PPT4J: Patch Presence Test for Java Binaries

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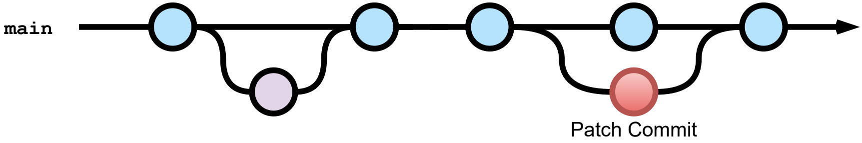
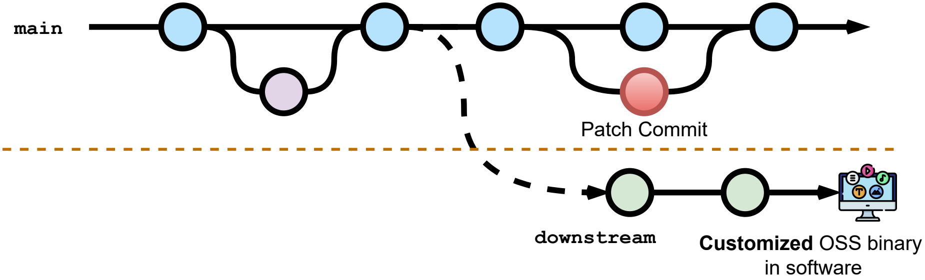
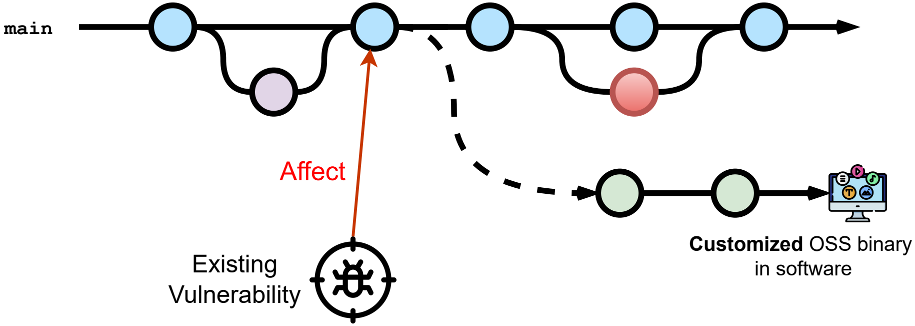
Background




main
Patch Commit
downstream
Customized OSS binary in software

Background


main
Affect
Existing Vulnerability
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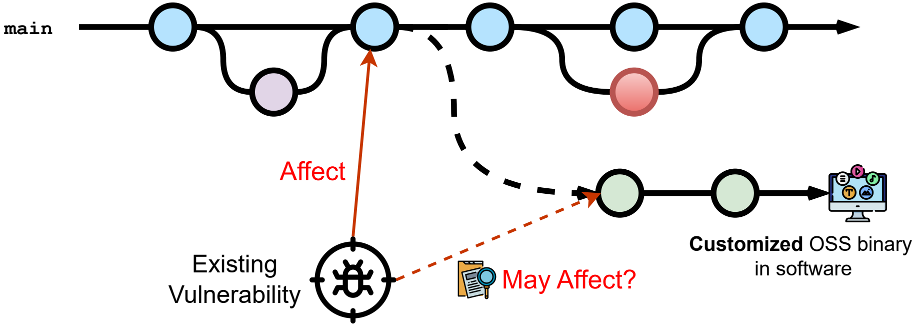
Background


main
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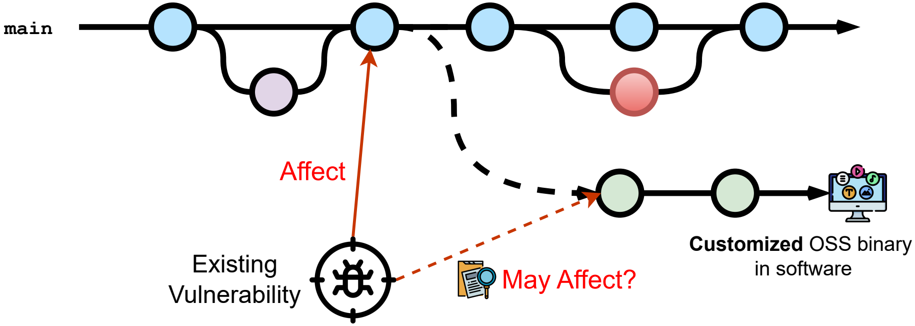
Vulnerability
May Affect?
Customized OSS binary
in software



Patch Presence Test

Checks if a specific patch is applied to an unknown target binary.

Motivation

```
- XmlPullParser         parser = Xml.newPullParser();
- XPPAttributesWrapper attributes = new XPPAttributesWrapper(parser);
+ try
+ {
+   XmlPullParser         parser = Xml.newPullParser();
+   XPPAttributesWrapper attributes = new XPPAttributesWrapper(parser);
```

```
- Document<T> doc = parser.parse(is);
+ XMLStreamReader reader = StaxUtils.createXMLStreamReader(is);
+ Document<T> doc = parser.parse(reader);
```

```
-    if (A == Algorithm.none && B == 2 && C == 0) {
-      return Mapper.deserialize(base64Decode(...), JWT.class);
+    if (B == 2 && C == 0) {
+      if (A == Algorithm.none) {
+        return Mapper.deserialize(base64Decode(...), JWT.class);
+      } else {
+        throw new InvalidJWTSignatureException();
+      }
```

Figure 1: Text diffs[1] $\neq$ Semantic changes

Facts

- Some (−) and (+) diff lines end up with no semantic changes.
- These lines introduce unrelated information to existing work that utilizes the complete patch diff.

[1] CVE-2017-1000498, CVE-2016-8739, and CVE-2018-11797 respectively. Diffs are simplified for illustration.

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- To extract precise semantic changes from diff that reflect all semantic information while not including unrelated information.

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Our Proposal

- A feature-based approach that highlights semantic changes.

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Our Approach

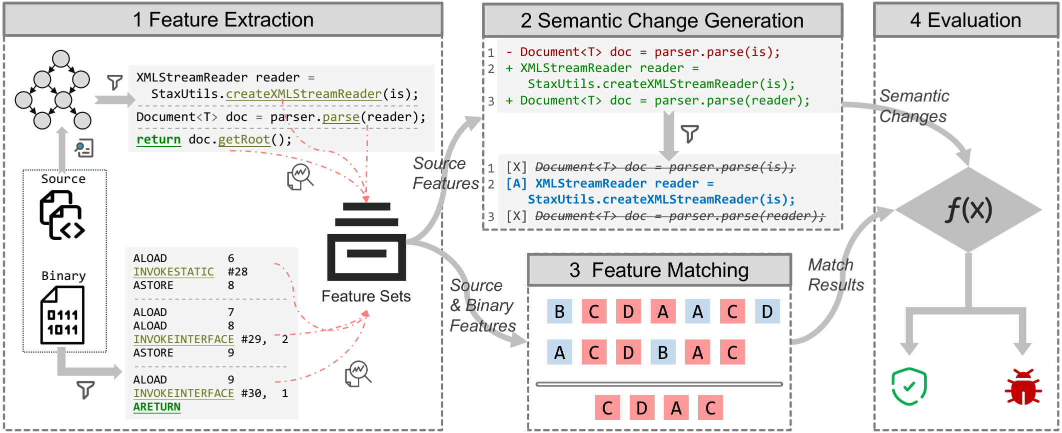


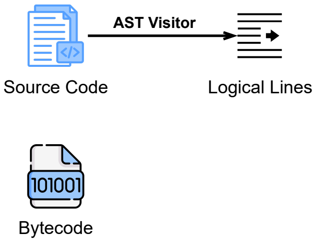
Figure 2: Overview of PPT4J

Source Code

Bytecode

Figure 3: Feature Extraction each generates a list of **unified feature sets** for source code and binary.

Feature Extraction



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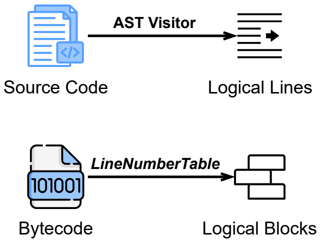

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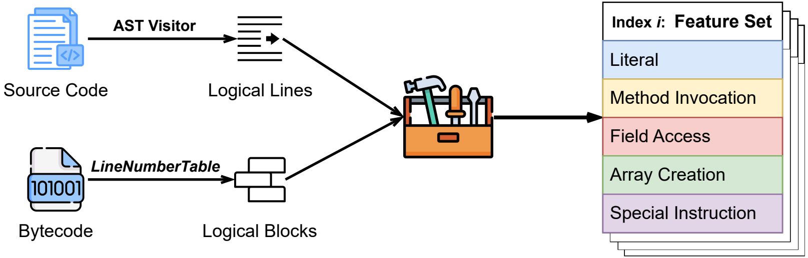

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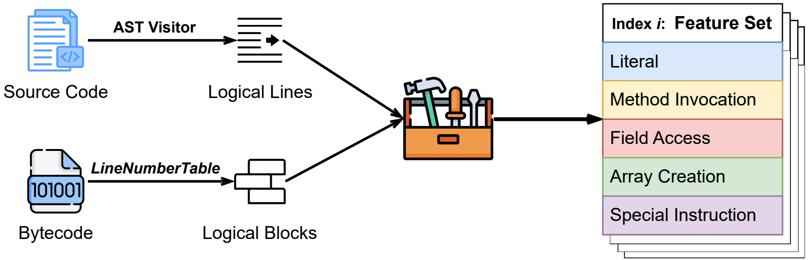

Figure 3: Feature Extraction each generates a list of **unified feature sets** for source code and binary.

- **Literal** ⟵ Extract directly & Simplify arithmetic expressions
- **Method** ⟵ Use type analysis to acquire signatures with more precise argument types

- **Special**
  1. Distinctive operators: `instanceof`, `++`/`--`, `shift`, ⋯
  2. Control flow manipulations: `return`, `throw`, `if`, `loop`[1] ⋯
  3. Syntactic sugars

[1]We analyze CFGs of bytecode to distinguish condition & loop blocks.

A sliding window-based heuristic algorithm, which utilizes **feature set similarity** to filter out semantic redundant lines.

$$\mathcal{J}(A,B) = \begin{cases} 1 & \text{A and B are both empty} \\ \dfrac{|A \cap B|}{|A \cup B|} & \text{otherwise} \end{cases}$$

1. Split diff hunks into finer-grained blocks (Type-**A**, Type-**D** or Type-**M**).
2. For each **M**-block, find the "optimal overlay" of (−) and (+) part.
3. Evaluate the similarity of feature sets within the overlay parts:
   - i. $\mathcal{J} = 1 \Rightarrow$ mark as *excluded* lines.
   - ii. $\mathcal{J} >$ threshold $\sigma_f \Rightarrow$ mark as *modification* lines.
4. Keep non-overlay parts as is, i.e., *addition* & *deletion* lines.

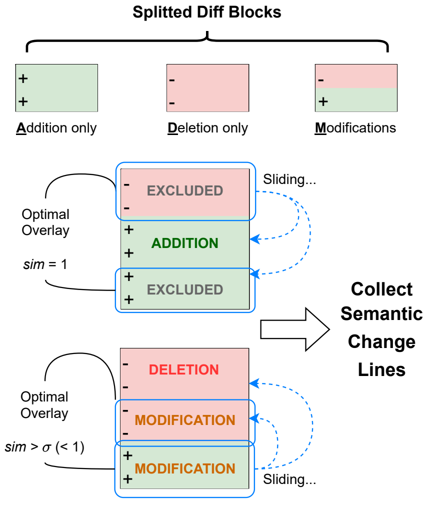

Figure 4: Examples of processing **M**-blocks

Feature Matching & Patch Presence Evaluation

What we have now:

- Lists of unified feature sets for:
  1. Reference source code before patch
  2. Reference source code after patch
  3. Target binary from user input
- Semantic change lines of the patch

It's time to figure out to what extent the binary resembles the diff part of reference sources.

1. We apply the *Longest Common Subsequence* algorithm[1] to match the feature set sequences of the binary and the source code (i.e., (i, iii) and (ii, iii)).

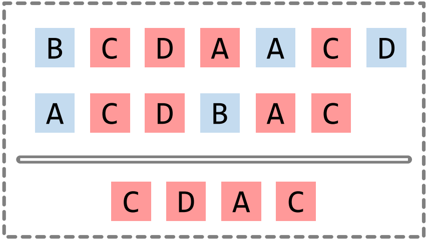

Figure 5: A simple example of the LCS algorithm. Each element in the sequence is a feature set.

[1] To make the algorithm work, we define the equivalence of two elements (i.e., feature sets) as: $\mathcal{J}(A, B) \geq \sigma_f$

Feature Matching & **Patch Presence Evaluation**

What we have now:

- Lists of unified feature sets for:
  - i Reference source code before patch
  - ii Reference source code after patch
  - iii Target binary from user input
- Semantic change lines of the patch
- **NEW:** The matching results of (i, iii) and (ii, iii)

2 Each semantic change line votes for the final result: **A**) patched; **B**) unpatched
Weighted vote: # votes = # features

- *Addition* line: if appears in Match(ii, iii), vote **A**; otherwise vote **B**
- *Deletion* line: if **not** appears in Match(i, iii), vote **A**; otherwise vote **B**
- *Modification* line pair `(pre, post)`: if "$\mathcal{J}(\text{post}, \text{binary}) > \mathcal{J}(\text{pre}, \text{binary})$", vote **A**; otherwise vote **B**
- *Excluded* lines are ignored in this procedure

Patch Support Rate $= \dfrac{\#\ \text{vote}_A}{\#\ \text{vote}}$ $\xrightarrow{\geq \sigma_p}$  $\xrightarrow{< \sigma_p}$ 

Dataset

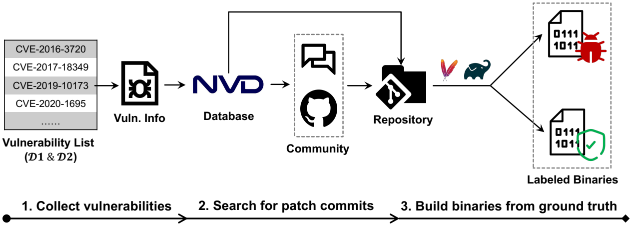

Figure 6: Steps to construct the dataset

- $\mathcal{D}1$: The Java library vulnerabilities evaluated by the baseline
- $\mathcal{D}2$: Vulnerabilities collected by Vul4J[1]

Baseline

- BScout[2] (reimplemented): A patch presence test framework specifically designed for Java binaries.

Metrics

- Accuracy
- Precision
- Recall
- F1 Score

[1]Bui et al., "Vul4J: A Dataset of Reproducible Java Vulnerabilities Geared Towards the Study of Program Repair Techniques"
[2]Dai et al., "BScout: Direct Whole Patch Presence Test for Java Executables"

Effectiveness

RQ.1: How **accurate** is the patch presence test framework compared to previous work?

Table 1: Test results on the dataset

Test Suite		Metrics			
		Accuracy	Precision	Recall	F1
BScout[1]	$\mathcal{D}$**1**[2]	100%	100%	100%	100%
	$\mathcal{D}$**2**	87.9%	100%	75.8%	86.2%
PPT4J	$\mathcal{D}$**1**	100%	100%	100%	100%
	$\mathcal{D}$**2**	**98.5%**	100%	**97.0%**	**98.5%**

- PPT4J does not generate false positive results.
- PPT4J outperforms the baseline BScout by 14.2% in terms of F1 score.

[1] This refers to our reimplemented version.

[2] The results on $\mathcal{D}$**1** is consistent with the original paper.

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- PPT4J does not generate false positive results.
- PPT4J outperforms the baseline BScout by 14.2% in terms of F1 score.
- PPT4J is also effective in handling patches with minor changes.

[1] This refers to our reimplemented version.
[2] The results on $\mathcal{D}$**1** is consistent with the original paper.

```
@@ -174,7 +174,7 @@ public <T> T deserialze(DefaultJSONParser parser,
    Type type, Object fieldName) {
            componentType = componentClass = clazz.getComponentType();
        }
        JSONArray array = new JSONArray();
-       parser.parseArray(componentClass, array, fieldName);
+       parser.parseArray(componentType, array, fieldName);

        return (T) toObjectArray(parser, componentClass, array);
    }
```

Figure 7: CVE-2017-18349

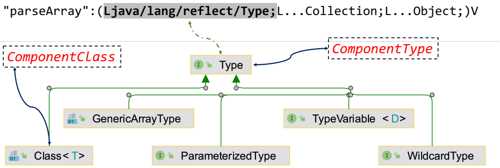

Figure 8: Class hierarchy of java.lang.reflect.Type

Case Study: Minor Changes

```
@@ -174,7 +174,7 @@ public <T> T deserialze(DefaultJSONParser parser,
↪   Type type, Object fieldName) {
            componentType = componentClass = clazz.getComponentType();
        }
        JSONArray array = new JSONArray();
-       parser.parseArray(componentClass, array, fieldName);
+       parser.parseArray(componentType, array, fieldName);

        return (T) toObjectArray(parser, componentClass, array);
    }
```

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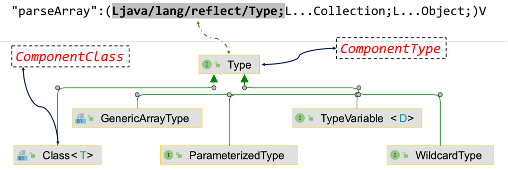

Figure 8: Class hierarchy of `java.lang.reflect.Type`

```
- parseArray(3)
       ↓
+ parseArray(3)
```

BScout ☹

V.S.

```
- parseArray(Class, ...)
       ↓
+ parseArray(Type,  ...)
```

PPT4J 😄

Efficiency

RQ.2: How **efficient** is the patch presence test framework, especially when dealing with large code repositories?

Table 2: Time consumption[1] on the dataset

Framework	Average	∼75%[a]
BScout[b]	0.34 sec/patch	0.28 sec/patch
PPT4J	0.48 sec/patch	0.30 sec/patch

[a] 75% of test cases are analyzed within this amount of time.
[b] This refers to our reproduction of Dai et al., "BScout: Direct Whole Patch Presence Test for Java Executables".

- Most patches can be quickly analyzed.
- Time cost is not proportional to the project size because only dependent[2] bytecodes are analyzed.
- A bit slower than BScout, but the advantages in effectiveness can compensate for this.

[1] The startup time of the virtual machine and third-party dependencies is not considered.
[2] Java classes fixed by the patch, and their dependent classes.

RQ.3: How do the analyses in *Feature Extraction*[1] contribute to the overall effectiveness?

Four variants:

1. PPT4J_**FULL**: Complete version
2. PPT4J_**Δ1**: Remove type analysis
3. PPT4J_**Δ2**: Ignore special instructions (e.g., loop and branch)
4. PPT4J_**Δ3**: Remove constant propagation/folding

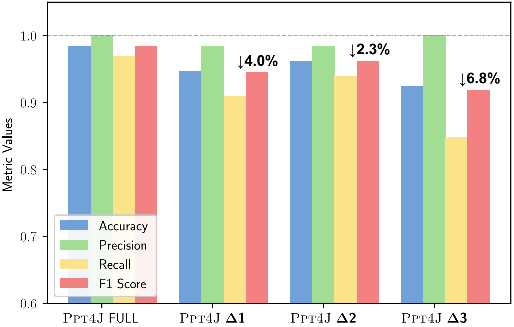

Figure 9: Test results for different variants of PPT4J

[1] Please refer to Section 3.2.3 of our paper for more details.

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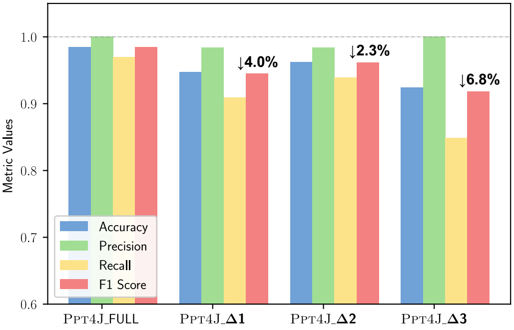
The above analyses contribute to the performance improvement.



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[1] Please refer to Section 3.2.3 of our paper for more details.

In-the-wild Evaluation

RQ.4: Can our approach analyze open-source libraries in real-world applications?

Test Procedures:

1. Extract OSS binaries from IntelliJ IDEA[1].
2. Run PPT[2] with specific patches.
3. Utilize unit tests in patch commits.
4. Check if **UT** results = **PPT** results.

Table 3: Results on open-source libraries within IntelliJ IDEA

	[a]	Version Timeline[b]				
		V1	V2	V3	V4	V5
CVE-2019-12402	08/19	TN	TN	TP	TP	TP
CVE-Anonymous-1	-	TN	TN	TN	TN	TN
CVE-Anonymous-2[c]	-	TN	TN	TN	TN	TN
CVE-2021-29425	05/18	TN	TN	TP	TP	TP
HTTPCLIENT-1803	01/17	TN	FN	FN	FN	FN
CVE-2017-1000487	10/13	TP	TP	TP	TP	TP
CVE-2015-6748	07/15	N/A	TP	TP	TP	TP
CVE-2015-6420	11/15	TN	TP	TP	TP	TP

[a] Patch commit time. Retrieved from Github, in MM/YY format.
[b] V1 - V5 are 5 versions of IntelliJ IDEA Ultimate, sorted in ascending order of release time. V1: IU-181.5684.4; V2: IU-191.8026.42; V3: IU-203.8084.24; V4: IU-213.7172.25; V5: IU-231.8109.175. The first two digits in the version string specify the release year, e.g., V1 was released in 2018.
[c] Info. of *CVE-Anonymous-1/2* is omitted due to "responsible reporting" principle.

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4. Check if **UT** results = **PPT** results.

- PPT4J achieves 89.7% accuracy with no false positive results. (BScout accuracy: 76.9%, ↓ 14.3%)
- PPT4J detects two un-patched vulnerabilities. We have reported this potential problem to the vendor.

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HTTPCLIENT-1803	01/17	TN	FN	FN	FN	FN
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Conclusion

In summary, we made the following contributions:

1. We propose a novel patch presence test framework for Java binaries, PPT4J, which highlights semantic code differences in patches.
2. We construct a dataset to evaluate the effectiveness of PPT4J.
3. We evaluate PPT4J, with results suggesting that PPT4J outperforms the baseline and is also capable in real-world scenarios.
4. We release the replication package of PPT4J, to facilitate future research.

Thanks for your attention!

Replication Package

arXiv Preprint