SigmaDiff: Semantics-Aware Deep Graph Matching for Pseudocode Diffing

Lian Gao, Yu Qu, Sheng Yu, Yue Duan, Heng Yin

Pseudocode Diffing

Pseudocode of Two Given Binaries

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Locate Similar Tokens

Capture Different Tokens

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Vulnerability/patch Detection

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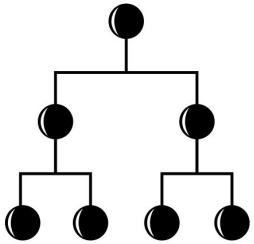


Lineage Analysis

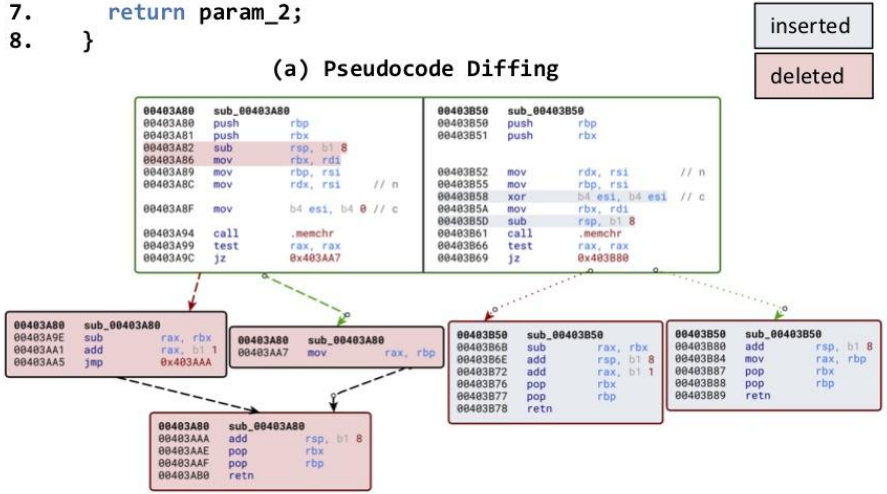
Comparison with Binary Diffing

Benefits:

- More concise and human-readable

```
1.    size_t FUN_00403a80(void *param_1,size_t param_2) {
2.      void *pvVar1;
3.      pvVar1 = memchr(param_1,0,param_2);
4.      if (pvVar1 != (void *)0x0) {
5.  -       param_2 = (long)pvVar1 + (1 - (long)param_1);
    +       return (long)pvVar1 + (1 - (long)param_1);
6.      }
7.      return param_2;
8.    }
```

(a) Pseudocode Diffing



(b) Binary Diffing

Comparison with Binary Diffing

Benefits:

- More concise and human-readable
- More fine-grained

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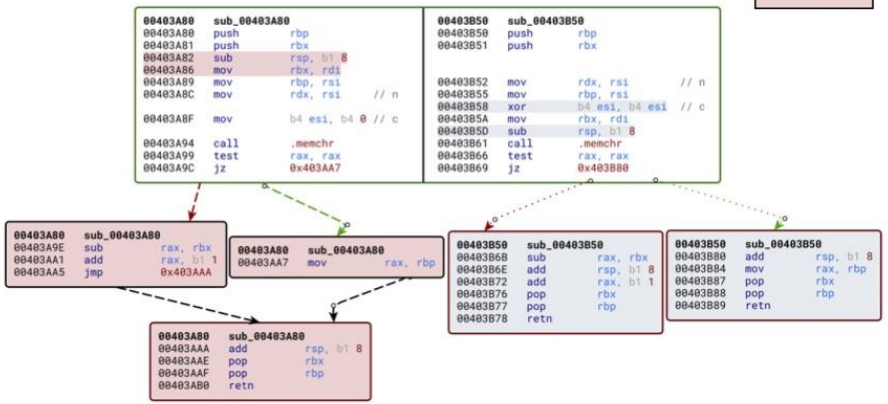
(a) Pseudocode Diffing



(b) Binary Diffing

Comparison with Binary Diffing

Benefits:

- More concise and human-readable
- More fine-grained
- The recovered semantic information could be leveraged

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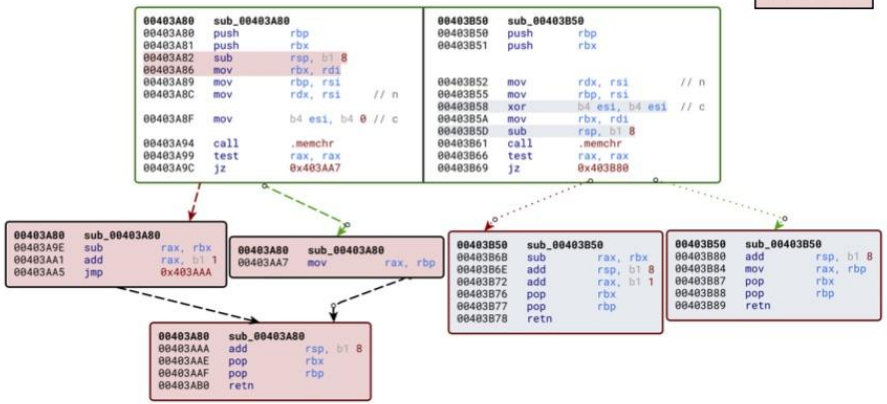

(b) Binary Diffing

Comparison with Binary Diffing

Benefits:

- More concise and human-readable
- More fine-grained
- The recovered semantic information could be leveraged
- Natural support of cross-architecture diffing

```
1.   size_t FUN_00403a80(void *param_1,size_t param_2) {
2.     void *pvVar1;
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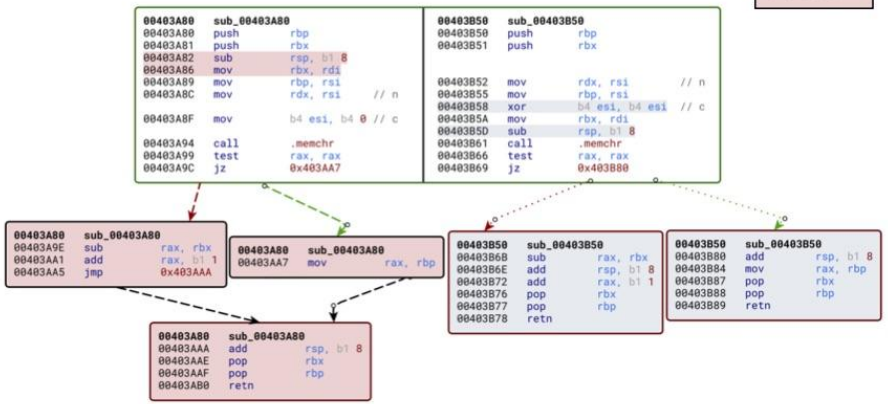

(b) Binary Diffing

Existing Work

Traditional approaches (e.g., BinDiff, Diaphora)

- rely on heuristics (e.g., function name) to find similar functions, perform basic block matching along the control flow graph (BinDiff), or simple string-based matching at the token level (Diaphora)
- not robust and can be easily thwarted by compiler optimizations

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Dynamic analysis-based approaches (e.g., BLEX, iBinHunt)

- capturing the semantics of binaries and have good resilience against code obfuscation
- low code coverage

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Traditional approaches (e.g., BinDiff, Diaphora)

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- capturing the semantics of binaries and have good resilience against code obfuscation
- low code coverage

Learning-based approaches (e.g., DeepBinDiff)

- encode graph information into numerical vectors, a.k.a, graph embeddings, and perform binary diffing
- distill unique semantic-level features of a program
- does not scale well on large binaries

Motivating Example (CVE-2020-13790)

Challenges:

Pseudocode-level changes (noises) that are caused by compilers and decompilers

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      (*cinfo->mem->alloc_small)
      ((j_common_ptr)cinfo, JPOOL_IMAGE,
      -     (size_t)(((long)maxval + 1L) *
      +     (size_t)(((long)MAX(maxval, 255) + 1L) *
            sizeof(JSAMPLE)));
      ......
      ......
2.    for (val = 0; val <= (long)maxval; val++) {
3.      source->rescale[val] = (JSAMPLE)((val *
      MAXJSAMPLE + half_maxval) / maxval);
4.    }
```

Pseudocode (old version)

```
1.    uVar18 = (ulong)uVar12;
2.    lVar16 = (**(code
      **)param_1[1])(param_1,1,uVar18 + 1);
      ......
      ......
3.    while( true ) {
4.      *(char *)(lVar16 + lVar17) =
      (char)((long)uVar14 / (long)uVar18);
5.      lVar17 = lVar17 + 1;
6.      if ((long)uVar18 < lVar17) break;
7.      lVar16 = *(long *)(param_2 + 0x48);
8.      uVar14 = uVar14 + 0xff;
9.    }
```

Pseudocode (new version)

```
1.    uVar13 = 0xff;
2.    if (0xfe < uVar12) {
3.      uVar13 = (ulong)uVar12;}
4.    __s = (void *)(**(code
      **)param_1[1])(param_1,1,uVar13 + 1);
      ......
5.    do {
6.      *(char *)(*(long *)(param_2 + 0x48) +
      lVar14) = (char)((long)uVar13 /
      (long)(ulong)uVar12);
7.      lVar14 = lVar14 + 1;
8.      uVar13 = uVar13 + 0xff;
9.    } while (lVar14 != (ulong)uVar12 + 1);
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Motivating Example (CVE-2020-13790)

Challenges:

Pseudocode-level changes (noises) that are caused by compilers and decompilers

- Different variable names

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Motivating Example (CVE-2020-13790)

Challenges:

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- Different expressions

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for (val = 0; val <= (long)maxval; val++) {
  source->rescale[val] = (JSAMPLE)((val *
MAXJSAMPLE + half_maxval) / maxval);
}
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Pseudocode (old version)

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uVar18 = (ulong)uVar12;
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**)param_1[1])(param_1,1,uVar18 + 1);
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while( true ) {    Different Expressions
  *(char *)(lVar16 + lVar17) =
(char)((long)uVar14 / (long)uVar18);
  lVar17 = lVar17 + 1;
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} while (lVar14 != (ulong)uVar12 + 1);
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Motivating Example (CVE-2020-13790)

Challenges:

Pseudocode-level changes (noises) that are caused by compilers and decompilers

- Different variable names
- Different expressions
- Different control constructs

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Different Control Constructs

Pseudocode (new version)

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9.    } while (lVar14 != (ulong)uVar12 + 1);
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Motivating Example (CVE-2020-13790)

Observations:

- A large number of syntax level changes in decompilation are introduced during the transformation from intermediate representation (IR) to pseudocode

Design Choice:

- Perform diffing at IR level and map the IR-level diffing results up to the pseudocode level

Source Code

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    ......
    ......
3.  while( true ) {      Different Expressions
4.    *(char *)(lVar16 + lVar17) =
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Motivating Example (CVE-2020-13790)

Challenges:

- Different variable names

Design Choice:

- Perform a lightweight symbolic analysis to associate each IR variable with a symbolic expression that reveals how the value of that IR variable is calculated

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Motivating Example (CVE-2020-13790)

Challenges:

- Unstable control flow

Design Choice:

- Leverage data and control dependencies to capture contextual information for each IR

Source Code

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Motivating Example (CVE-2020-13790)

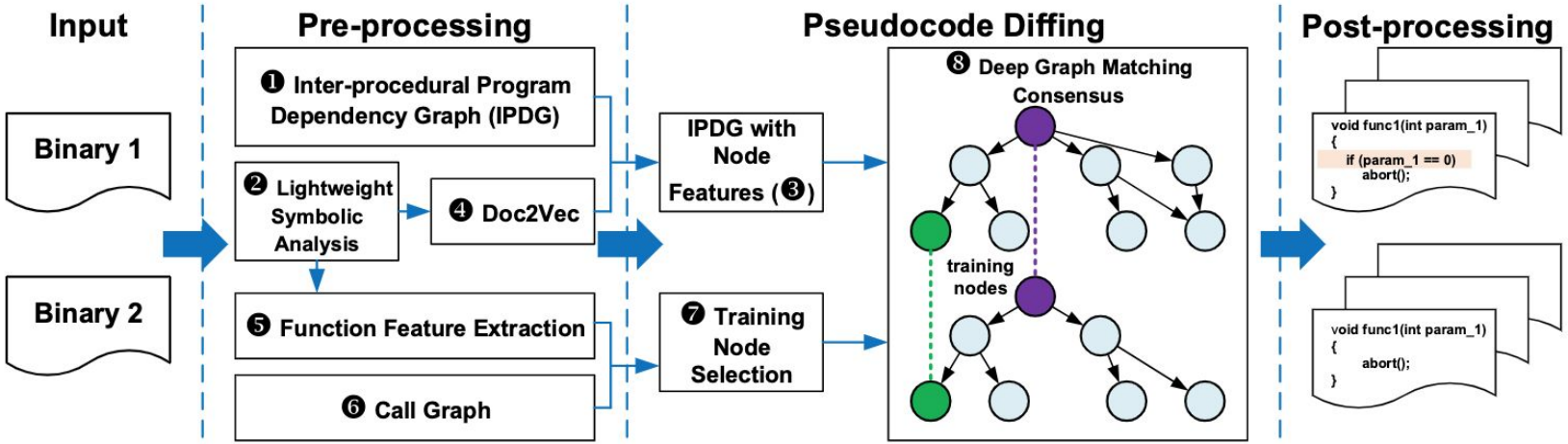
Challenges

- Noises in the graph matching
- Large number of tokens
- NP-hard graph matching problem

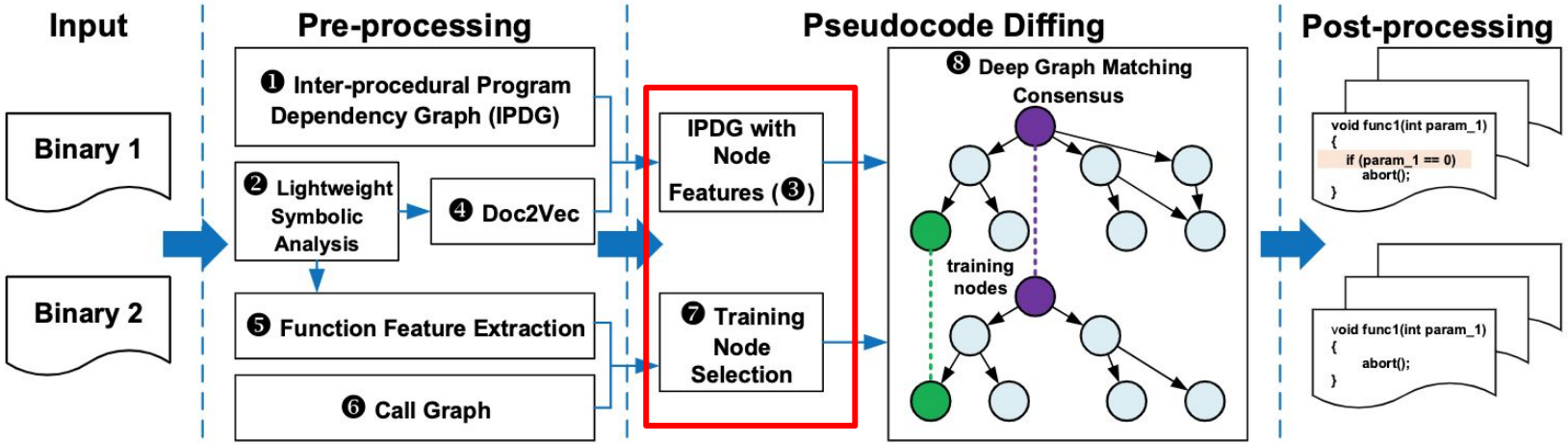
Design Choice

- Apply deep graph matching consensus (DGMC) model to fully exploit the neighboring contextual information
- Leverages the computing power of modern GPUs

Approach Overview



Approach Overview



IPDG with Node Features

```
1.  void foo(undefined8* param_1) {
2.    lVar2 = bar(param_1);
3.    if (lVar2 != 0) {
4.      *(param_1 + 8) = lVar2;
5.    }
6.  }
```

```
1.  undefined8* bar(undefined8* param_1){
2.    return param_1 + 20;
3.  }
```

IPDG with Node Features

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1.  void foo(undefined8* param_1) {
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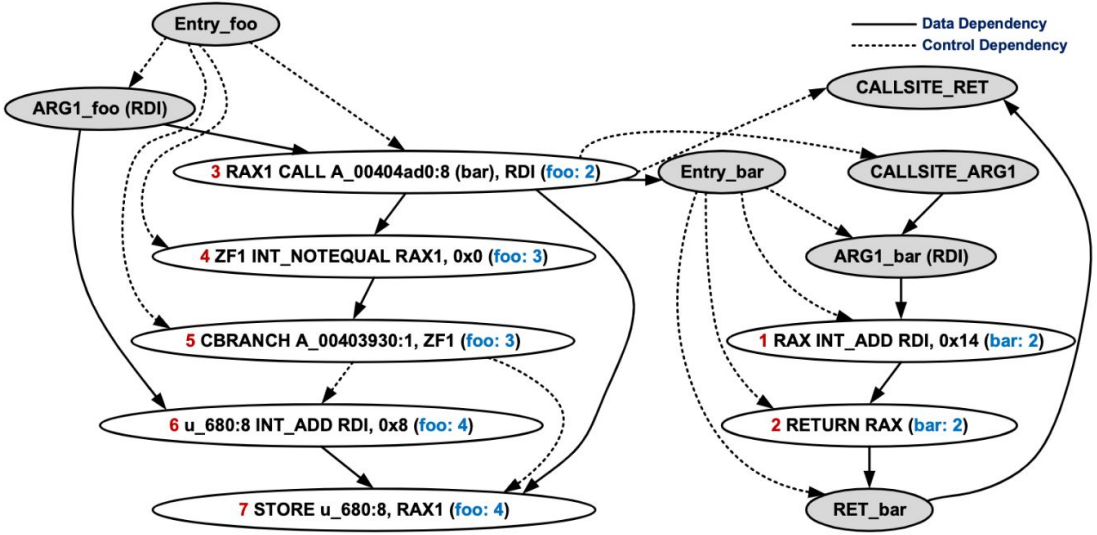
4.      *(param_1 + 8) = lVar2;
5.    }
6.  }
```

```
1.  undefined8* bar(undefined8* param_1){
2.    return param_1 + 20;
3.  }
```

(1) Generate inter-procedural program dependency graph



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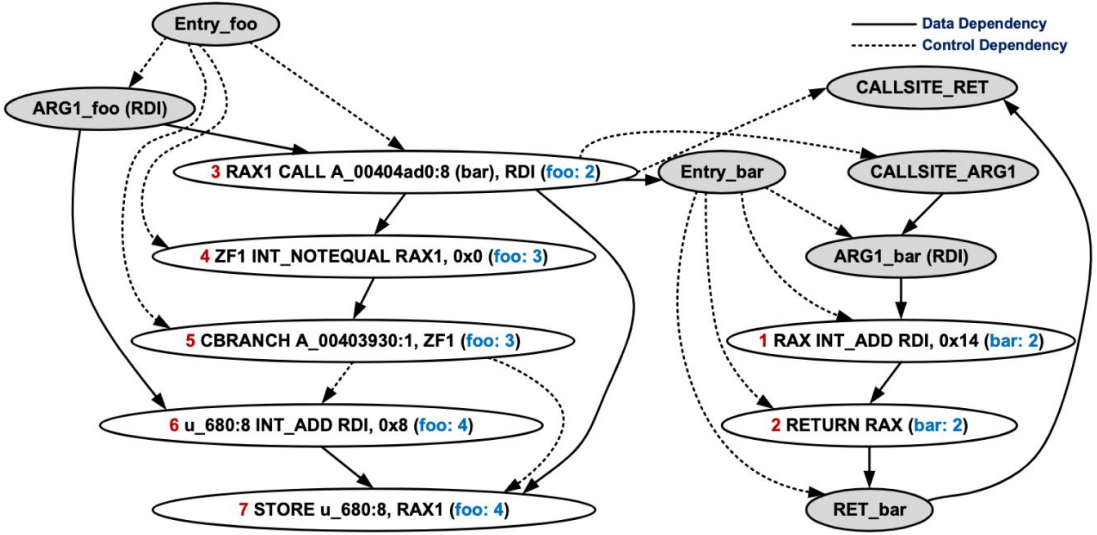
3.    if (lVar2 != 0) {
4.      *(param_1 + 8) = lVar2;
5.    }
6.  }
1.  undefined8* bar(undefined8* param_1){
2.    return param_1 + 20;
3.  }
```

ID	Symbolic Analysis Results	Node Features
1	α(RDI) := ARG1 α(RAX) := ARG1 + 20	ARG1 + 20 INT_ADD ARG1 20
2	N/A	RETURN ARG1 + 20
3	α(RDI) := ARG1 α(RAX1) := ARG1 + 20	ARG1 + 20 CALL ADDR ARG1
4	α(ZF1) := 0/1	0 INT_NOTEQUAL ARG1 + 20 CONST
5	N/A	CBRANCH ARG1 + 20 CONST
6	α(u_680:8) := ARG1 + 8	ARG1 + 8 INT_ADD ARG1 CONST
7	α([ARG1 + 8]) := ARG1 + 20	STORE CONST ARG1 + 8 ARG1 + 20

(2) Perform lightweight symbolic analysis
=> Node Features

(1) Generate inter-procedural program dependency graph



Training Node Selection

Training Nodes:

- Node pairs with high similarity and uniqueness

Used in semi-supervised learning:

- Source and target graphs + small
  set of training nodes => mappings for the rest of the nodes

Training Node Selection

Select IRs (nodes):

- that have unique node feature
- that appear in both graphs

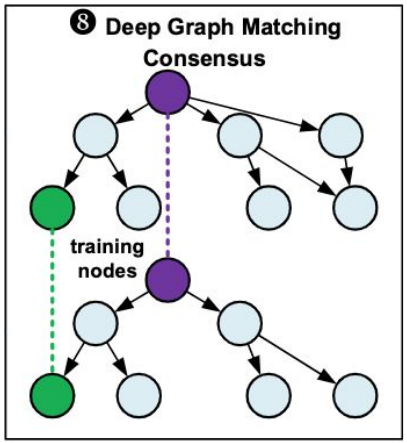
```
1.  void foo(undefined8* param_1) {
2.    lVar2 = bar(param_1);
3.    if (lVar2 != 0) {
4.      *(param_1 + 8) = lVar2;
5.    }
6.  }
```

```
1.  void foo(undefined8* param_1) {
2.    lVar2 = bar(param_1);
3.    if (lVar2 == 0) {
4.      return;
5.    }
6.    *(param_1 + 8) = lVar2;
7.  }
```

STORE CONST ARG1+8 ARG1+20

ID	Symbolic Analysis Results	Node Features
1	α(RDI) := ARG1 α(RAX) := ARG1 + 20	ARG1 + 20 INT_ADD ARG1 20
2	N/A	RETURN ARG1 + 20
3	α(RDI) := ARG1 α(RAX1) := ARG1 + 20	ARG1 + 20 CALL ADDR ARG1
4	α(ZF1) := 0/1	0 INT_NOTEQUAL ARG1 +20 CONST
5	N/A	CBRANCH ARG1 + 20 CONST
6	α(u_680:8) := ARG1 + 8	ARG1 + 8 INT_ADD ARG1 CONST
7	α([ARG1 + 8]) := ARG1 + 20	STORE CONST ARG1 + 8 ARG1 +20

Diffing

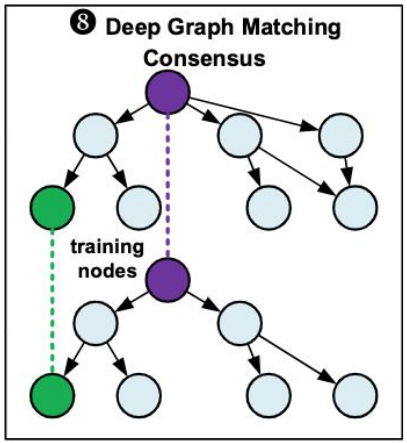


Deep Graph Matching Consensus (DGMC) model [1]

- A two-stage deep graph matching architecture
  - Leveraging Graph Neural Network (GNN) to obtains the initial matchings
  - Iteratively reaching neighborhood consensus (ensuring the neighbors of the matched nodes are correctly matched to each other as well)

[1] Fey, Matthias, et al. "Deep Graph Matching Consensus." *International Conference on Learning Representations*. 2019.

Diffing



Deep Graph Matching Consensus (DGMC) model [1]

- A two-stage deep graph matching architecture
  - Leveraging Graph Neural Network (GNN) to obtains the initial matchings
  - Iteratively reaching neighborhood consensus (ensuring the neighbors of the matched nodes are correctly matched to each other as well)

Modifications:

- Increase the penalty of incompatible types
- Add more hops
- Introduce the “pre-training and fine-tuning” schema
- Design an iterative algorithm to avoid the out-of-memory problem in GPU

[1] Fey, Matthias, et al. "Deep Graph Matching Consensus." *International Conference on Learning Representations*. 2019.

Evaluation

- Compare with Diaphora and DeepBinDiff
  - Cross-version
  - Cross-optimization-level
  - Cross-compiler
  - Cross-architecture
- Conduct Patch Detection
  - Case studies on real-world vulnerabilities
  - Zoom

Evaluation

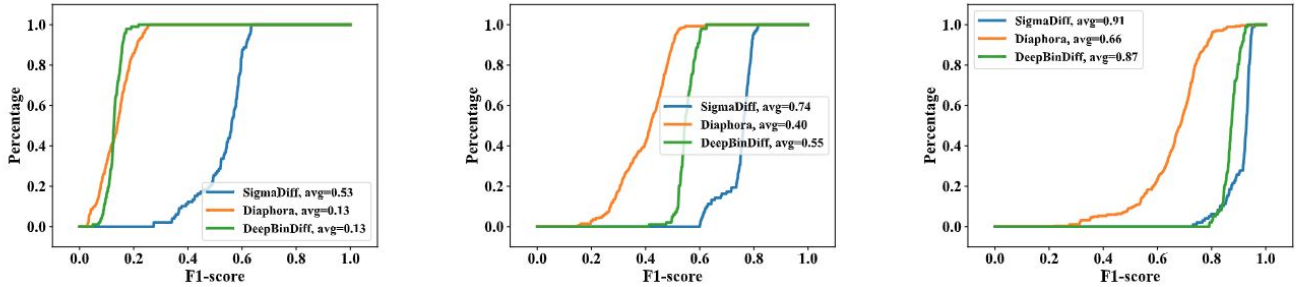
TABLE V: Cross-version Pseudocode Diffing Results. Si: SIGMADIFF, De: DeepBinDiff, Di: Diaphora

		Recall			Precision			F1		
		Si	De	Di	Si	De	Di	Si	De	Di
Coreutils	v5.93 - v8.1	**0.624**	0.589	0.438	**0.770**	0.743	0.759	**0.687**	0.654	0.549
	v6.4 - v8.1	**0.689**	0.631	0.551	**0.793**	0.767	0.643	**0.735**	0.691	0.592
	Average	**0.656**	0.610	0.494	**0.781**	0.755	0.701	**0.711**	0.673	0.571
Diffutils	v2.8 - v3.6	**0.694**	0.660	0.348	**0.848**	0.806	0.406	**0.763**	0.725	0.375
	v3.4 - v3.6	**0.928**	0.909	0.788	0.957	**0.960**	0.844	**0.942**	0.934	0.815
	Average	**0.811**	0.784	0.568	**0.903**	0.883	0.625	**0.853**	0.829	0.595
Findutils	v4.233 - v4.6	**0.685**	0.579	0.366	**0.825**	0.758	0.773	**0.748**	0.655	0.487
	v4.41 - v4.6	**0.769**	0.690	0.499	**0.868**	0.847	0.786	**0.814**	0.759	0.609
	Average	**0.727**	0.635	0.433	**0.847**	0.803	0.779	**0.781**	0.707	0.548
Gmp	v6.0.0 - v6.2.1	**0.815**	N/A	0.691	0.871	N/A	**0.892**	**0.842**	N/A	0.779
	v6.1.1 - v6.2.1	**0.858**	N/A	0.771	0.894	N/A	**0.920**	**0.876**	N/A	0.839
	Average	**0.836**	N/A	0.731	0.882	N/A	**0.906**	**0.859**	N/A	0.809
Putty	v0.75 - v0.77	**0.781**	N/A	0.741	0.899	N/A	**0.897**	**0.836**	N/A	0.812
	v0.76 - v0.77	**0.798**	N/A	0.732	**0.908**	N/A	0.881	**0.849**	N/A	0.800
	Average	**0.789**	N/A	0.737	**0.904**	N/A	0.889	**0.842**	N/A	0.806

TABLE VII: Cross-architecture Pseudocode Diffing Results (ARM vs. x86-64). Si: SIGMADIFF, Di: Diaphora

	Recall		Precision		F1	
	Si	Di	Si	Di	Si	Di
Coreutils 8.1	**0.720**	0.429	0.725	**0.954**	**0.723**	0.586
Diffutils 3.6	**0.751**	0.003	**0.754**	0.674	**0.752**	0.006
Findutils 4.6	**0.620**	0.003	**0.642**	0.521	**0.631**	0.006
Gmp 6.2.1	**0.362**	0.165	0.386	**0.827**	**0.373**	0.275
Putty 0.76	**0.143**	0.038	0.436	**0.591**	**0.216**	0.072

Evaluation



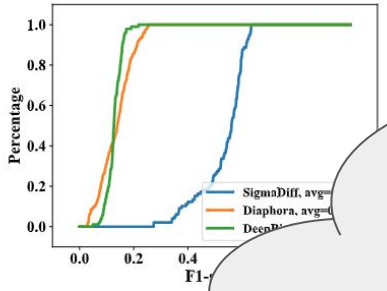
(a) O0 vs. O3 (b) O1 vs. O3 (c) O2 vs. O3

Fig. 6: Cross-optimization-level Pseudocode Diffing F1-score CDF (merging results of Coreutils, Diffutils, and Findutils)

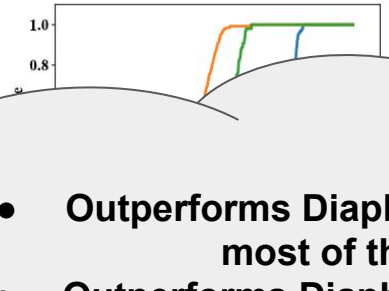
TABLE VI: Cross-compiler Pseudocode Diffing Results (Clang vs. GCC). Si: SIGMADIFF, De: DeepBinDiff, Di: Diaphora

	Recall			**Precision**			**F1**		
	Si	De	Di	Si	De	Di	Si	De	Di
Coreutils 8.1	**0.595**	0.203	0.262	**0.807**	0.482	0.720	**0.681**	0.285	0.382
Diffutils 3.6	0.295	0.187	0.029	**0.574**	0.445	0.535	**0.390**	0.263	0.055
Findutils 4.6	0.363	0.202	0.051	**0.619**	0.458	0.597	**0.457**	0.279	0.094
Gmp 6.2.1	**0.393**	N/A	0.227	0.597	N/A	**0.821**	**0.474**	N/A	0.356
Putty 0.76	**0.273**	N/A	0.095	0.507	N/A	**0.610**	**0.354**	N/A	0.164

Evaluation



(a) O0



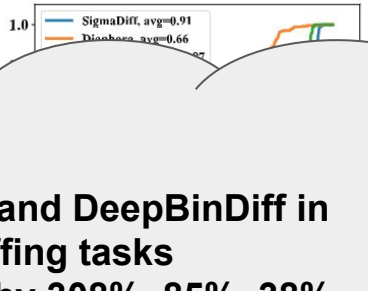


Fig. 6: Cross-optimizat

- **Outperforms Diaphora and DeepBinDiff in most of the diffing tasks**
- **Outperforms Diaphora by 308%, 85%, 38% in terms of F1-scores in O0 vs. O3, O1 vs. O3, and O2 vs. O3, respectively**

TABLE VI: Cross-comp

Coreutils 8.1	**0.595**								
Diffutils 3.6	0.295	0.187	0.029	**0.574**	0.445				0.055
Findutils 4.6	0.363	0.202	0.051	**0.619**	0.458	0.597		0.279	0.094
Gmp 6.2.1	**0.393**	N/A	0.227	0.597	N/A	**0.821**	**0.474**	N/A	0.356
Putty 0.76	**0.273**	N/A	0.095	0.507	N/A	**0.610**	**0.354**	N/A	0.164

Vulnerability/Patch Analysis

TABLE XI: Diffing results for Zoom. Si: SIGMADIFF, Di: Diaphora, Bi: BinDiff

Library	Ver.	Confirmed CVEs	Function-lvl			Token-lvl		
			Si	Di	Bi	Si	Di	Bi
OpenSSL	1.1.1k	CVE-2023-0464	✓		✓	✓		
		CVE-2023-0215	✓					
		CVE-2022-4450	✓	✓		✓		
		CVE-2022-0778	✓	✓	✓	✓		✓
		CVE-2021-3712	✓	✓		✓		
		CVE-2021-3711	✓			✓		
SQLite	3.33.0	CVE-2022-35737	✓					
		CVE-2021-20227	✓					
resiprocate	1.11	CVE-2021-3672	✓	✓				
		CVE-2017-9454	✓	✓				
libjpeg-turbo	2.0.4	CVE-2020-13790	✓	✓	✓	✓	✓	✓
FFmpeg	4.2.3	CVE-2021-38291	✓	✓	✓	✓	✓	✓
		CVE-2020-22037	✓	✓	✓	✓		

Vulnerability/Patch Analysis

TABLE XI: Diffing results for Zoom. Si: SIGMADIFF, Di: Diaphora, Bi: BinDiff

Library	Ver.	Confirmed CVEs	Function-lvl			Token-lvl		
			Si	Di	Bi	Si	Di	Bi
OpenSSL	1.1.1k	CVE-2023-0464 CVE-2023-0215 CVE-202 CVE CVI	✓ ✓		✓	✓		
SQLite	3.33.0							
resiprocate	1.11							
libjpeg-turbo	2.0.4	CVE-202						
FFmpeg	4.2.3	CVE-2021-3829 CVE-2020-22037	✓	✓	✓	✓		

- **Identify thirteen vulnerabilities in Windows (v5.9.7.3931) and Linux (v5.9.6.2225)**
- **Precisely pinpoint eight vulnerabilities at token level**

Open Source Project

https://github.com/yijiufly/SigmaDiff

Thank you!