Silence False Alarms: Identifying Anti-Reentrancy Patterns on Ethereum to Refine Smart Contract Reentrancy Detection

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NDSS
SYMPOSIUM/2025

Infamous Smart Contract Bug: Reentrancy

- Reentrancy bugs have caused massive financial losses on the blockchain

  - Since DAO hack (2016)

    $50+ million stolen

    How The DAO Hack Back in 2016 Changed Ethereum and Crypto Forever

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    Millions of assets stolen

    How Spankchain Got Hacked

    Explained: A Reentrancy attack which drained 165 Ether

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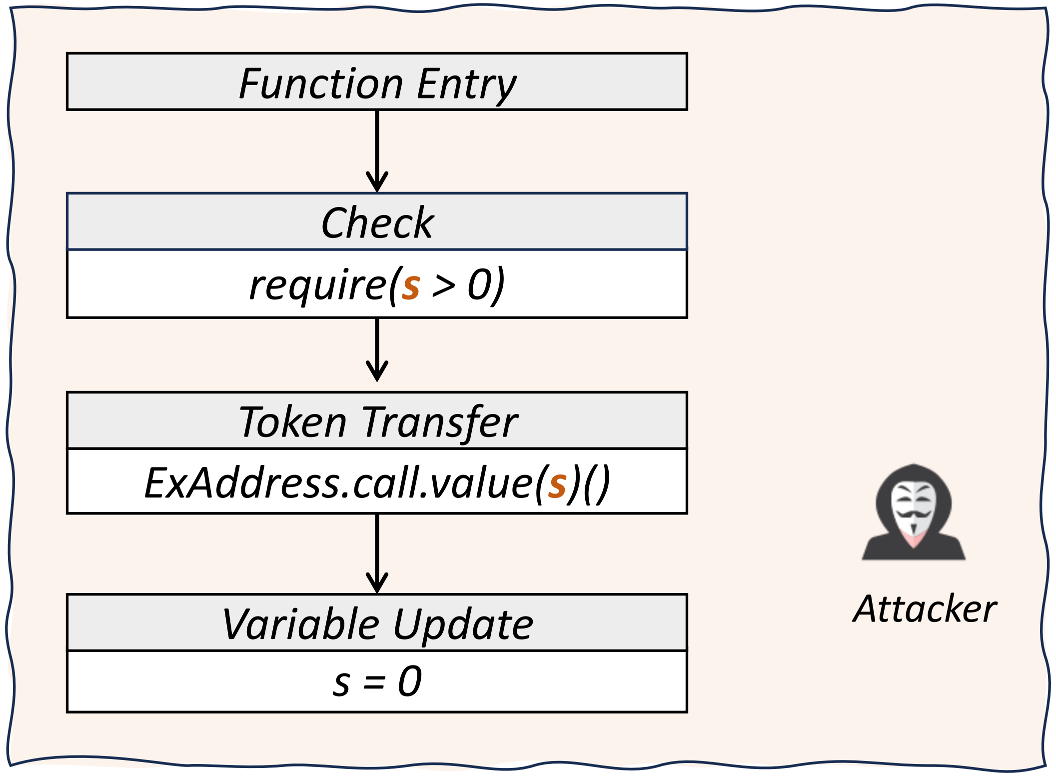

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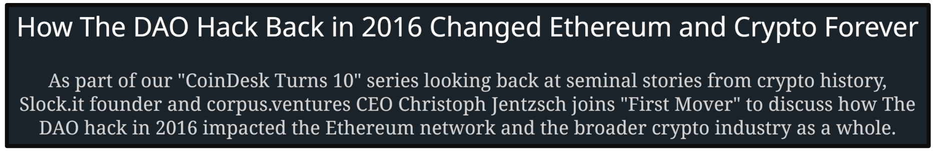

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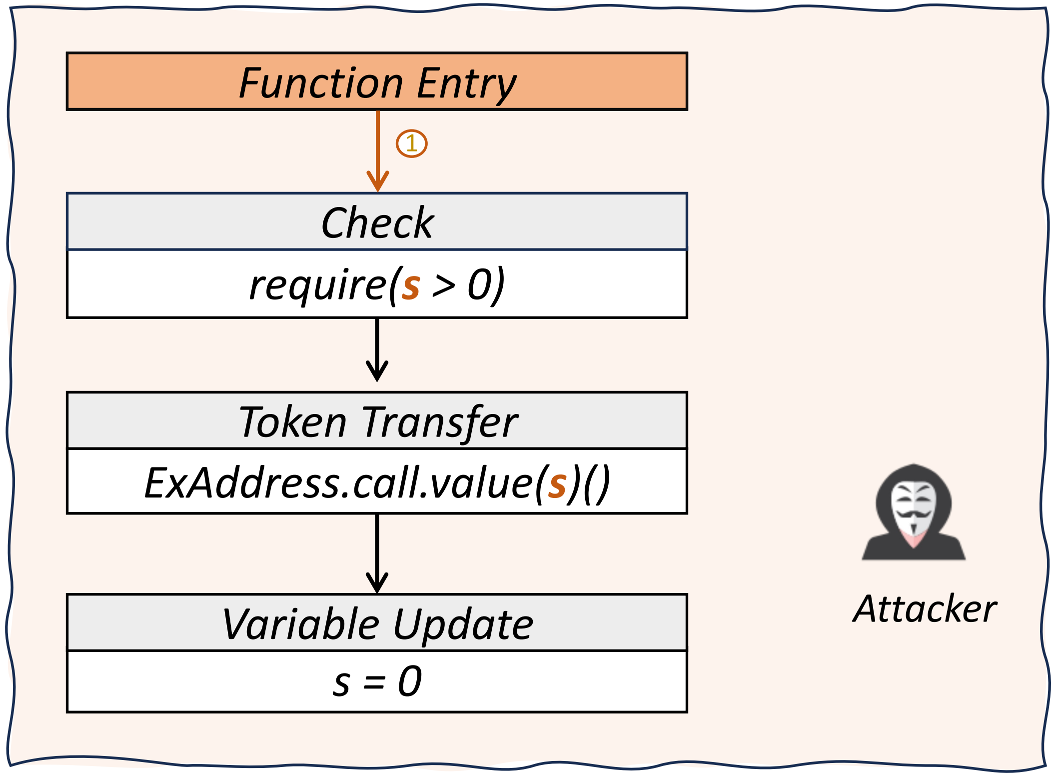

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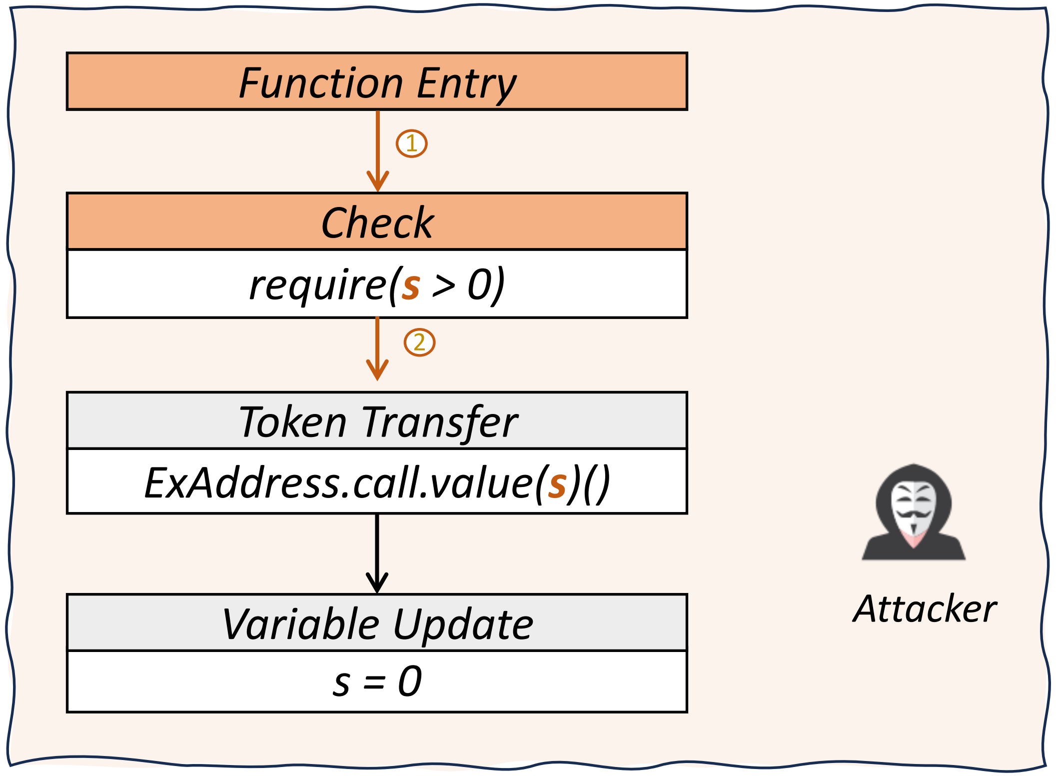

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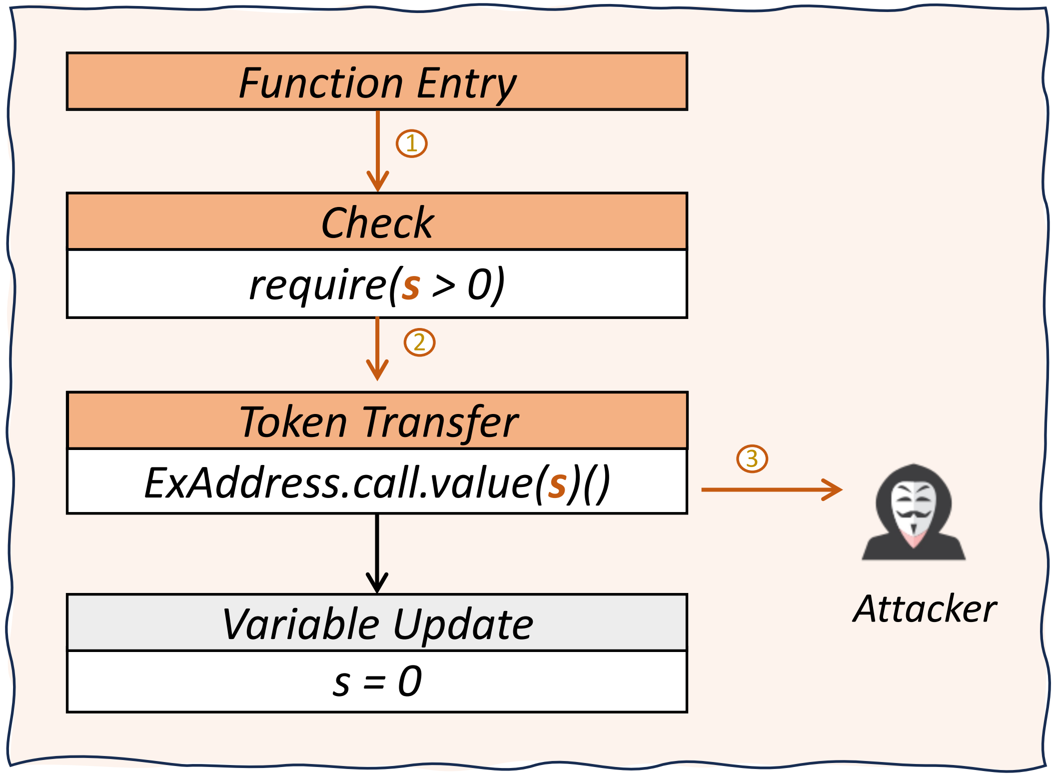

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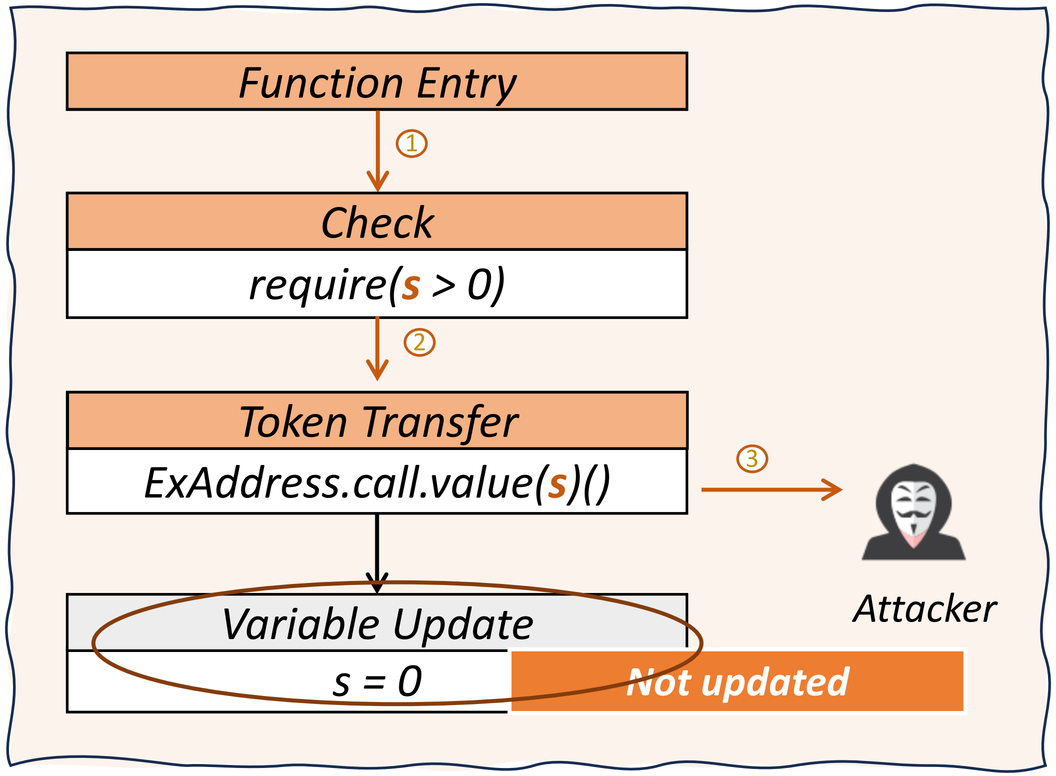

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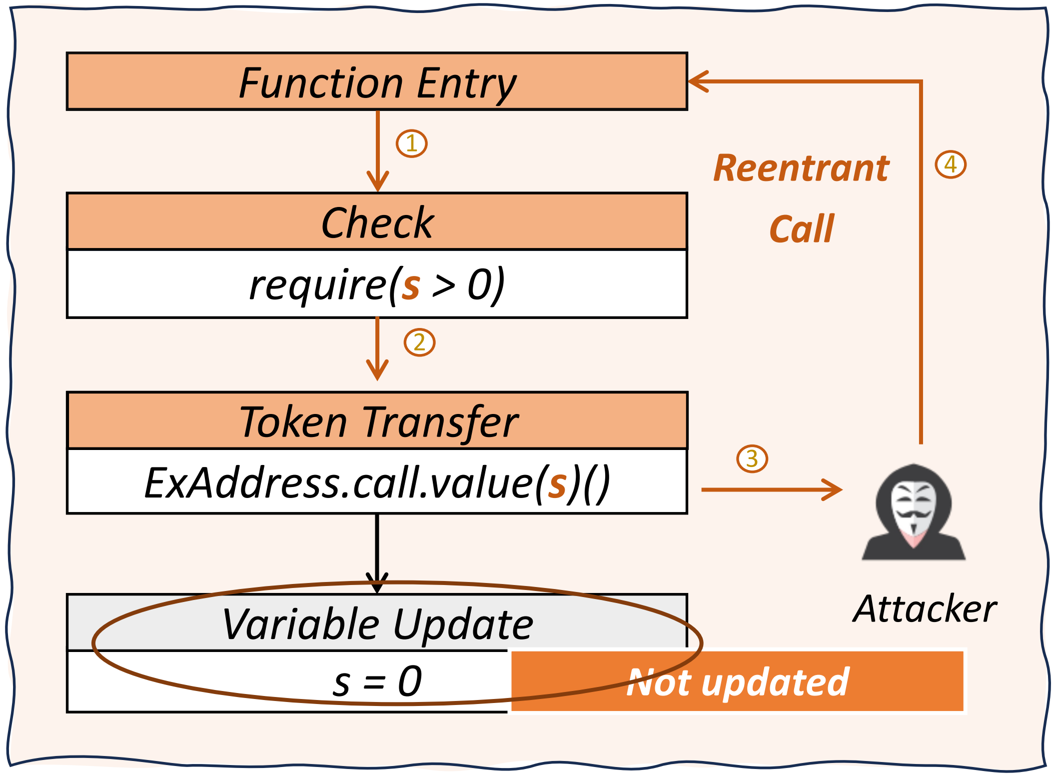

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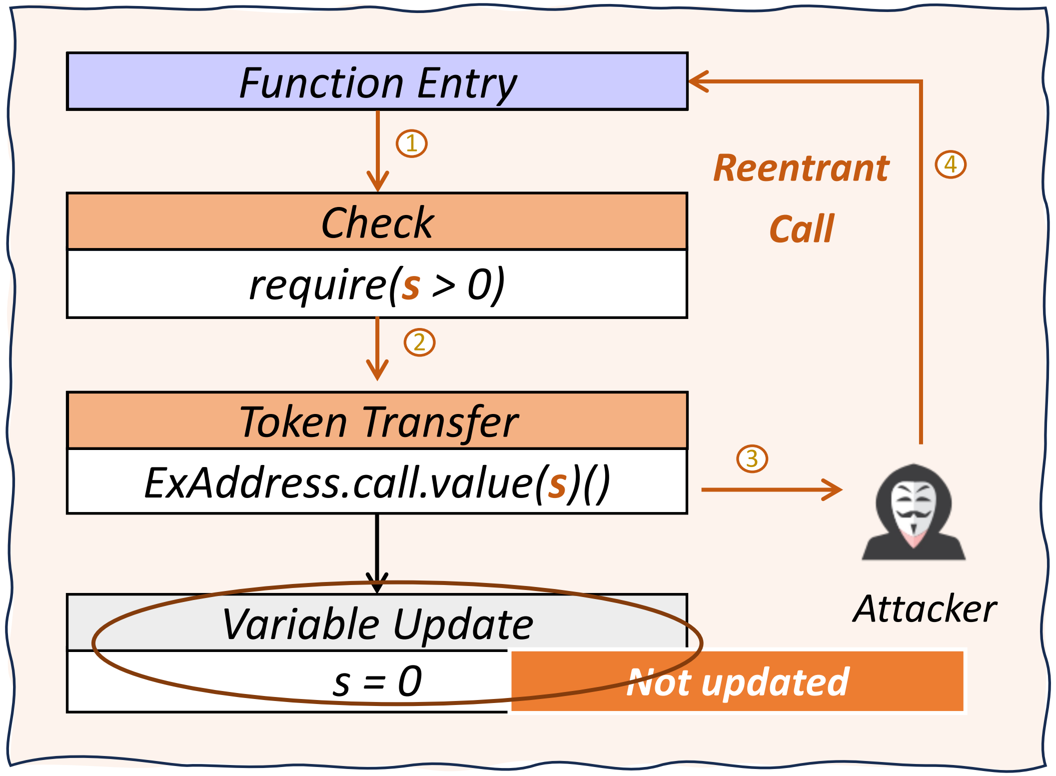

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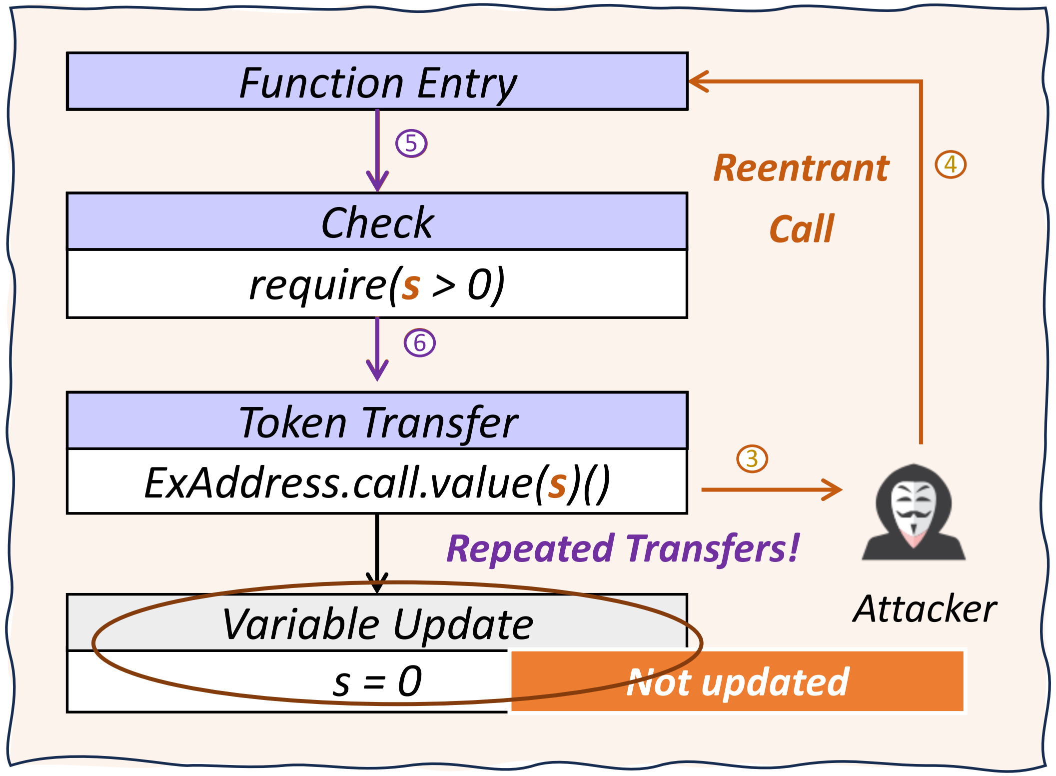

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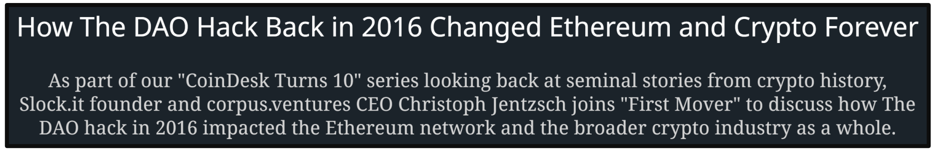

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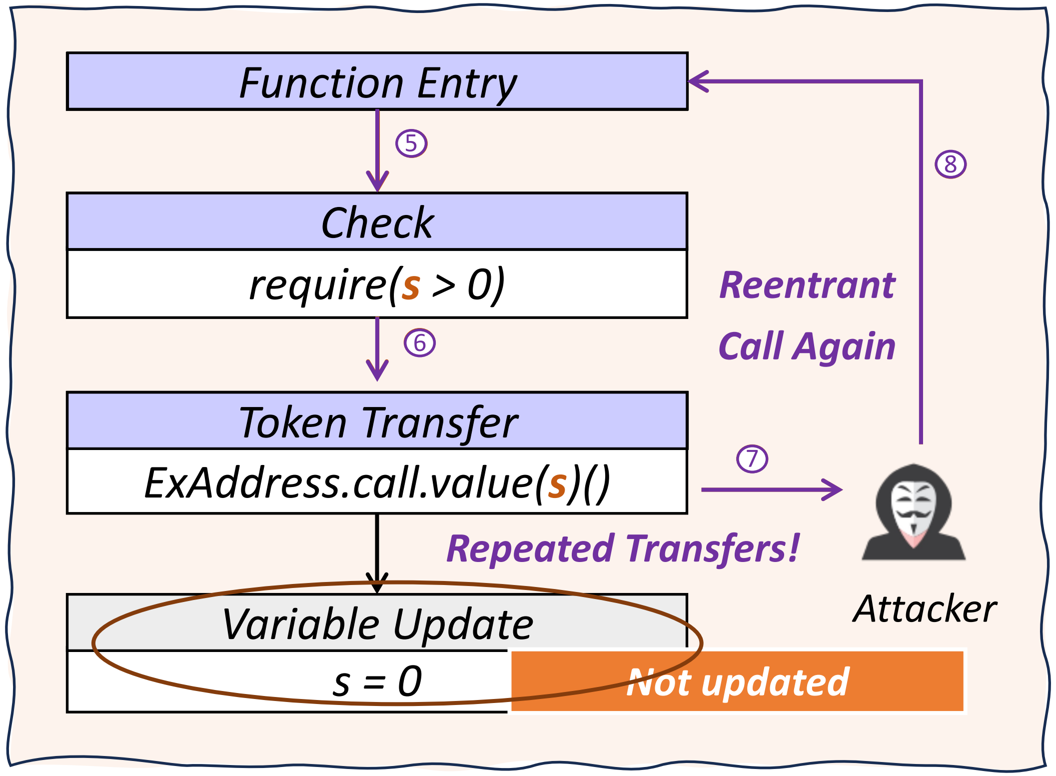
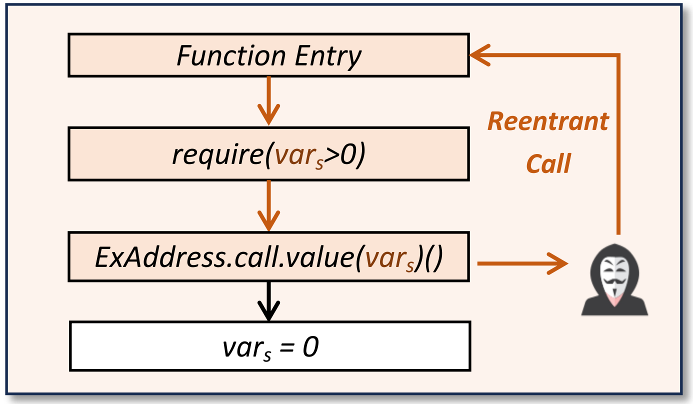


Reentrancy Attack Example

Reentrancy Vulnerability Detection



- Existing Reentrancy Detectors
  - According to Basic Reentrancy Patterns

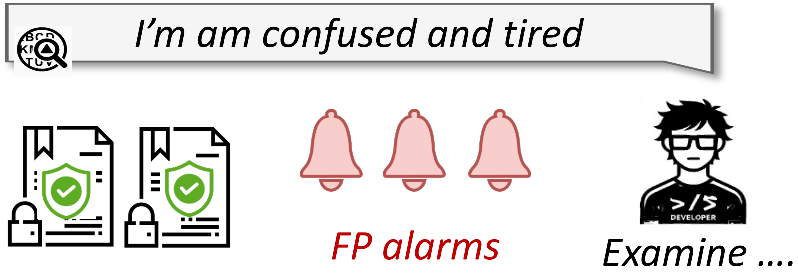
Read Variable X --> External Call --> Write Variable X

  - Based on static analysis/symbolic execution

SLITHER | Mythril | SECURIFY 2.0 new!

2022 IEEE Symposium on Security and Privacy (SP)
SAILFISH: Vetting Smart Contract State-Inconsistency Bugs in Seconds

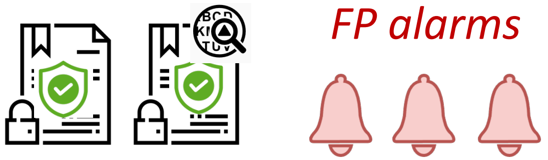
  - **A high rate of false positives (FPs)**
    - Leads to alert fatigue



*Durieux, T et al. Empirical review of automated analysis tools on 47,587 ethereum smart contracts. ICSE'20

False Alarms Caused by Anti-reentrancy Patterns

- Exiting tools ignore **anti-reentrancy patterns**[*]
  - **FPs:** misclassify safe contracts as vulnerable

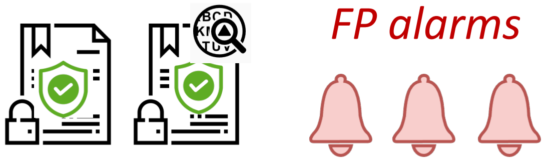


Ignore anti-reentrancy patterns

[*] Xue, Y. et al. Cross-contract static analysis for detecting practical reentrancy vulnerabilities in smart contracts. ASE 2020.

False Alarms Caused by Anti-reentrancy Patterns

- Exiting tools ignore **anti-reentrancy patterns***
  - **FPs:** misclassify safe contracts as vulnerable
  - Anti-reentrancy patterns prevent illegal users from reentering functions to gain profits



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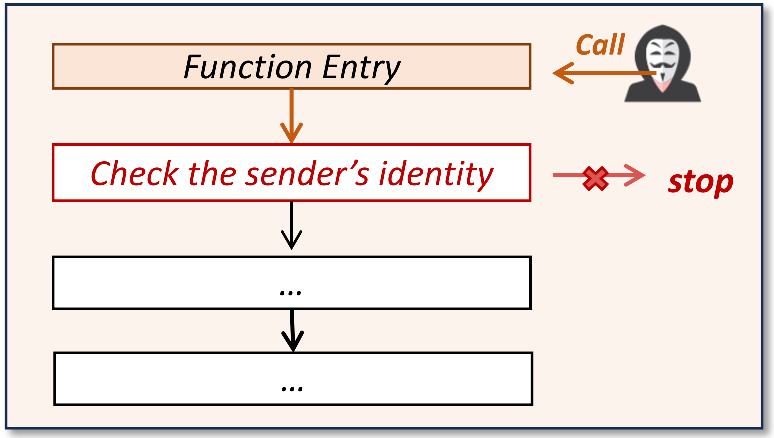
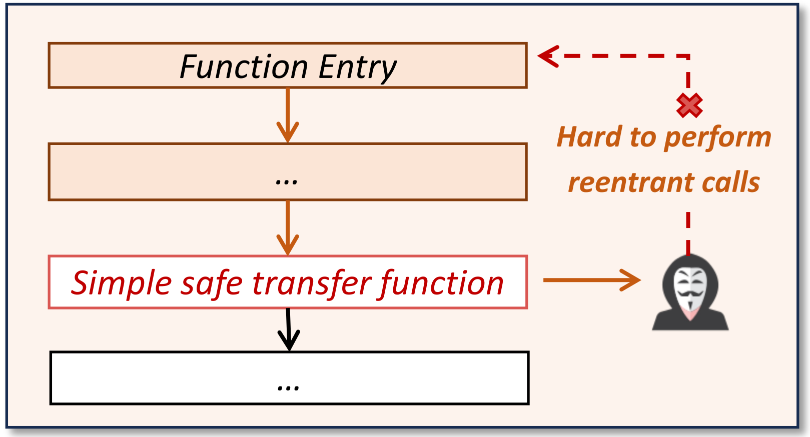


Example 1: sender check



Example 2: Safe transfer

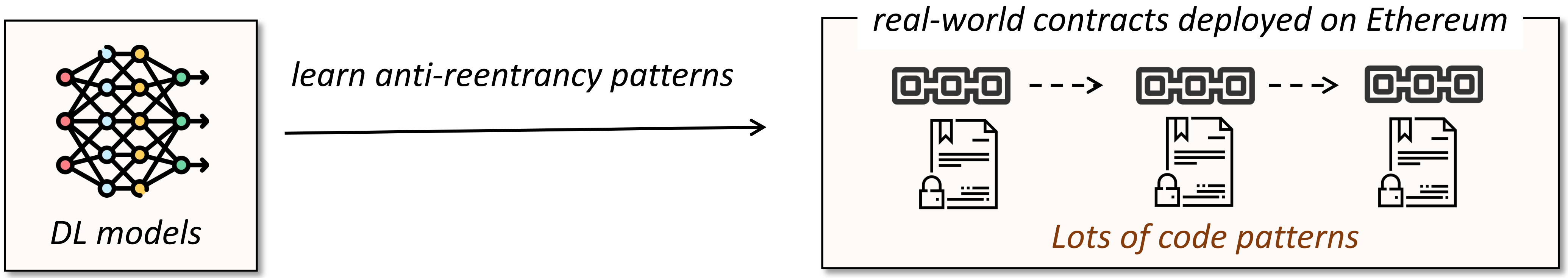
* Xue, Y. et al. Cross-contract static analysis for detecting practical reentrancy vulnerabilities in smart contracts. ASE 2020.

To reduce false positives, we

develop an automated tool to
identify anti-reentrancy patterns

Our Solution

- Use deep learning to learn anti-reentrancy patterns from various contracts



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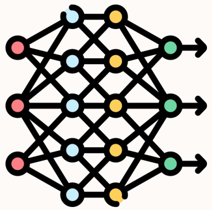

DL models

learn anti-reentrancy patterns

real-world contracts deployed on Ethereum

How to precisely learn anti-reentrancy patterns from mixed code patterns?

Our Solution

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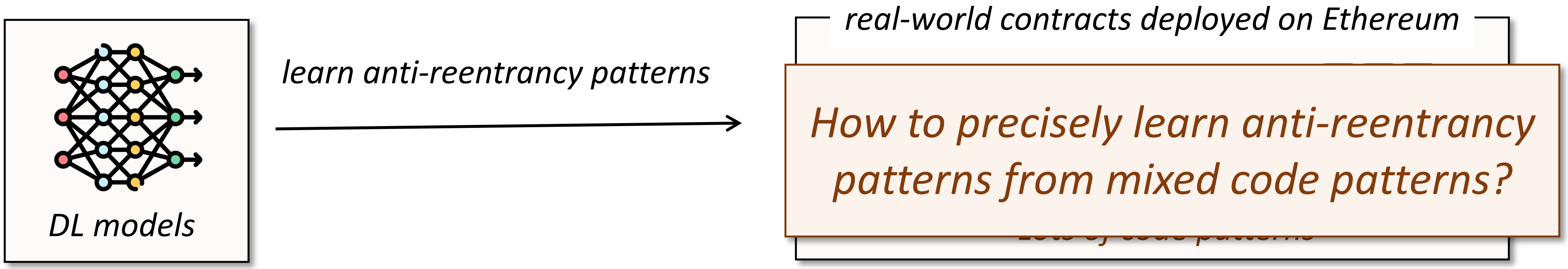


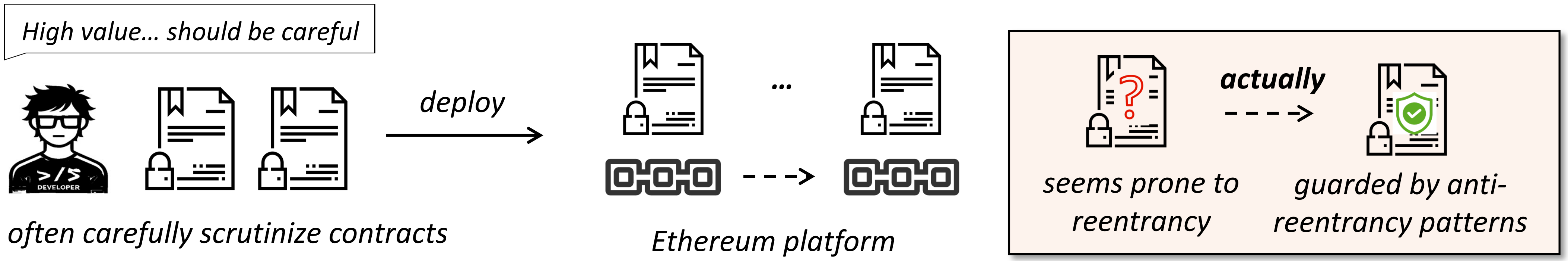
- Design specific methods and data structures to capture related semantics

Step #1:

We begin by filtering contracts **potentially with anti-reentrancy patterns**

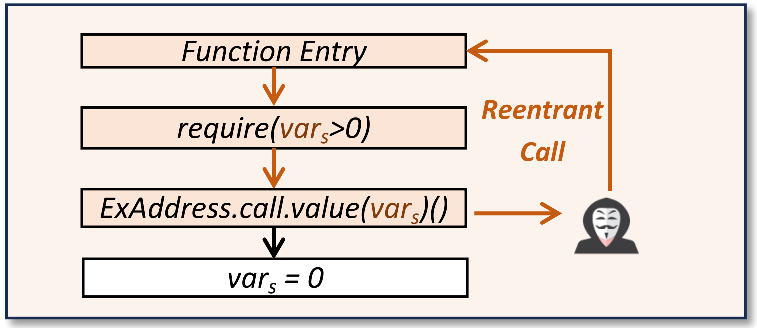
Smart Contract Filtering

- Insight: Ethereum contracts prone to reentrancy often **contain anti-reentrancy patterns***



- Utilize reentrancy knowledge to identify related smart contracts
  - Static analysis

Read Variable X --> External Call --> Write Variable X



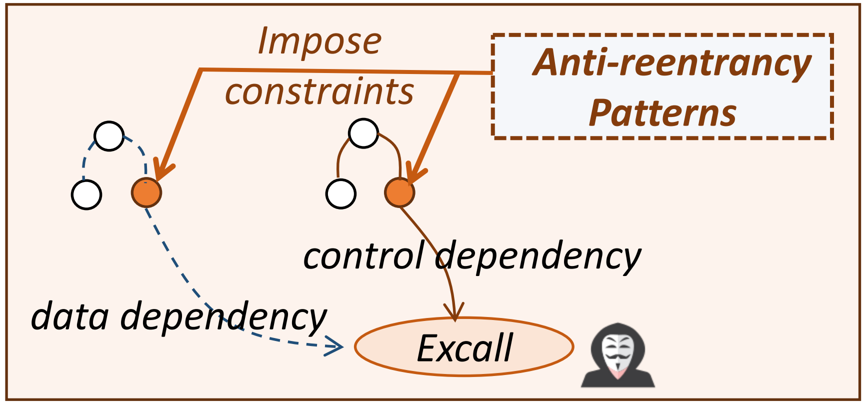
* *According to our investigation and related paper* "Xue, Y. et al. Cross-contract static analysis for detecting practical reentrancy vulnerabilities in smart contracts. ASE 2020."

Step #2:

Design a data structure to further capture anti-reentrancy semantics from selected contracts

Program Dependency Graph for Anti-reentrancy (RentPDG)

- Observation: anti-reentrancy patterns often impose **data and control dependency constraints** on external calls



General anti-reentrancy semantics

Program Dependency Graph for Anti-reentrancy (RentPDG)

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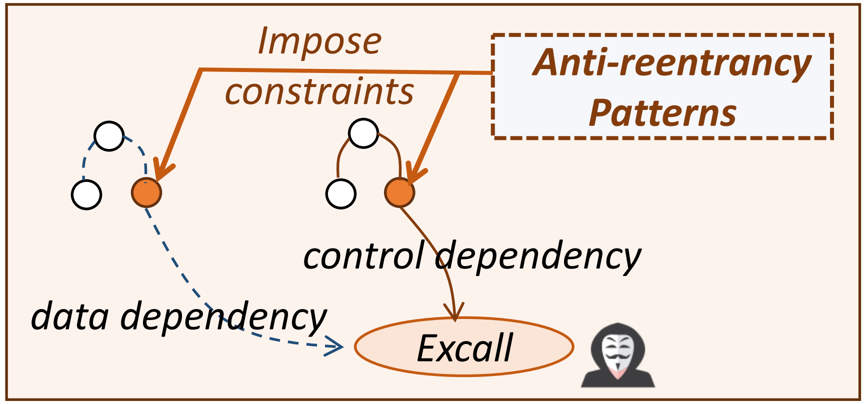
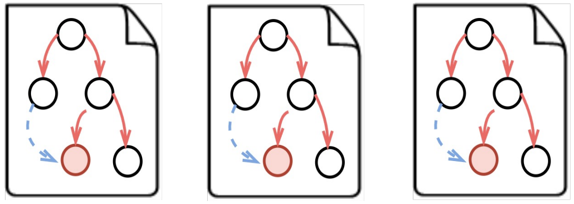
- To capture the semantics, we use program dependency graphs



General anti-reentrancy semantics

To capture the semantics

Program dependency graphs (PDG)



Reveal Control and Data dependency

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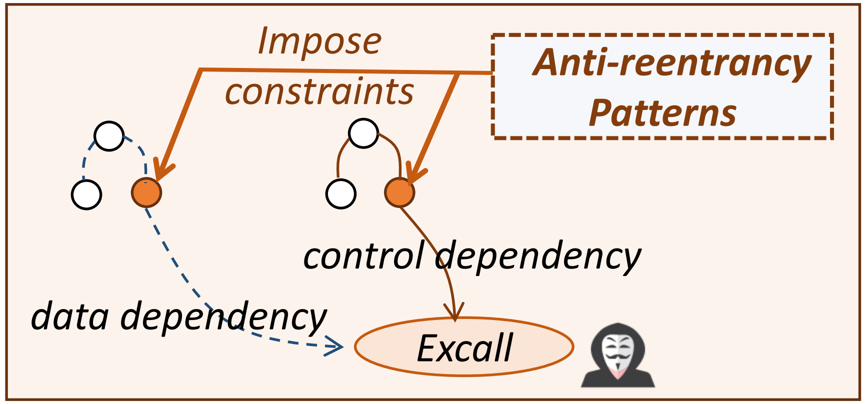

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Program Dependency Graph for Anti-reentrancy (RentPDG)

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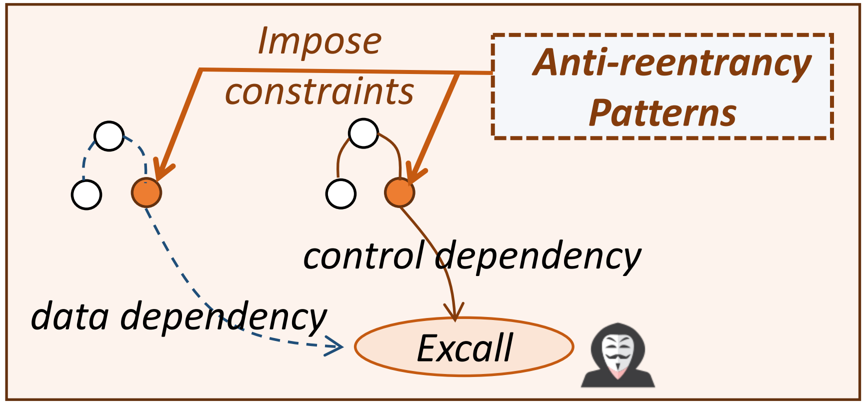
A variant of program dependency graphs (RentPDG)



General anti-reentrancy semantics

To capture the semantics

Variant of Program Dependency Graph

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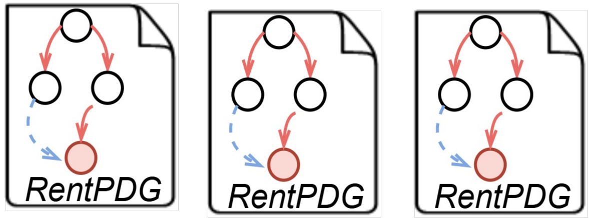


Only preserve components

related to external calls

Constructing RentPDGs from Smart Contracts

- Intuitive RentPDG construction

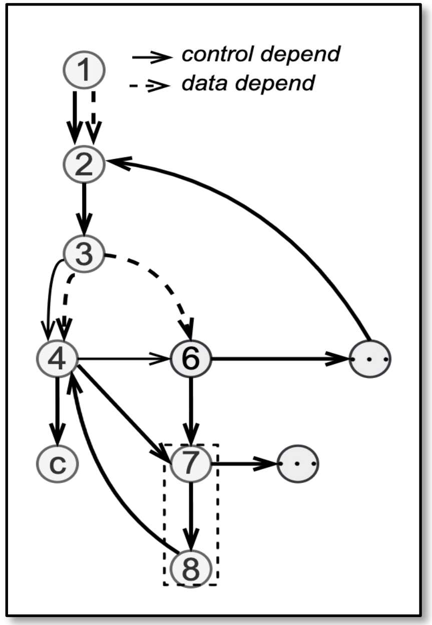
Smart Contract Code

```
1:  function transfer(address to,address[] tokenId){
2:        _transfer(msg.sender,to,tokenId));
}

3:  function _transfer(address from,address to,address[] tokenId){
4:        require(_approve(from,to,tokenId[0]));
c:        marketingAddr.call.value(fee)();     // external call
6:        require(_approve(from, to, tokenId[1])); ...;
      }


7:  function _approve(from, to, tokenId) returns (bool){ ...;
8:        return true;
      }
```

Inter-procedural PDG



Constructing RentPDGs from Smart Contracts

- Intuitive RentPDG construction
  - use deep-first search (DFS) to extract external-call related PDG components

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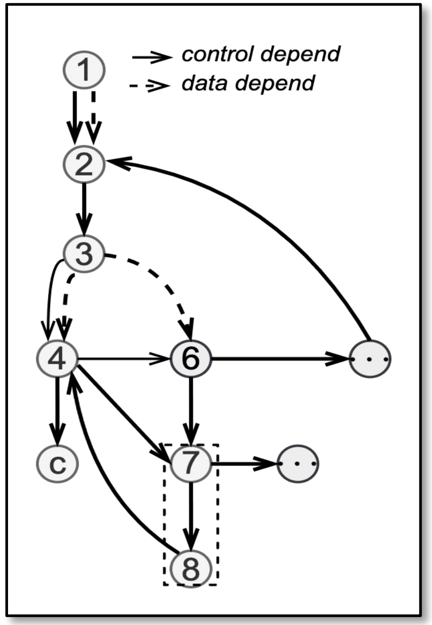
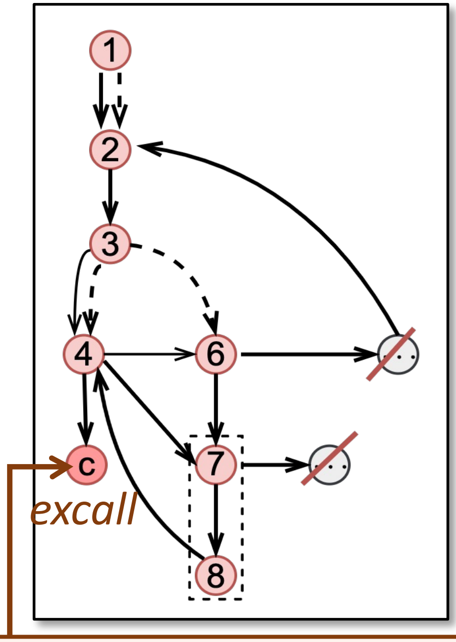


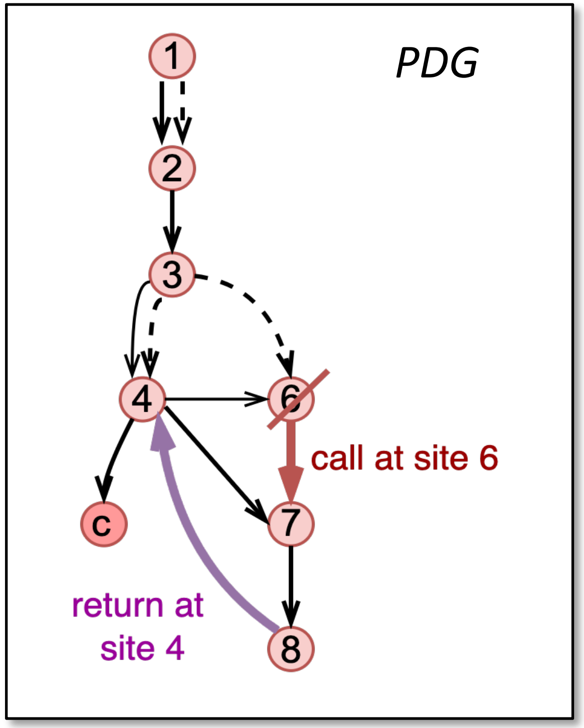
RentPDG



Use DFS to extract call-related components

Constructing RentPDGs from Smart Contracts

- **Issues of DFS**: not consider **inter-procedural call contexts**
  - may falsely include nodes in **infeasible paths,** which are actually not connected to external calls

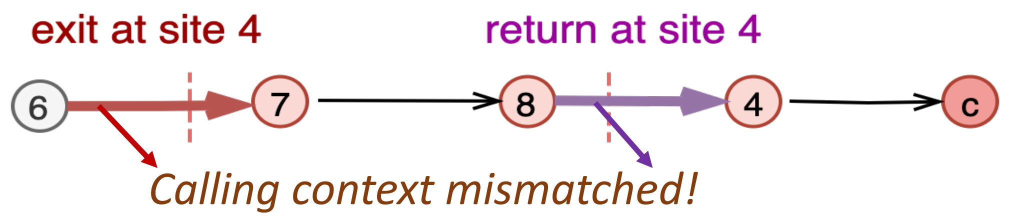


(Example) DFS-based RentPDG Construction

Nodes: {c, 4, 3, 2, 1, 7, 8, ~~6~~} *No feasible paths from 6 to external calls*

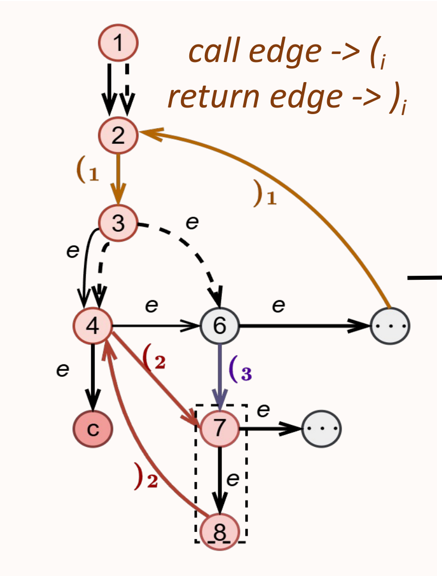
Edges: $\{e_{1\text{->}2},\ e_{2\text{->}3}, \cdots, \cdots\}$

Infeasible Path: 6 to c



Constructing RentPDGs from Smart Contracts

- Context-sensitive reachability analysis
  - Symbolize edges via a **context-free language** (CFL) => analyze path feasibility
  - Combine CFL with adjacency-matrix-based reachability analysis



Edge Symbolization

$$
\begin{array}{c|ccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & c \\
\hline
1 & \emptyset & (_1 & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset \\
2 & \emptyset & \emptyset & e & e & \emptyset & \emptyset & \emptyset \\
3 & \emptyset & \emptyset & \emptyset & e & (_2 & \emptyset & e \\
4 & \emptyset & \emptyset & \emptyset & \emptyset & (_3 & \emptyset & \emptyset \\
5 & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & e & \emptyset \\
6 & \emptyset & \emptyset &)_2 &)_3 & \emptyset & \emptyset & \emptyset \\
c & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset & \emptyset
\end{array}
\longrightarrow
\underbrace{\begin{pmatrix} \emptyset \\ \emptyset \\ e \\ \emptyset \\ \emptyset \\ \emptyset \\ \emptyset \end{pmatrix}}_{\boldsymbol{\mu}_1^c}
+
\underbrace{\begin{pmatrix} \emptyset \\ ee \\ \emptyset \\ \emptyset \\ \emptyset \\ )_2e \\ \emptyset \end{pmatrix}}_{\boldsymbol{\mu}_2^c = \mathbf{A} \cdot \boldsymbol{\mu}_1^c}
+ \cdots =
\underbrace{\begin{pmatrix} \{(_1ee, \cdots\} \\ \{ee, \cdots\} \\ \{e, (_2e)_2e, \cdots\} \\ \cancel{(_3e)_2e} \\ \{e)_2e\} \\ \{)_2e, \cdots\} \\ \emptyset \end{pmatrix}}_{\boldsymbol{\mu}^c}
$$

Infeasible

Symbolic Adjacency Matrix **A**

1-order reachability

2-order reachability

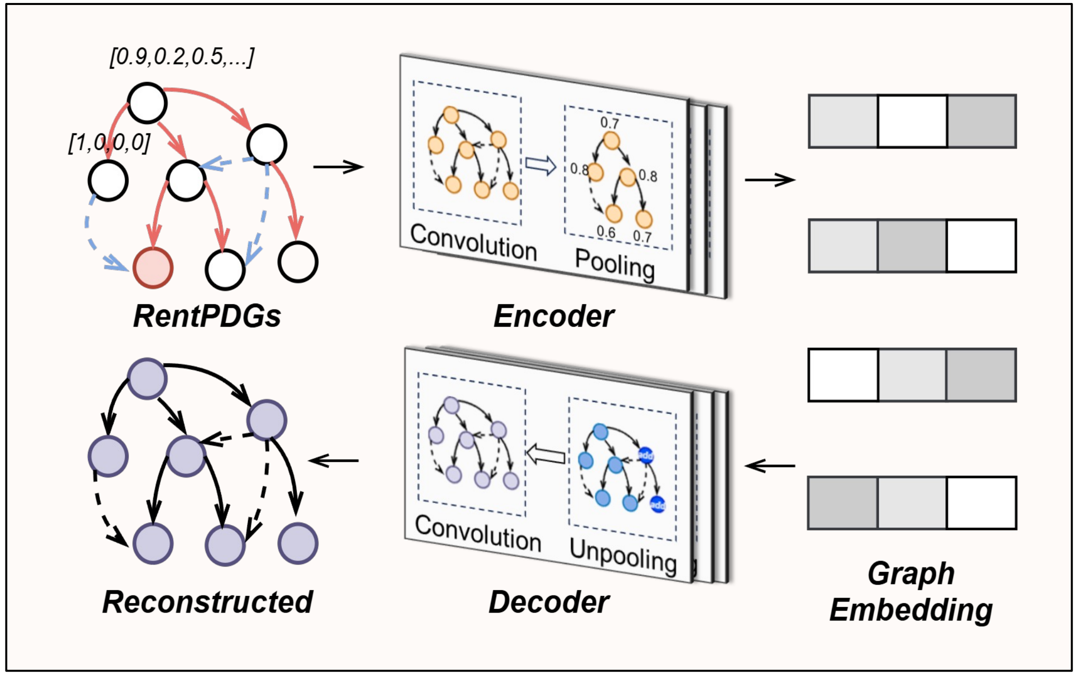
complete reachability

Step #3:

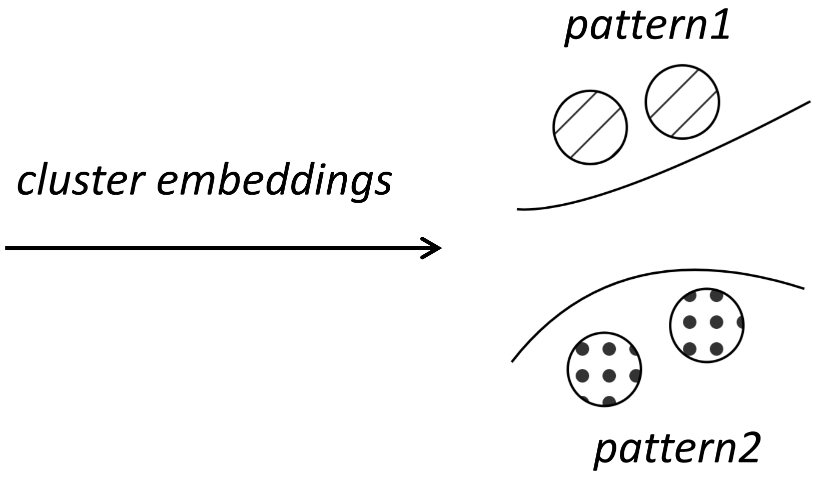
Use **a recognition model** to automatically learn anti-reentrancy semantics inherent in RentPDGs

Anti-Reentrancy Recognition Model

- We train a graph autoencoder
  - To capture semantics into **graph embedding vectors**
- Cluster embedding vectors => find typical anti-reentrancy patterns

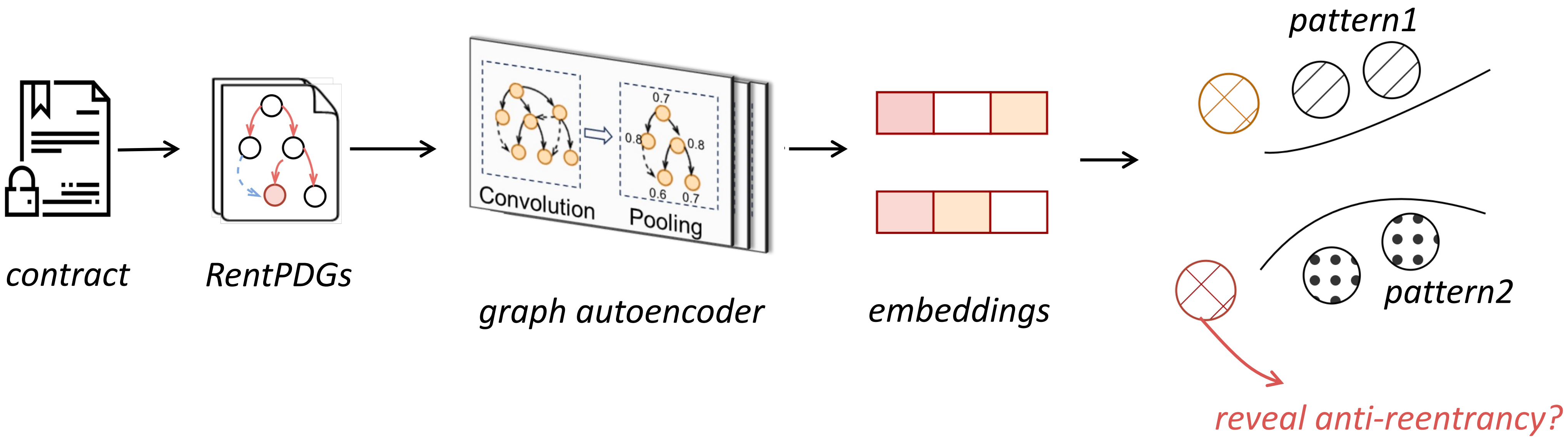


Training a graph auto-encoder



Anti-reentrancy Recognition Model

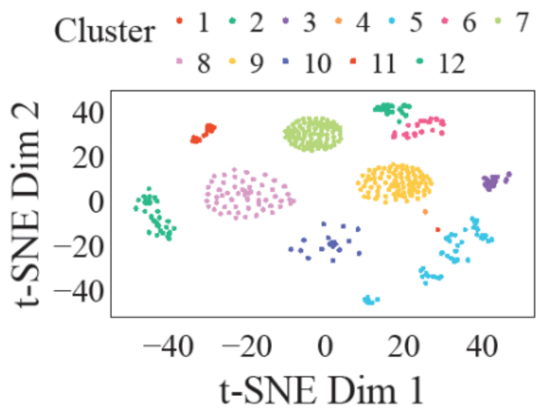
- Recognizing anti-reentrancy patterns
  - If **RentPDG embeddings** fall within learned clusters => protected with anti-reentrancy patterns



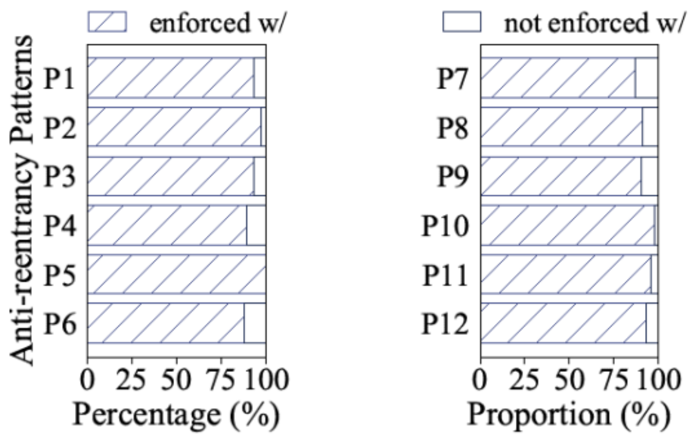
Experiment Evaluation

- Dataset: **40K real-world** smart contracts on Ethereum
  - Diverse types: ERC721, ERC777, ERC 1155, etc
- Clustering result: 12 clusters
  - For each cluster, we randomly select some contracts to review code patterns

Visualized Clustering Result

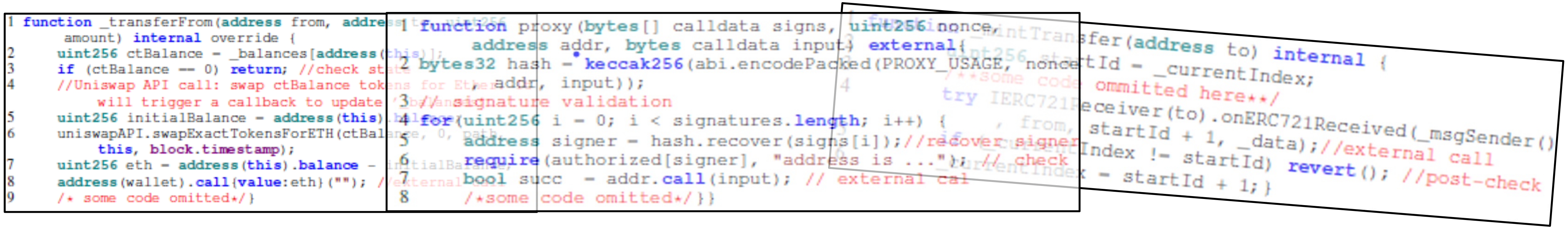


Clustering Statistics



Exp 1: Anti-reentrancy Patterns Learned

- By manually inspecting, we found 12 anti-reentrancy patterns
  - ➢ reentrancy guard, EOA restriction, ... (see details in our paper)



- Out of 12 patterns, 8 patterns are newly explored

Anti-reentrancy Type	Literature		
	Research	Blog	Official Document
Safe Ether Transfer (P1)	✓	✓	✓
Mutex Variable (P2)	✓	✓	-
Sender Check (P3)	✓	-	-
Reentrancy Guard (P6)	✓	✓	✓
P4-5, P7-12	-	-	-

Literature Review

Exp 1: Anti-reentrancy Patterns Learned (Examples)

- External owned account (EOA) restriction
  - EOA does not have any code
  - If caller is EOA => cannot make a reentrant call

variable 'tx.origin' denotes EOA

```
modifier callerIsUser() {
    require(tx.origin == msg.sender, "...");// require caller is user
}
function mint(uint256 _mintAmount) public payable callerIsUser {
    /* some code omitted */
}
```

The anti-reentrancy patterns are rarely discussed in the literature

Exp 1: Anti-reentrancy Patterns Learned (Examples)

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      callerIsUser {
    /* some code omitted */
}
```

- Access Frequency Limitation
  - Attackers cannot reenter a function in a time frame

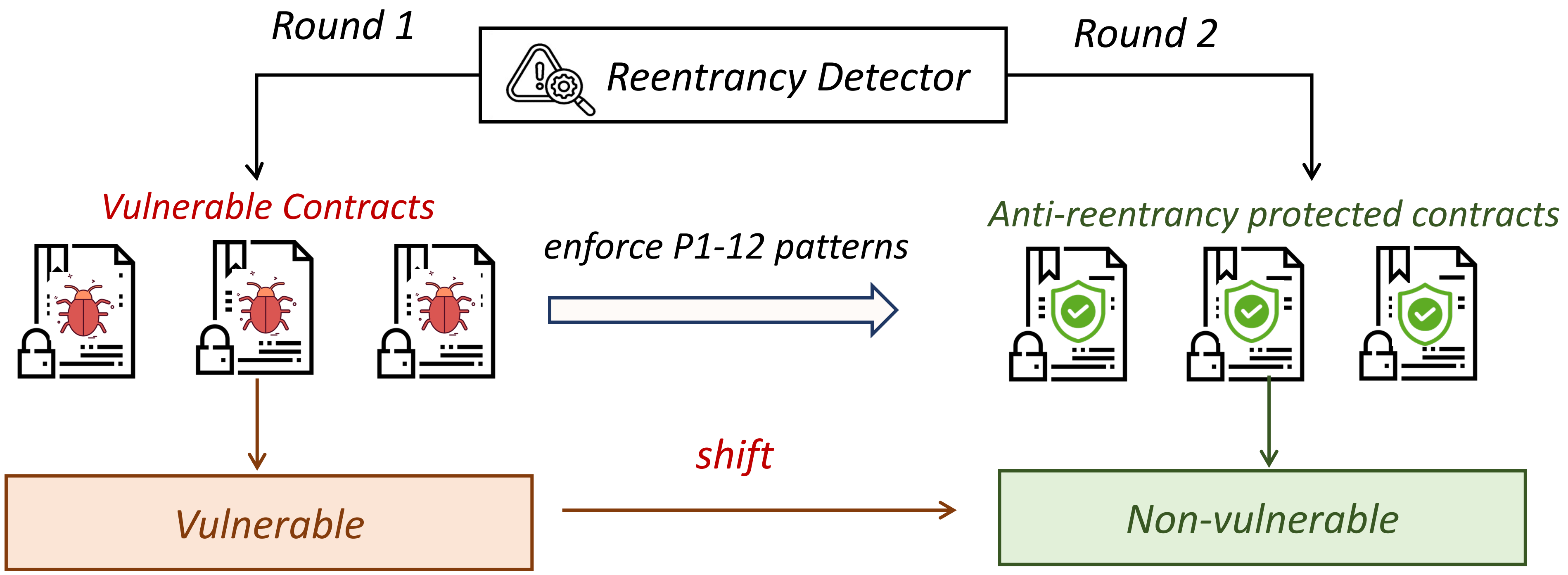
```
function _transfer(address from, address to, uint256 amount)
      internal override {
    if (block.timestamp > lastBurnTime + BurnFreq)
        //check access frequency
        autoBurnLPTokens();
}
function autoBurnLPTokens() internal returns (bool) {
    lastBurnTime=block.timestamp; //record last access time
    pair.sync(); //external call
}
```

Control the access frequency

The anti-reentrancy patterns are rarely discussed in the literature

Exp 2: Can Existing Tools Detect the Learned Patterns?

- For reliable evaluation, we conduct scanning comparison experiments



We say the detector can identify anti-reentrancy patterns

Exp 2: Can Existing Tools Detect the Learned Patterns?

- For reliable evaluation, we conduct scanning comparison experiments

TABLE I: Comparison Experiments. Here, 6 tools are applied to scan contracts before and after anti-reentrancy enforcement.

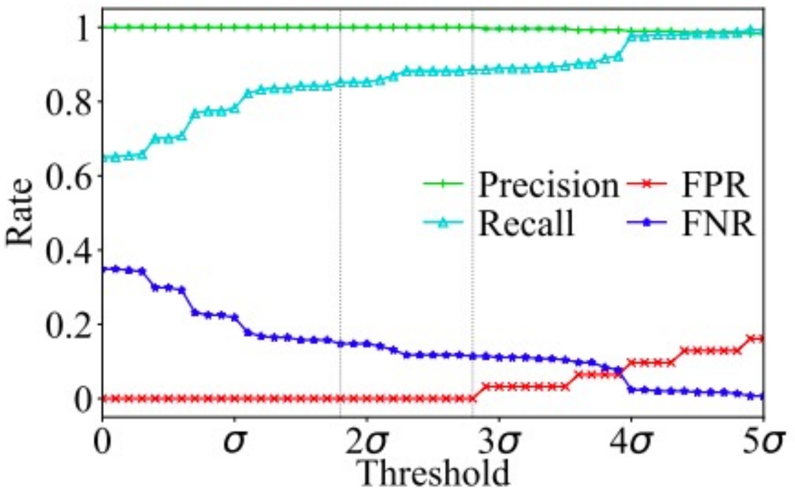
Setup		Slither	Securify	Mythril	Conkas	Smartian	Sailfish
Detection Round #1	Original*	31	29	10	31	13	28
Detection Round #2	w/ P1	**0/31**	29/29	10/10	31/31	**0/13**	**0/28**
	w/ P2	31/31	29/29	10/10	**4/31**	**0/13**	**2/28**
	w/ P3	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P4	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P5	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P6	31/31	29/29	10/10	**4/31**	**0/13** *shift*	**2/28**
	w/ P7	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P8	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P9	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P10	31/31	29/29	10/10	31/31	**0/13**	28/28
	w/ P11	31/31	29/29	10/10	31/31	13/13	28/28
	w/ P12	31/31	29/29	10/10	31/31	13/13	28/28

* It refers to original, vulnerable contracts without anti-reentrancy patterns enforced.

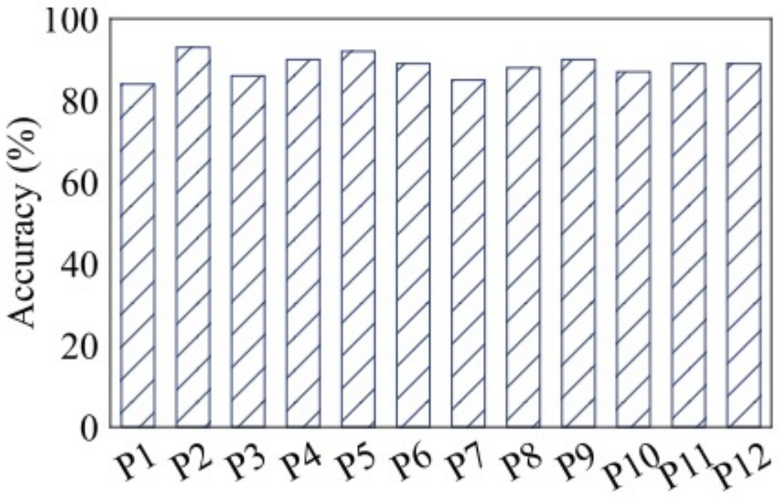
Existing tools only detect 4 patterns at most

Exp 3: Anti-reentrancy Recognition Performance

- Our system can detect anti-reentrancy patterns with recall rates over 85% and 100% precision



(a) Precision, Recall, FNR, and FPR by Varying Detection Thresholds



(b) Anti-reentrancy Recognition Accuracy w/ 2.3σ Threshold

Exp 4: Integrated with Existing Detection Tools

- Integrate our system into the workflow of existing tools
  - Reduce FPs by at least 85%
  - Not compromise their original detection capability

TABLE II: Integrating AutoAR with 6 Tools to Scan 31 Vulnerable and 298 Non-Vulnerable Contracts

Detectors		Recall	Precision	#TPs	#FPs	FNR	FPR
Slither	Original	1	0.128	31	211	0	0.708
	w/ AutoAR	1	0.596	31	21	0	0.070 ↓**(90%)**
Securify	Original	0.935	0.184	29	129	0.065	0.433
	w/ AutoAR	0.935	0.644	29	16	0.065	0.054 ↓**(88%)**
Mythril	Original	0.323	0.161	10	52	0.677	0.174
	w/ AutoAR	0.323	0.588	10	7	0.677	0.023 ↓**(87%)**
Conkas	Original	1	0.164	31	158	0	0.530
	w/ AutoAR	1	0.564	31	24	0	0.081 ↓**(85%)**
Smartian	Original	0.419	0.283	13	33	0.581	0.111
	w/ AutoAR	0.419	0.867	13	2	0.581	0.007 ↓**(94%)**
Sailfish	Original	0.903	0.184	28	124	0.097	0.416
	w/ AutoAR	0.903	0.636	28	16	0.097	0.054 ↓**(87%)**

Conclusion

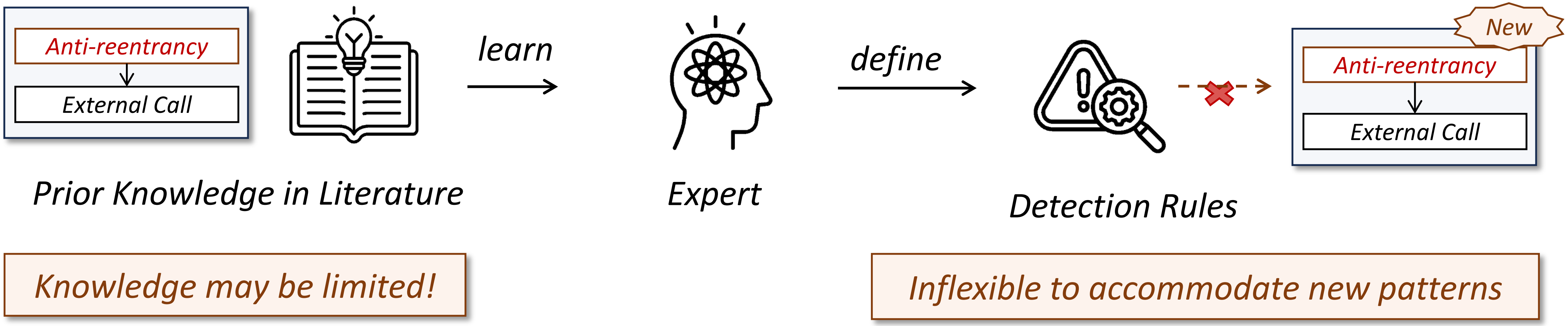
- An automated tool for identifying anti-reentrancy patterns on Ethereum
  - Help refine existing reentrancy detectors
- Utilize deep learning with a specialized data structure to precisely capture anti-reentrancy semantics
- Experimental evaluation shows our tool can significantly reduce FPs from existing reentrancy detectors

Thank You!

Q & A

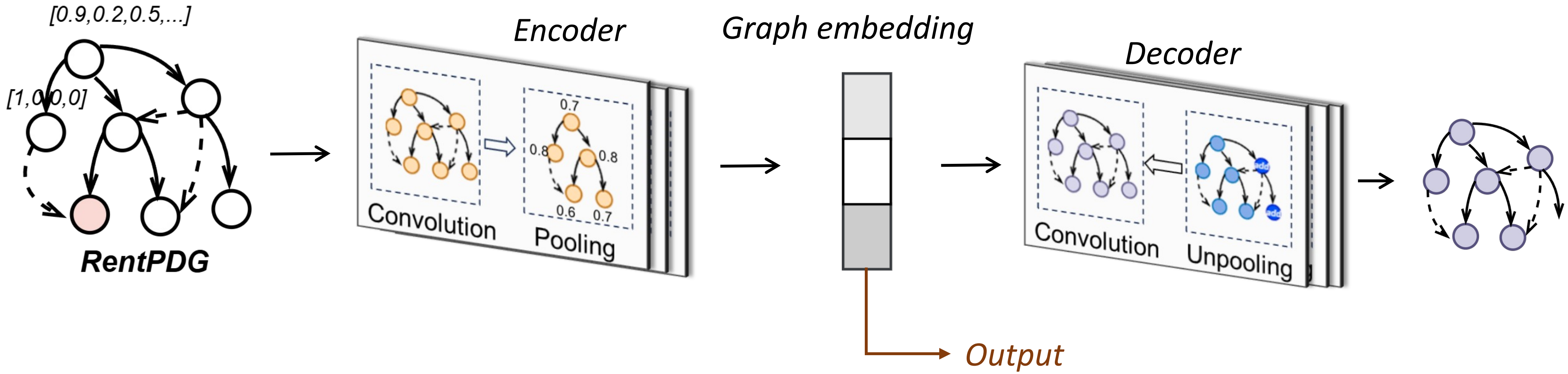
Backup: Intuitive Anti-reentrancy Detection Method

- Intuitive: **manually defining detection rules** with prior knowledge
  - Challenge 1: prior knowledge may not cover all anti-reentrancy patterns
  - Challenge #2: cannot swiftly accommodate new patterns



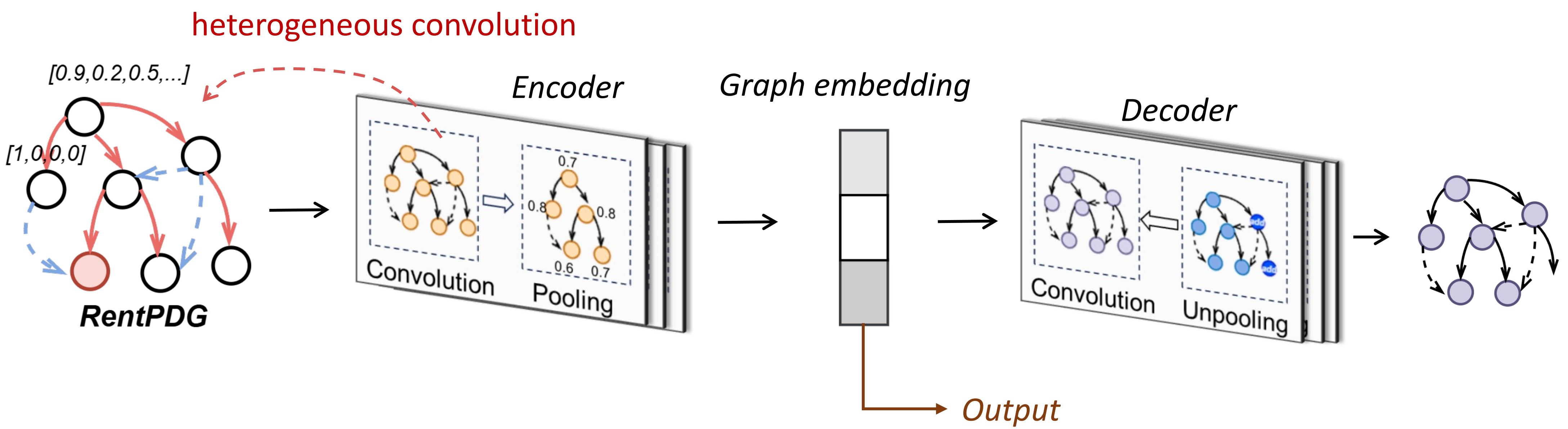
Backup: Graph AutoEncoder

- Graph auto-encoder automatically learn semantics from RentPDGs



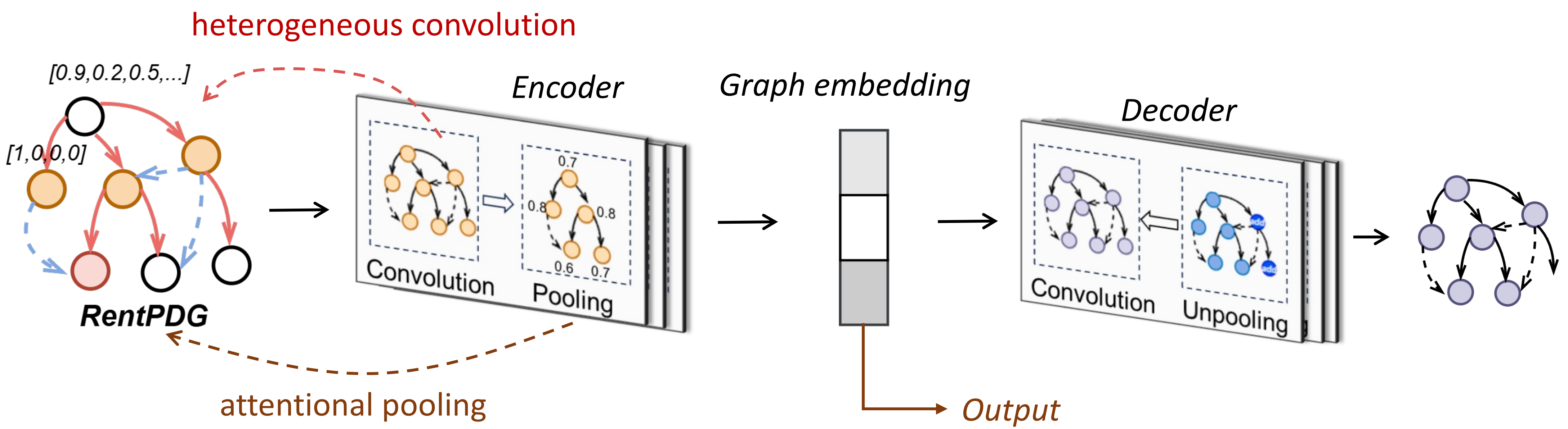
Backup: Graph AutoEncoder

- Graph auto-encoder automatically learn semantics from RentPDGs
  - Heterogeneous graph convolution => manages different types of edges



Backup: Graph AutoEncoder

- Graph auto-encoder automatically learn semantics from RentPDGs
  - Heterogeneous graph convolution => manages different types of edges
  - graph attentional pooling => capture crucial nodes



Backup: Anti-reentrancy Detection

- Clustering-based detection
  - Use cluster centroids to detect if anti-reentrancy semantics are within RentPDG embeddings
  - Set a distance detection threshold τ