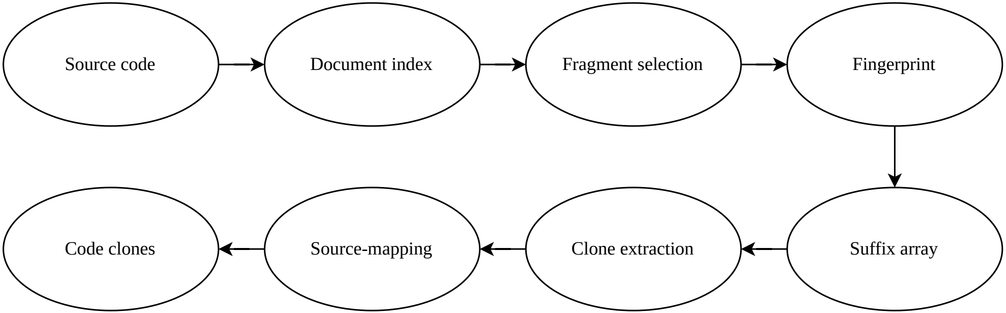


Figure: Overview of detection algorithm phases

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
- For type-2 detection, hash the token type instead

```
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, <u>1</u>, 2, 3, 14, 5, 3, 6, 7, 8, 9, 6, 15, 11, <u>1</u>, <u>0</u>]

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

Phase 4: Clone extraction

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

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

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

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 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
- Binary-search speeds this process up

Implementation: Incremental clone detection

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

Phase 1 and 2: Fragment selection and fingerprinting

- Mainly reuse results from previous computation, except for changed file
- Fragment selection
  - Store the AST of the opened files
  - Incrementally parse the changed file with Tree-sitter
- 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 $\rightarrow$ 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

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**	Inserted
5	B	A	
3	**N**	**B**	$A \to B$

(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$ $\to$ BABNANA$

Dynamic extended suffix array

- Updating suffix array is slow ($O(n)$), new data structure needed

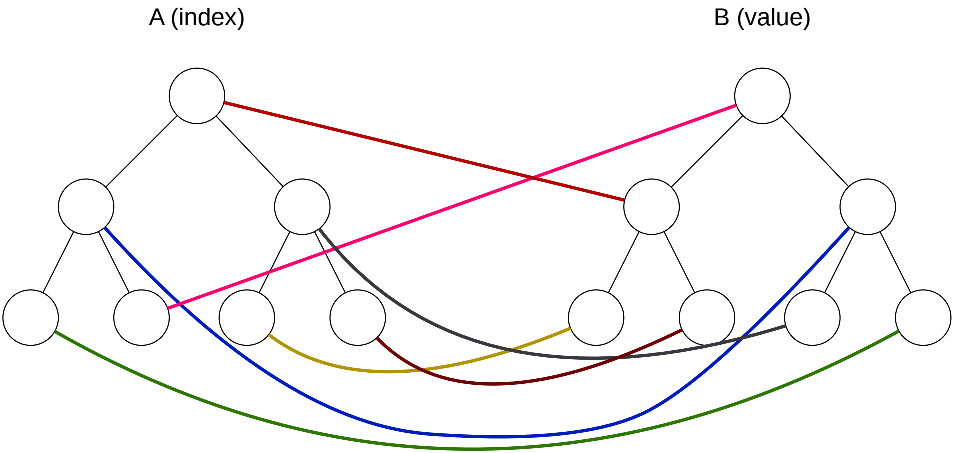


Figure: Dynamic permutation for the permutation $[6, 5, 3, 1, 0, 4, 2]$.

Dynamic extended suffix array

- Updating suffix array is slow ($O(n)$), new data structure needed

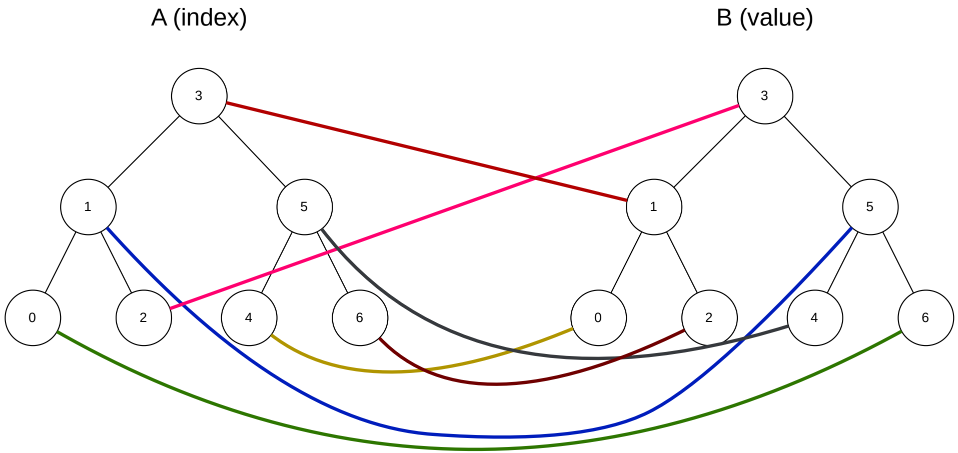


Figure: Dynamic permutation for the permutation $[6, 5, 3, 1, 0, 4, 2]$.

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	$\underline{1}$	$\underline{3}$	$\underline{0}$	$\underline{\text{N}}$	$\underline{0}$	2
New LCP	0	0	1	1	0	1	0	2

Phase 4 and 5: Clone extraction and source-mapping

- Similar to the initial detection
- Store nodes with LCP values $\geq$ threshold
- 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 = 0.998590358049055
         Type-2 (blind): 242 / 245 = 0.987755102040816
    Type-2 (consistent): 3300 / 3302 = 0.999394306480920
```

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**	**$\mathrm{LCP}_{\mathrm{avg}}$**	**$\mathrm{LCP}_{\geq 100}$**
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)

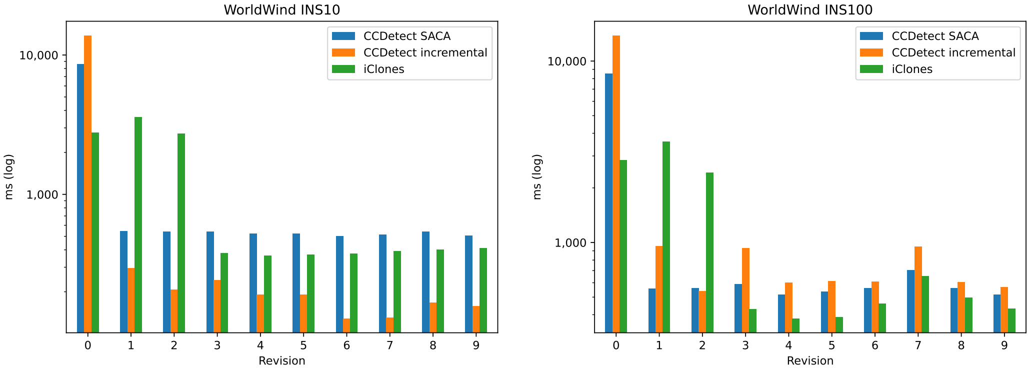


Figure: WorldWind performance benchmark

neo4j (1MLOC)

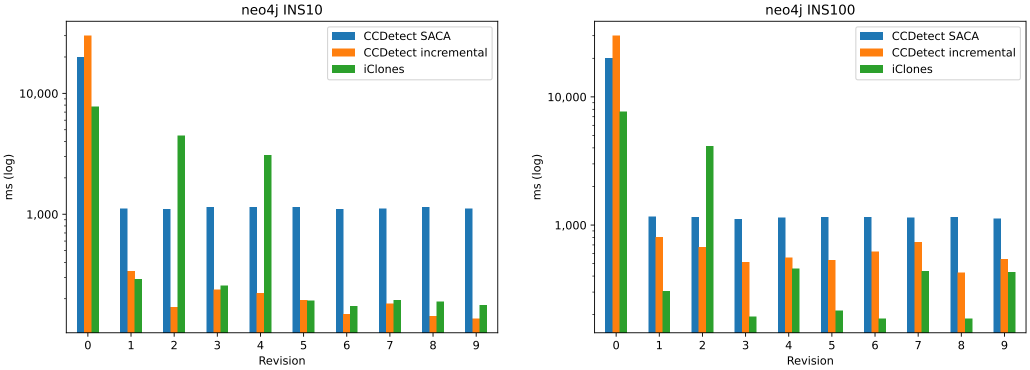


Figure: neo4j performance benchmark

graal (2.2MLOC)

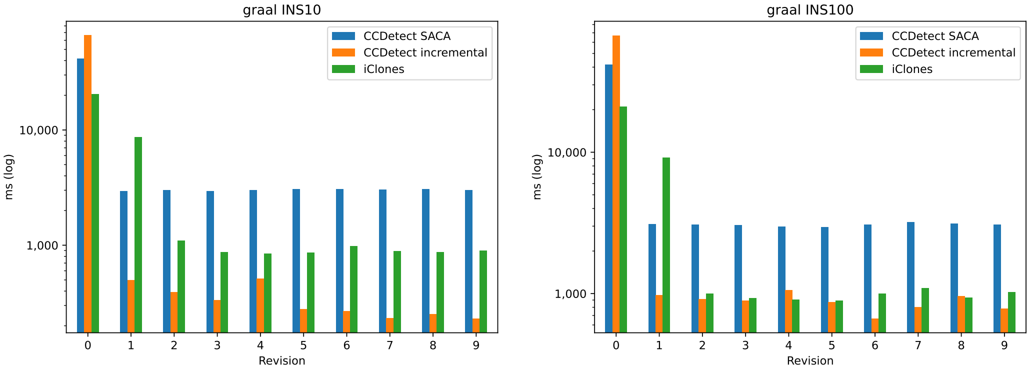


Figure: graal performance benchmark

flink (2.3MLOC)

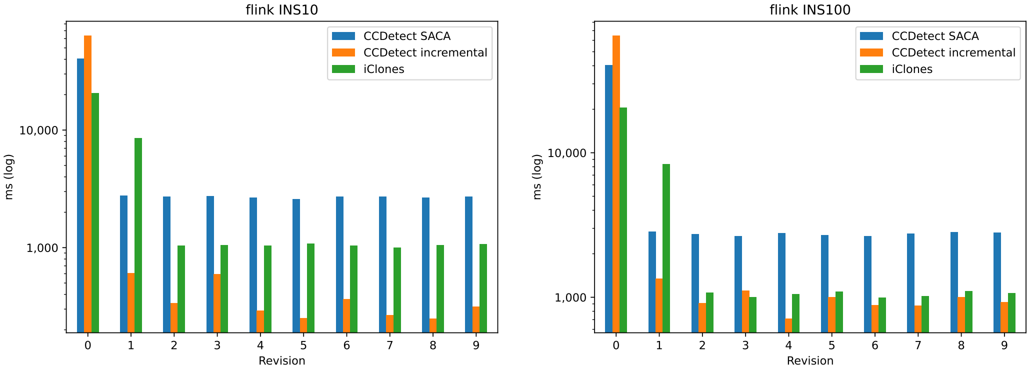


Figure: flink performance benchmark

elasticsearch (3.2MLOC)

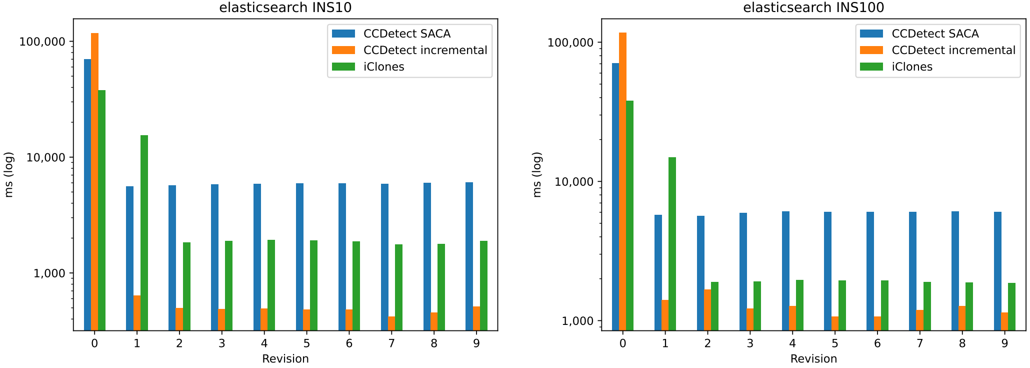


Figure: elasticsearch performance benchmark

intellij-community (5.8MLOC)

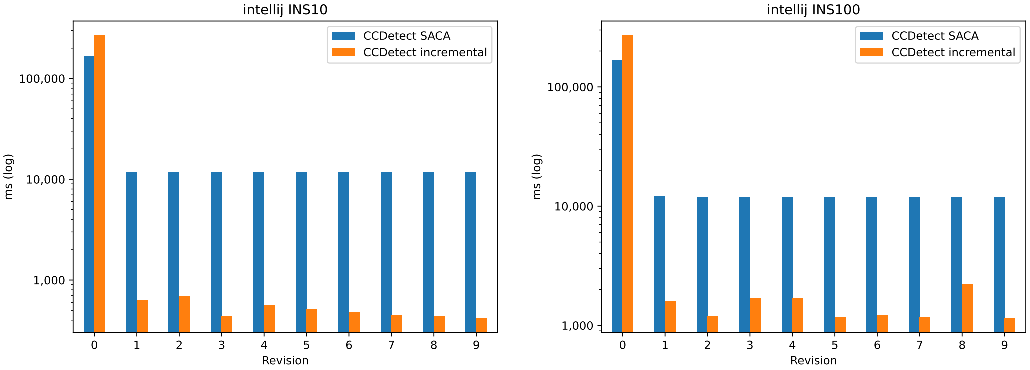


Figure: intellij-community performance benchmark

elasticsearch (3.2MLOC)

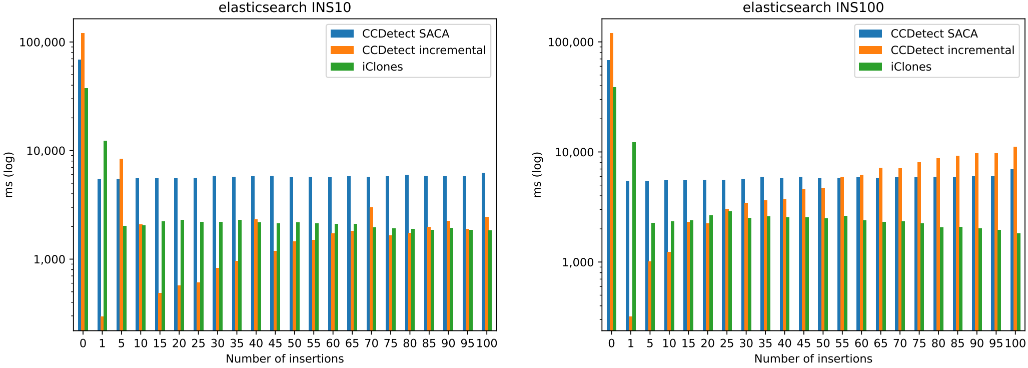


Figure: Elasticsearch performance benchmark with increasing number of edits

Memory usage

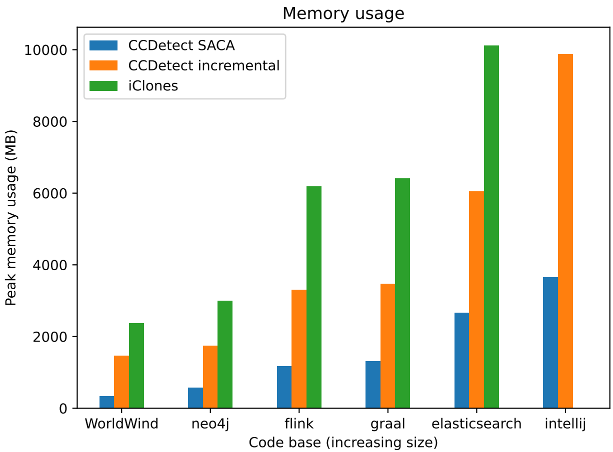


Figure: Peak memory usage of each tool when running the DEL10 test for each code base.

Language and IDE agnostic

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

Discussion

- Performance and memory usage
  - Incremental detection has the best performance if edits are “small”
  - Memory usage is lower than other incremental algorithms, but could still be a bottle-neck for practical use
- Language- and IDE agnostic
  - Works well for any language if grammar is correct
  - Setup and configuration depends on the IDE
- Practical usage in the IDE scenario
  - Live manual/automatic refactoring of code clones
  - Clone information used by other tools/refactorings

Conclusion

- CCDetect-LSP is a performant incremental clone detection tool
  - Facilitates fast incremental updates
  - Lower memory usage than existing solutions
  - Language- and IDE agnostic clone detection
- Future work
  - Type-3 clones
  - Refactoring clones
  - Compressing data structures

LSP

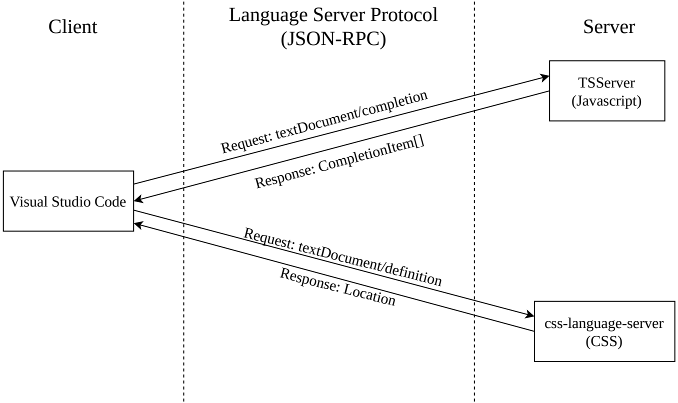


Figure: Example LSP server communication

LSP architecture

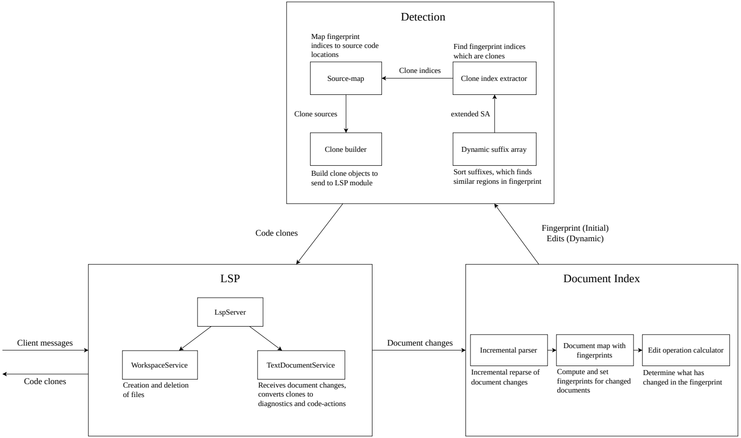


Figure: Architecture of CCDetect-LSP

Clone types: 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