BINALIGNER: Aligning Binary Code for Cross-Compilation Environment Diffing

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Background – Binary Diffing

Definition

align code portions corresponding to the same source code snippets between two binaries

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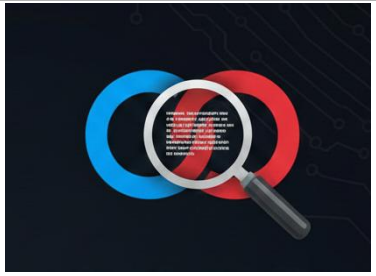
Application

vulnerability&patch analysis



code plagiarism detection

malware analysis

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Distinction

Binary Code Similarity Detection → Binary Diffing:
how similar two functions are → which parts correspond to each other

Background – Challenge and Existing Methods

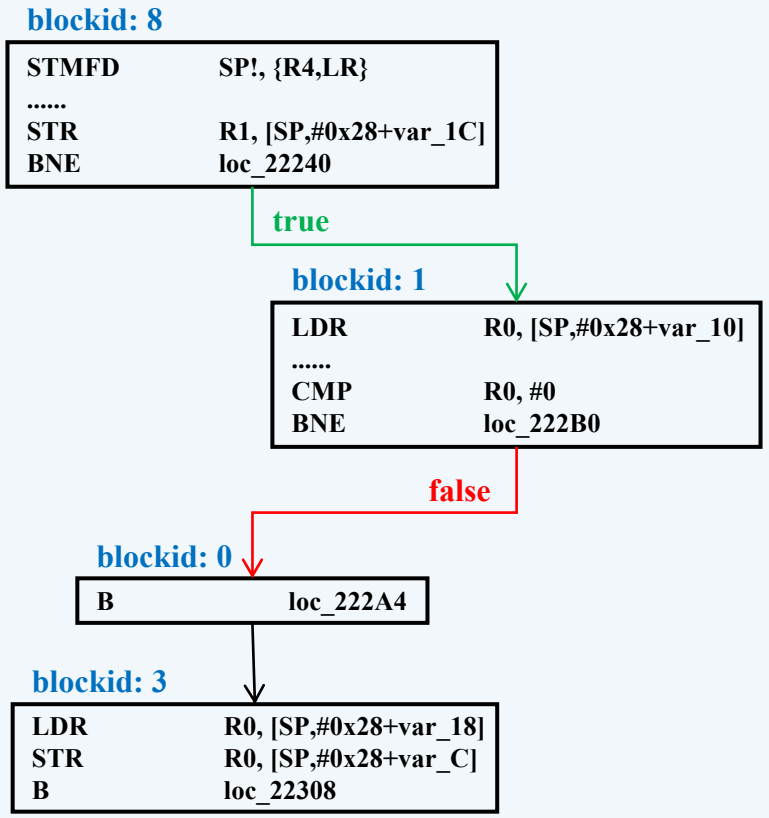
Challenge

boundaries of basic blocks are not stable across different compilation environments

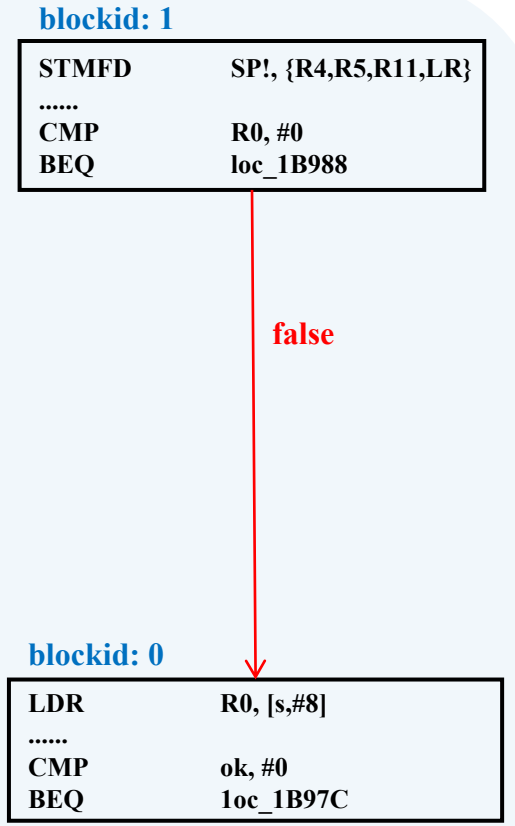
Existing Methods

- Traditional approaches: break easily
- ML-based approaches: node-level matching, rely on instruction sets

Partial CFGs of Function ssl3_check_finished



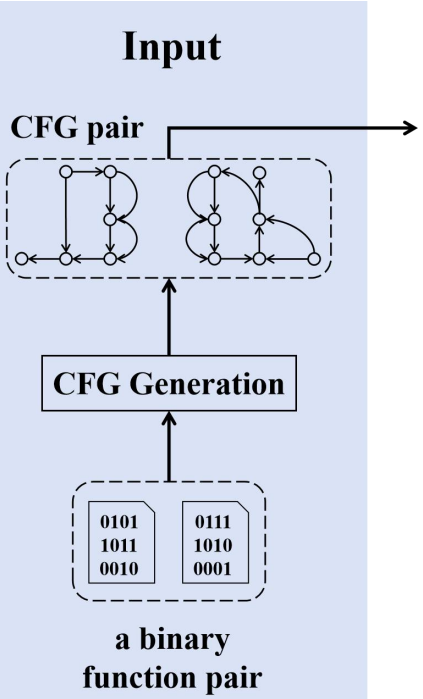
(a) OpenSSL 1.0.1f, clang-6.0, arm_32, O0



(b) OpenSSL 1.0.1f, clang-6.0, arm_32, O3

Approach – Overview

BINALIGNER: A Three-Step Pipeline for Subgraph Alignment



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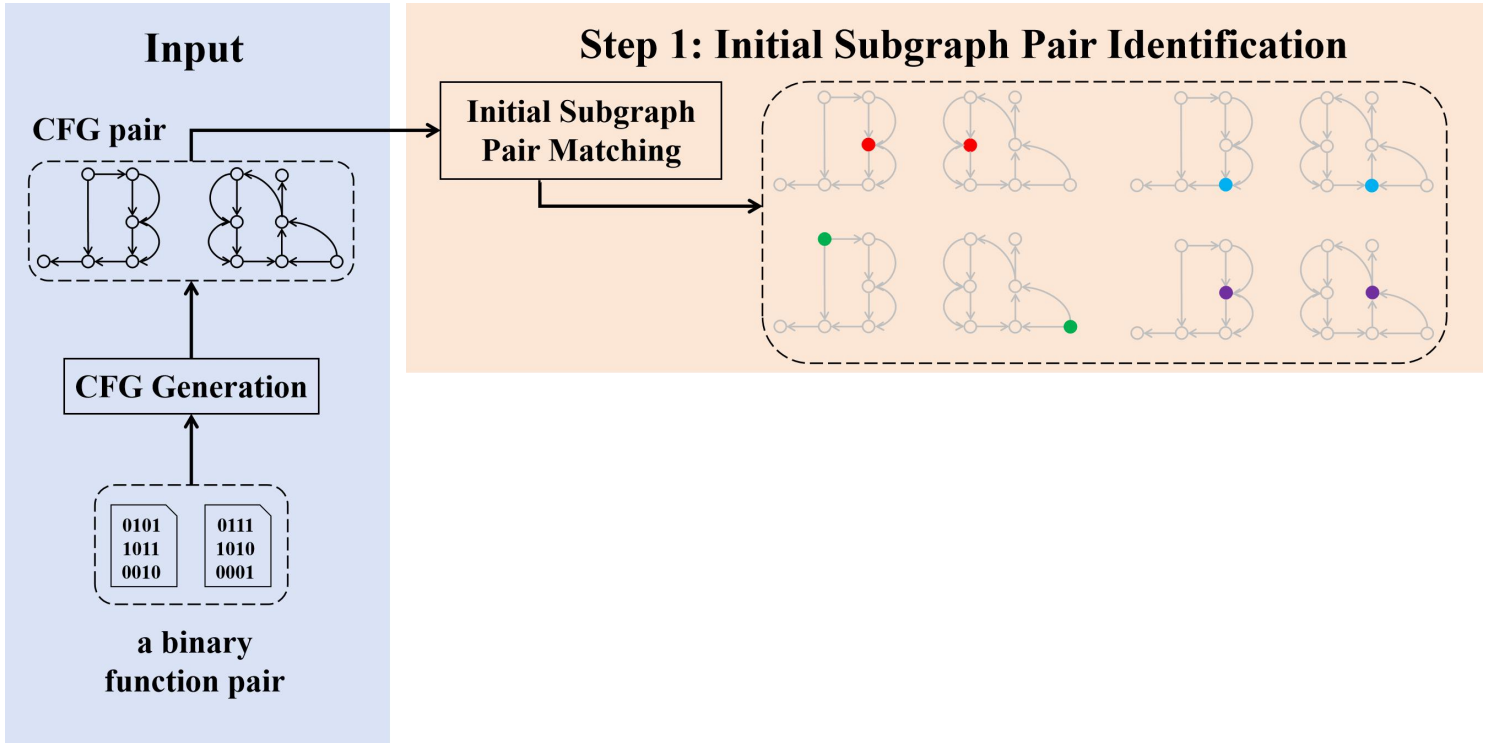

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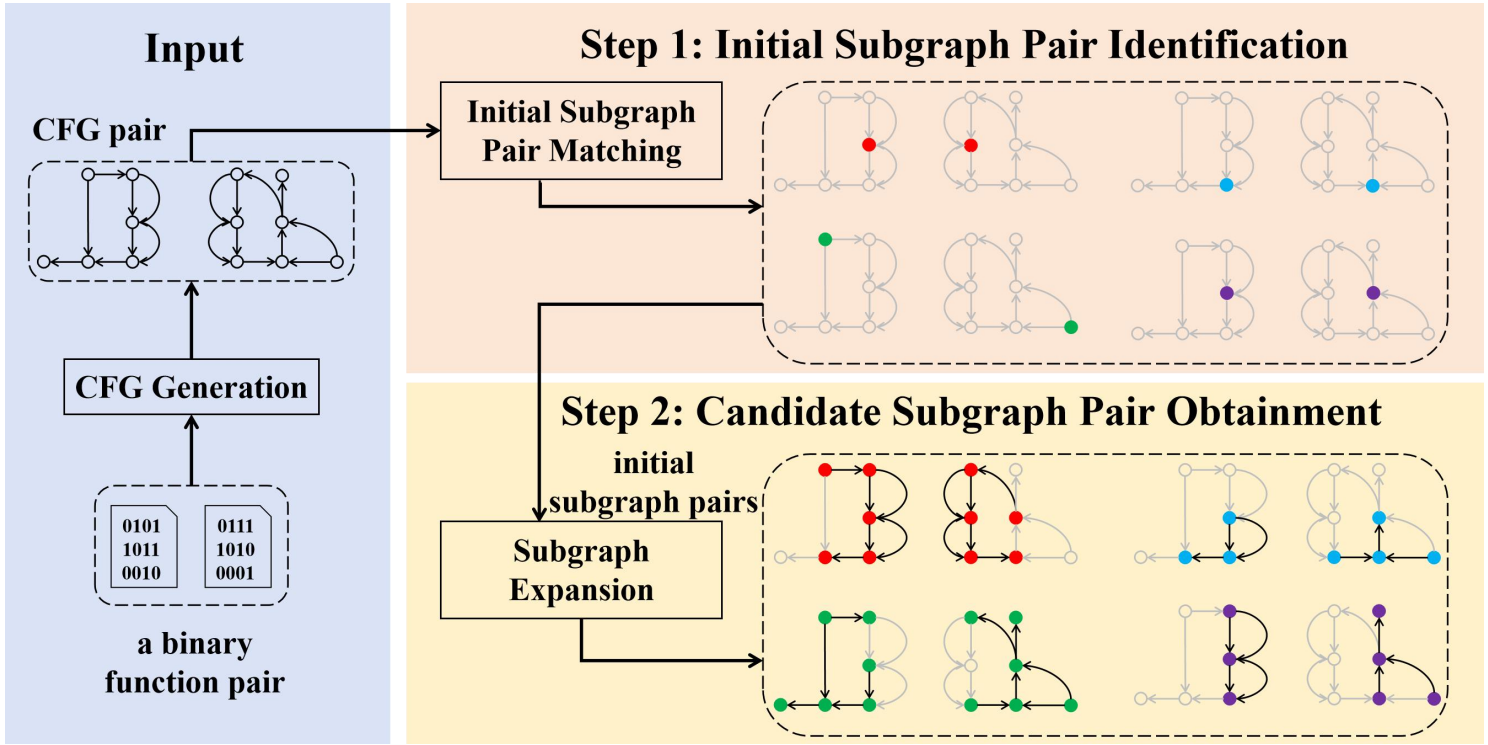

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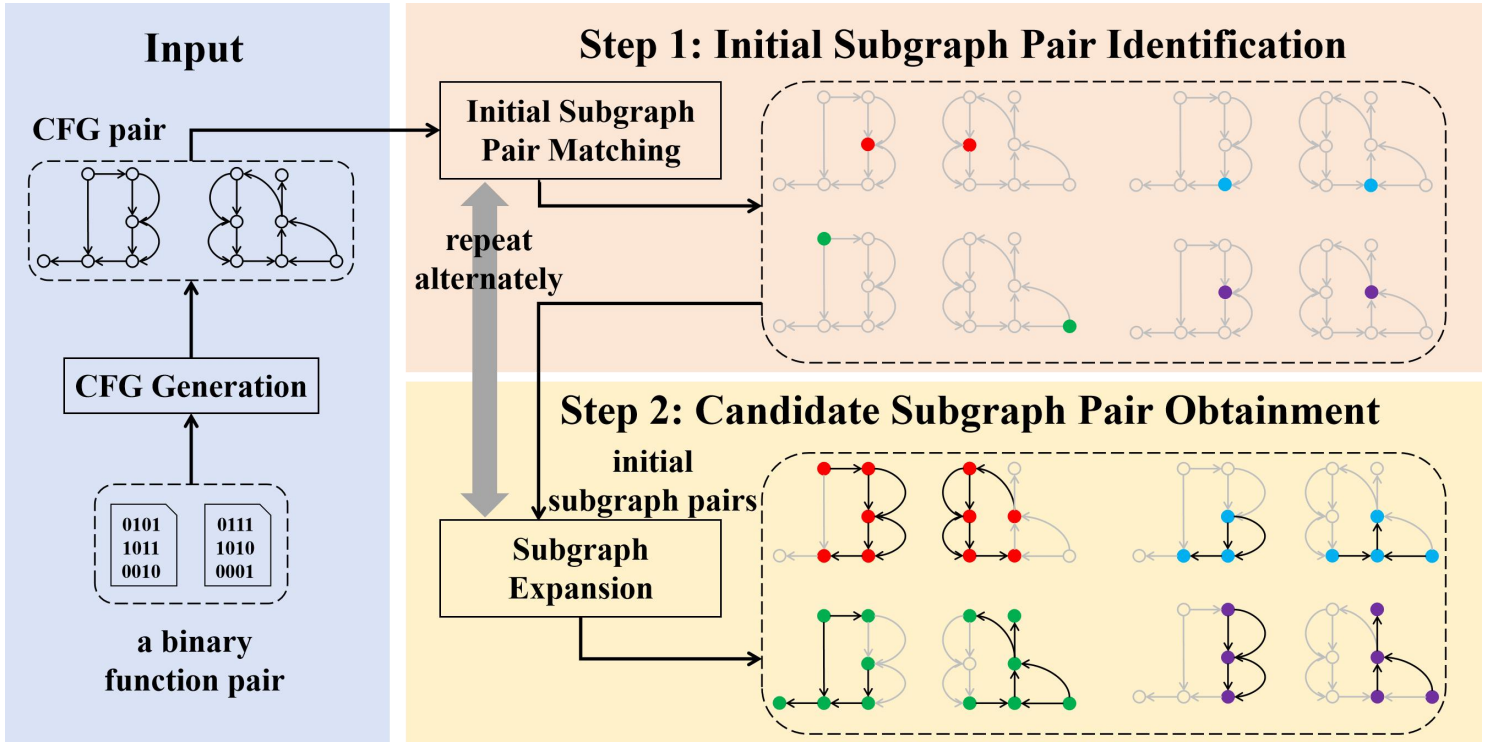

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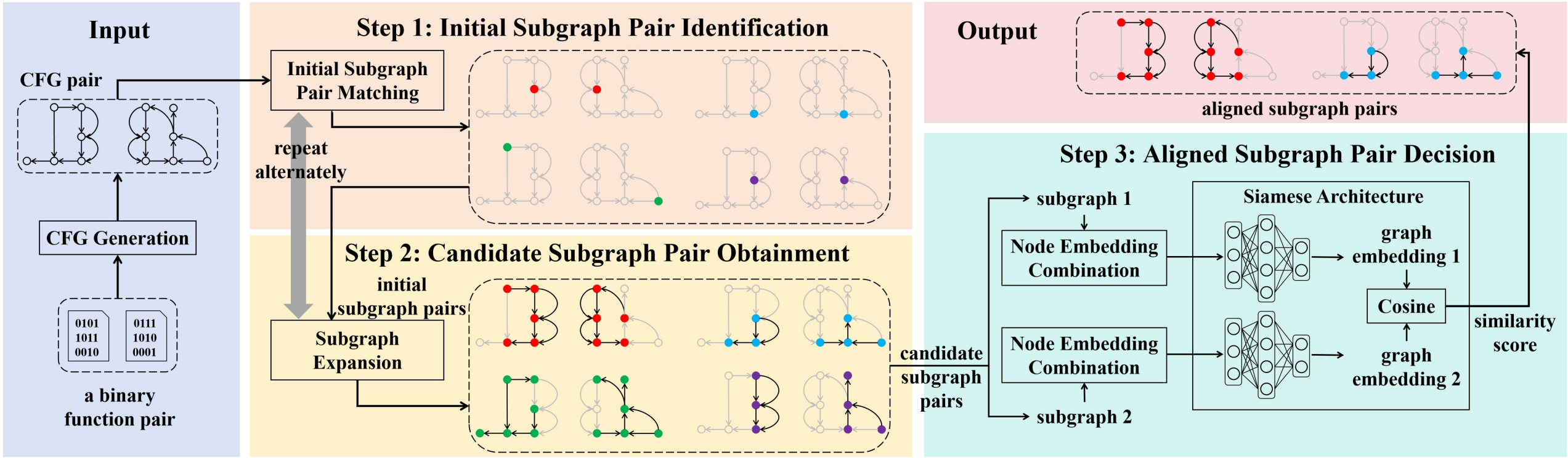

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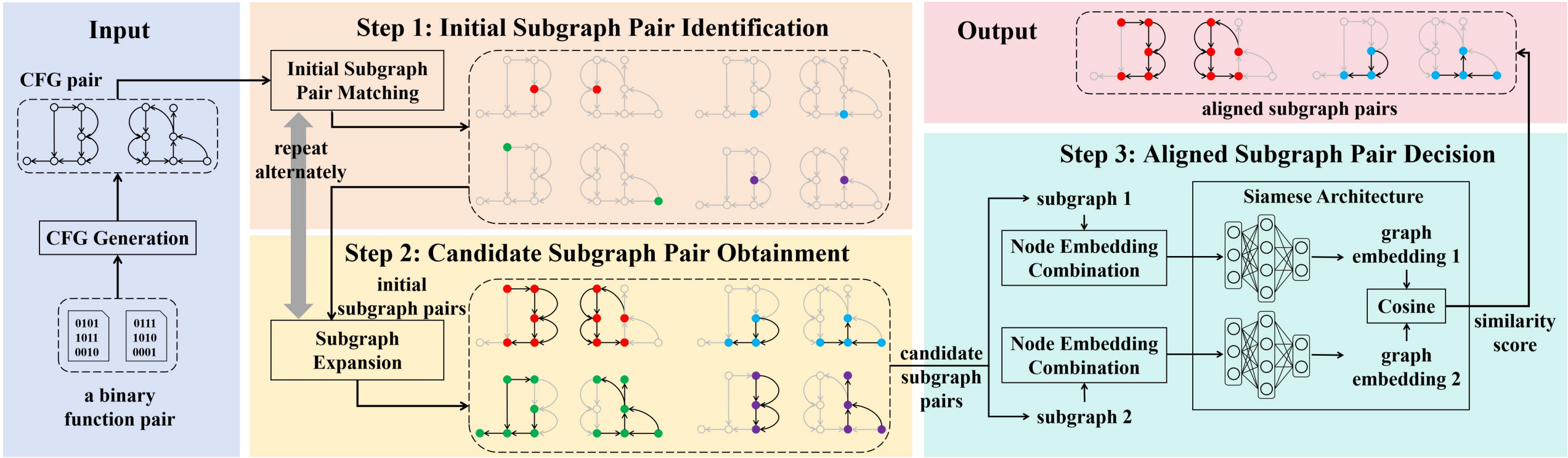


Two novelties:

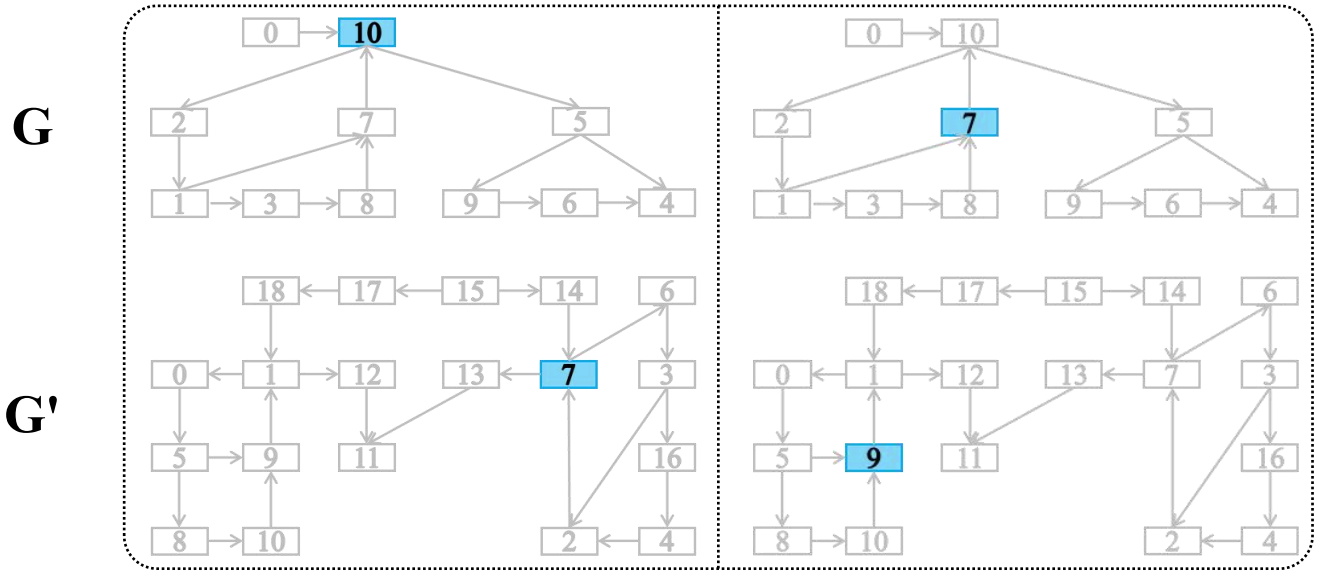
- graph-level matching instead of node-level matching
- architecture-independent node features that enable flexible cross-environment diffing

Approach – Candidate Subgraph Pair Obtainment

Step 2: Conditional Relaxation Strategies for Robust Subgraph Expansion

Chain Change <<< handle <<< $St.^{1st}$

Branch Change <<< mitigate <<< $St.^{2nd}$



Two candidate subgraph pairs expanded using two conditional relaxation strategies $St.^{1st}$ and $St.^{2nd}$

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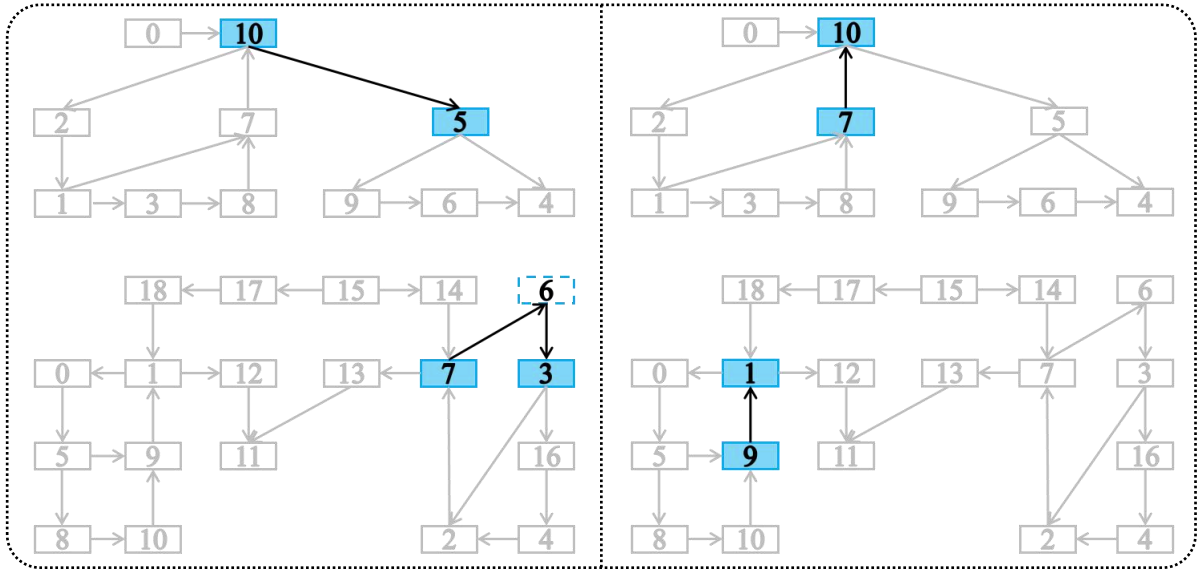
In(5) = **In**(3')=1
Out(5) = **Out**(3')=2



In(10) = **In**(1')=2
Out(10) = **Out**(1')=2

Two candidate subgraph pairs expanded using two conditional relaxation strategies $St.^{1st}$ and $St.^{2nd}$

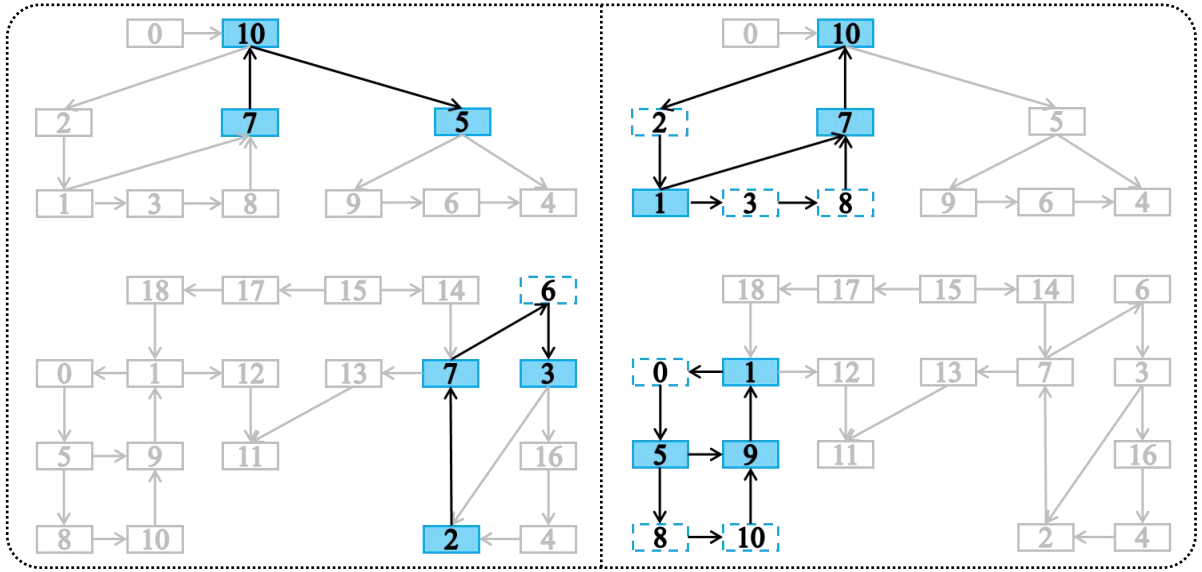
Approach – Candidate Subgraph Pair Obtainment

Step 2: Conditional Relaxation Strategies for Robust Subgraph Expansion

Chain Change << handle << *St.*^{1st}

Branch Change << mitigate << *St.*^{2nd}

In(7) = **In**(2')=2
Out(7) = **Out**(2')=1



In(1) = **In**(5')=1
Out(1) = **Out**(5')=2

Two candidate subgraph pairs expanded using two conditional relaxation strategies *St.*^{1st} and *St.*^{2nd}

Approach – Candidate Subgraph Pair Obtainment

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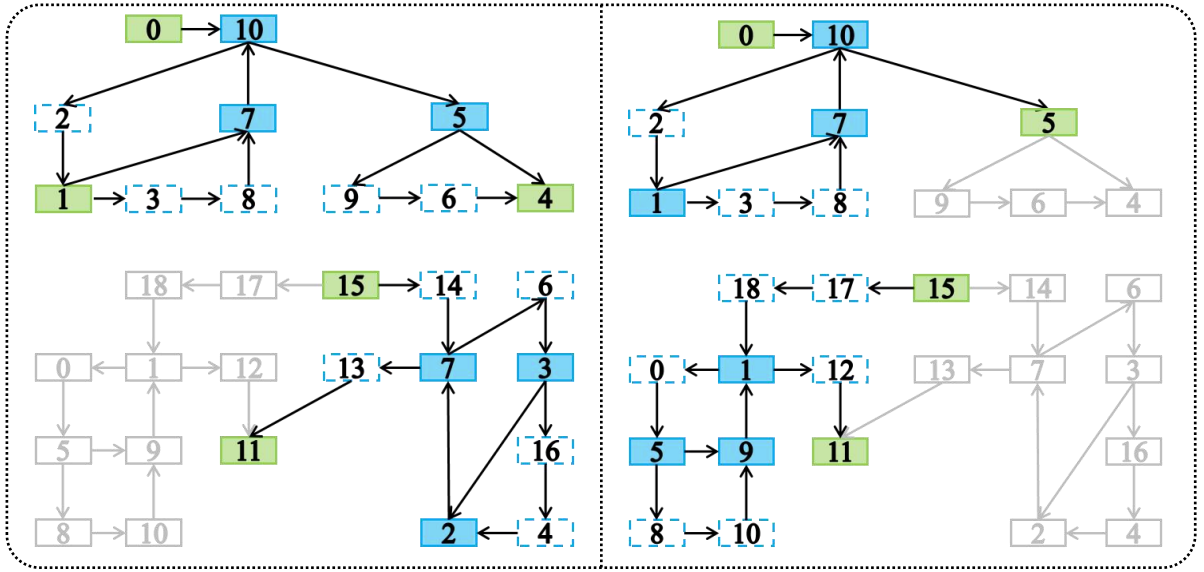


Two candidate subgraph pairs expanded using two conditional relaxation strategies $St.^{1st}$ and $St.^{2nd}$

Evaluation – Experimental Setup

Datasets

Binary Files:

- the GNU dataset: Coreutils, Diffutils, and Findutils
- the OpenSSL dataset: libssl.so, libcrypto.so

Compilation Environments:

- Compilers: GCC (5.4/8.2), Clang (3.8/6.0/7.0)
- Optimization level: O0-O3
- Architecture: x86, ARM, and MIPS(for training only)
- Code versions: Multiple versions spanning 7-10 years

Baselines

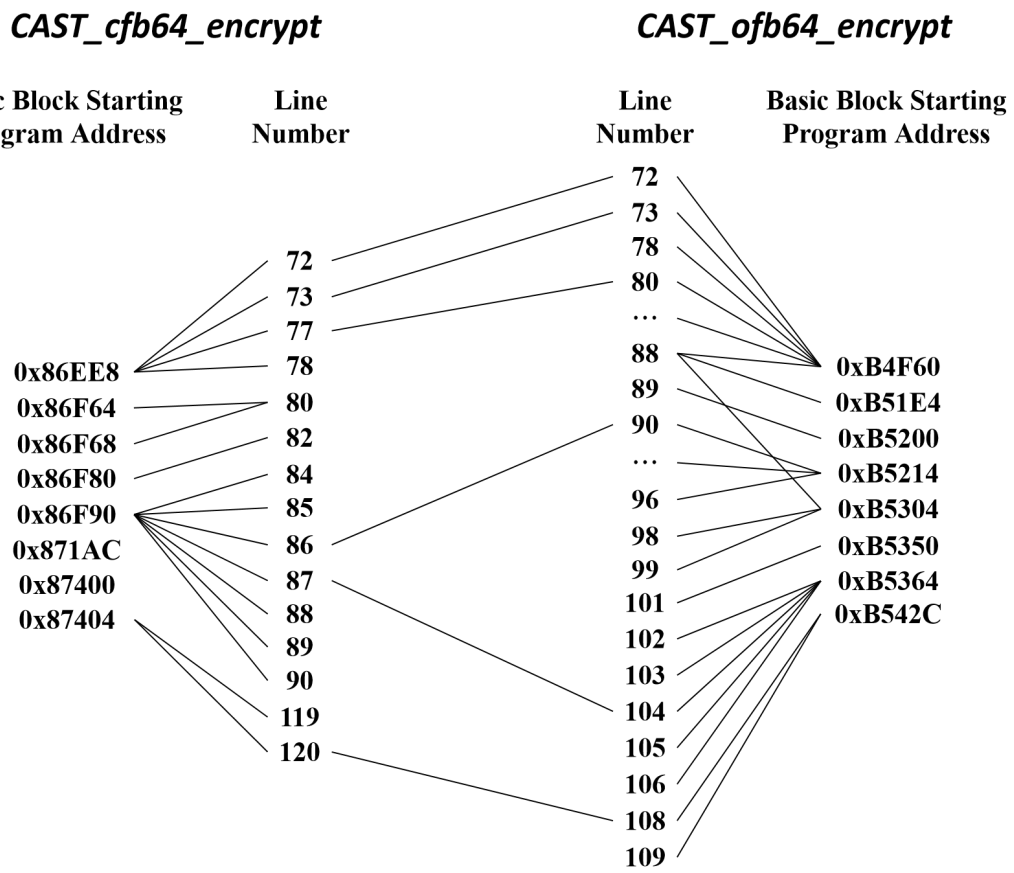
- InnerEye (IE)
- DeepBinDiff (DBD)
- DeepBinDiff-k-hop with InnerEye-embedding (DBD^{IE})
- SigmaDiff-DGMC with Gemini-embedding (SD^{G})

Evaluation – Experimental Setup

Ground Truth

The sets of nodes in subgraphs corresponding to the same source code snippets of two functions.

For example:
0x87404 ↔ 120 ↔ 108 ↔ 0xB542C



Evaluation – Four Cross-compilation Environment Scenarios

BINALIGNER performs optimally in most scenarios, especially in the cross-architecture scenario.

Cross-architecture Diffing

BINALIGNER **outperforms** the state-of-the-art methods. The highest R of baselines is 90.9% and the highest P is 73.7%, while all metrics of BINALIGNER are above 93%.

	Approach	Coreutils 8.30	Diffutils 3.6	Findutils 4.6
R	IE	0.081	0.09	0.074
	DBD^{IE}	0.098	0.121	0.1
	SD^{G}	0.34	0.366	0.371
	BA	**0.961**	**0.935**	**0.989**
	BA-0	0.941	0.897	0.953
	BA-1	0.936	0.92	0.971
	BA-GMN	0.929	0.932	0.967
P	IE	0.44	0.47	0.352
	DBD^{IE}	0.322	0.326	0.204
	SD^{G}	0.71	0.737	0.713
	BA	**0.991**	**0.977**	**1.0**
	BA-0	0.982	0.977	0.993
	BA-1	0.985	0.97	0.993
	BA-GMN	0.954	0.977	0.98
$F1$	IE	0.137	0.151	0.122
	DBD^{IE}	0.15	0.176	0.134
	SD^{G}	0.46	0.489	0.488
	BA	**0.976**	**0.956**	**0.994**
	BA-0	0.961	0.935	0.973
	BA-1	0.96	0.944	0.982
	BA-GMN	0.941	0.954	0.973

Evaluation – Complex Scenarios

BINALIGNER excels in complex scenarios (compilation environment evolution, across different similarity degrees).

Compilation Environment Evolution

	IE	DBD^{IE}	SD^{G}	BA
R	0.181	0.005	0.128	**0.688**
P	0.742	0.017	0.526	**0.921**
$F1$	0.291	0.008	0.206	**0.788**

Model train: Coreutils 8.30 (GCC-5.4, O0)
Model test: Coreutils 9.1 (GCC-8.2, O3)

BINALIGNER maintains a massive lead, with F1 49.7% to 78% higher than baselines. This demonstrates the **strongest resilience to environment changes**.

Evaluation – Case Study

BINALIGNER pinpoints real-world vulnerabilities and patches.

Practical Application

Approach	Vulnerability			Patch		
	X(A)	X(A+O)	X(A+O+C)	X(A)	X(A+O)	X(A+O+C)
IE	0.0	0.0	0.0	0.0	0.0	0.0
DBD^{IE}	**1.0**	**1.0**	0.5	0.5	0.667	0.375
SD^{G}	**1.0**	0.0	0.0	0.75	0.0	0.417
BA	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

X(A): (x86-64, O0, GCC-8.2.0) vs (ARM-64, O0, GCC-8.2.0)
X(A+O): (x86-64, O0, GCC-8.2.0) vs (ARM-64, O3, GCC-8.2.0)
X(A+O+C): (x86-64, O0, GCC-8.2.0) vs (ARM-64, O3, Clang-6.0)

BINALIGNER **achieves the highest recall** in pinpointing the vulnerable and patched code.

Evaluation – Case Study

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Robustness Verification

Library	Ver.	CVE	Vul./Pat.	Function	IE	DBD^{IE}	SD^{G}	BA
Binutils	2.4	CVE-2025-5245	Vul.	debug_type_samep				✓
		CVE-2025-5244	Vul.	bfd_elf_gc_sections	✓		✓	✓
		CVE-2025-1176	Vul.	_bfd_elf_gc_mark_rsec	✓		✓	✓
Tar	1.34	CVE-2023-39804	Vul.	xheader_decode	✓		✓	✓
		CVE-2023-39804	Vul.	xattr_decoder	✓		✓	✓
Libmicrohttpd	0.9.75	CVE-2023-27371	Vul.	MHD_create_post_processor	✓			✓
Inetutils	2.4	CVE-2022-39028	Pat.	telrcv	✓			✓
		CVE-2021-40491	Pat.	initconn			✓	✓
Recutils	1.9	CVE-2021-46022, CVE-2021-46019	Pat.	rec_parse_comment	✓			✓

Model train: Coreutils, Diffutils, Findutils (GCC-5.4, O0)
Model test: Binutils, Tar, Libmicrohttpd, Inetutils, Recutils (Clang-13, O3)

BINALIGNER successfully **identified all nine** vulnerabilities and patches.

Conclusion – Limitations and Future Work

BINALIGNER enables accurate and flexible cross-environment binary diffing.

Key Novelties

- graph-level matching with conditional relaxation strategies
- architecture-agnostic graph embeddings based on node statistical features

Main Results

- BINALIGNER significantly outperforms the state-of-the-art methods in most scenarios. Especially in the cross-architecture scenario and multiple combinations of cross-compilation environment scenarios.
- Two case studies using real-world vulnerabilities and patches further demonstrate the utility of BINALIGNER.

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Semantic Features

richer semantic analysis
via IR lifting and NLP

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stronger robustness to
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Disassembler Dependency

support for more disassemblers

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Indirect Jumps
better handling of indirect jumps