Analyzing and Securing Software via Robust and Generalizable Learning

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“Software is Eating the World”

- Marc Andreessen

Software is Plagued with Errors

"Bad software cost US businesses **$2.41 trillion** in 2022" **- SC Media**

"**280 days** average time companies need to detect and respond to cyber attacks…" **- Skybox**

"Cybercrime is predicted to cost the world **$7 trillion** in 2022" **- CISQ Report**

Hackers breach energy orgs via bugs in discontinued web server

By Sergiu Gatlan   November 22, 2022   02:55 PM   0

Florida Hack Exposes Danger to Water Systems

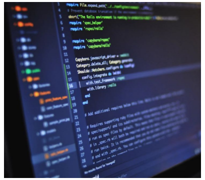
STATELINE ARTICLE | March 10, 2021 | By: Jenni Bergal | Read time: 7 min

CYBERSECURITY

Cyberattack on food supply followed years of warnings

Virtually no mandatory cybersecurity rules govern the millions of food and agriculture businesses that account for about a fifth of the U.S. economy. And now, the risk has become real.

Program Analysis is Crucial for Building Trustworthy Software



Software Programs

Questions

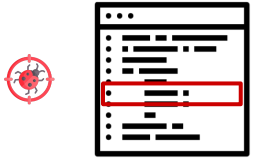
Can pointer p be NULL at line L?

Program Analysis

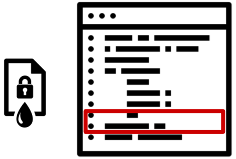
Answers

Help to Build

Vulnerability



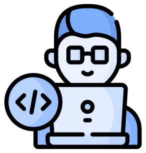
Privacy Leak



Trustworthy Software

- **Security**
- **Reliability**
- **Safety**
- **Privacy**
- **Performance**

Challenges of Traditional Program Analysis

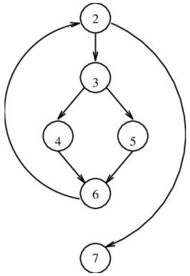


Human Expert

Hand-Curate

Rules and Heuristics

How to



Represent a program?

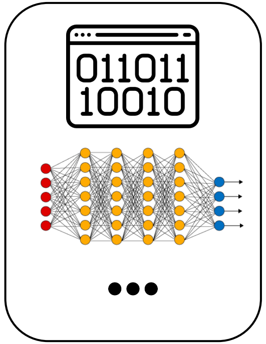
Input: $kill(B)$ and $gen(B)$ for every basic bloc B.

Output: $in(B)$ and $out(B)$ for every basic bloc B.

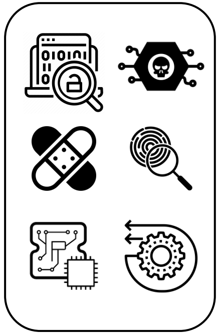
for each B **repeat**
  $out(B) := gen(B)$
while changes to any $out(B)$ occur **repeat**
  $in(B) := \bigcup_{B' \in \text{pred}(B)} out(B')$
  $out(B) := gen(B) \bigcup (in(B) \setminus kill(B))$

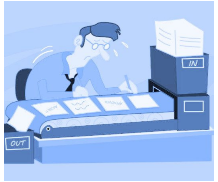
Design analysis rules?

Heterogeneous Software



Various Security Applications





Significant Manual Effort

Tune

Machine Learning Shows Promise for Analyzing Programs

Human Expert

Hand-Curate →

Rules and Heuristics

How to →

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Design analysis rules?

Abundant Public Code

+

Abundant Compute

Learn →

Program Representations

Analysis Rules

Machine Learning Shows Promise for Analyzing Programs

CHATGPT Detecting and Exploiting Vulnerabilities

devtooligan
@devtooligan

omg. seriously mind-blown 🤯

Brandon Rossi
@0xConda

I told ChatGPT to pentest a scope of IPs and it found me $69,420 worth of bugs.

Are there any vulnerabilities in this Solidity contract? I want to make sure no one can steal other peoples' deposits. If there are, how do I fix it?

```
contract Vault {
  mapping(address => uint256) public balances;

  function deposit() public payable {
    balances[msg.sender] += msg.value;
  }

  function withdraw(uint256 amount, address from) public {
    balances[from] -= amount;
    payable(from).transfer(amount);
  }
}
```

This contract appears to have a potential vulnerability in the `withdraw` function. The `withdraw` function allows anyone to specify the `from` address when calling the function, which means that a malicious user could potentially withdraw funds from an arbitrary address by calling `withdraw` and specifying a different `from` address.

To fix this issue, you could modify the `withdraw` function to only allow the caller to withdraw funds from their own account. You could do this by replacing the `from` parameter with `msg.sender`, which will always represent the caller's address. Here is an example of how you could do this:

Limitations: Lack Understanding of Program Semantics

A code summarization example (Alon et al., 2019, Yefet et al., 2020, Henkel et al. 2022)
[code2vec.org / code2seq.org]

```
void f1(int[] array){
  boolean swapped = true;
  for (int i = 0;
    i < array.length && swapped; i++){
    swapped = false;
    for (int j = 0;
    j < array.length-1-i; j++) {
      if (array[j] > array[j+1]) {
        int temp = array[j];
        array[j] = array[j+1];
        array[j+1]= temp;
        swapped = true;
      }
    }
  }
}
```

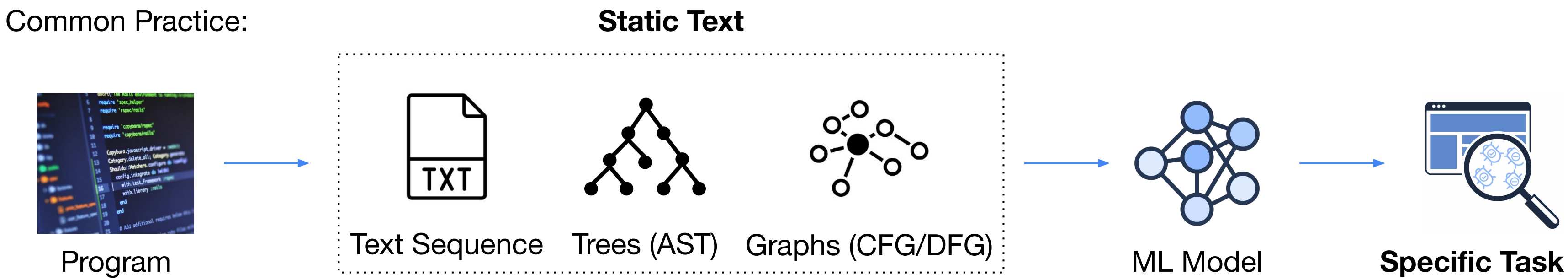
Prediction: **sort** (98.54%)

```
void f2(int[] ttypes){
  boolean swapped = true;
  for (int i = 0;
    i < ttypes.length && swapped; i++){
    swapped = false;
    for (int j = 0;
    j < ttypes.length-1-i; j++) {
      if (ttypes[j] > ttypes[j+1]) {
        int temp = ttypes[j];
        ttypes[j] = ttypes[j+1];
        ttypes[j+1]= temp;
        swapped = true;
      }
    }
  }
}
```

Prediction: **contains** (99.97%)

Yefet, Noam, Uri Alon, and Eran Yahav. "Adversarial examples for models of code." OOPSLA 2020.

Common Practice of ML on Code



Program semantics does not just manifest in **static text**

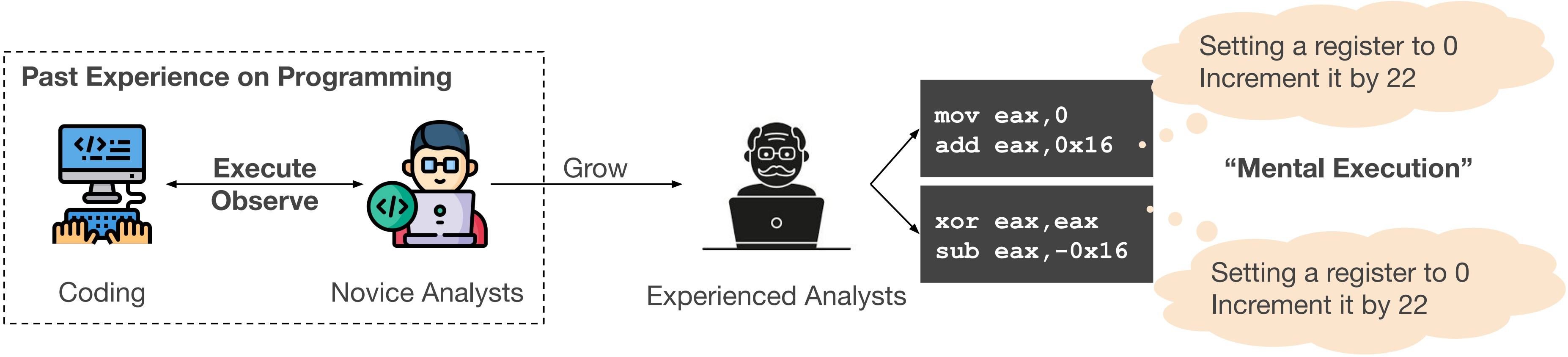
Consequences: Lacking Robustness and Generalization

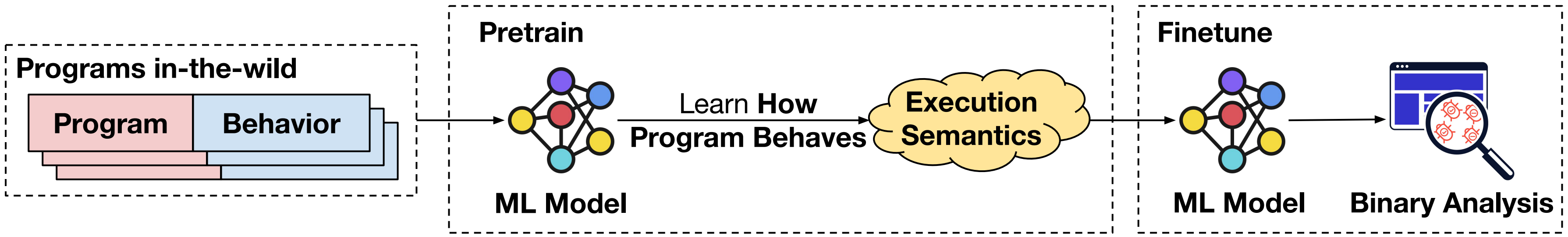
I. **Overfit** to **spurious textual** and **task-specific** patterns

II. **Distribution shift**: **program syntax** and **task requirement** changes

Security Applications Require More Rigorous Understanding of Program Semantics

Learning Execution Semantics and Transferring it without Dynamic Analysis





Case Studies: Vulnerability Search in Firmware

CVE	Library	Description
CVE-2019-1563	OpenSSL	Decrypt encrypted message
CVE-2017-16544	BusyBox	Allow executing arbitrary code
CVE-2016-6303	OpenSSL	Integer overflow
CVE-2016-6302	OpenSSL	Allows denial-of-service
CVE-2016-2842	OpenSSL	Allows denial-of-service
CVE-2016-2182	OpenSSL	Allows denial-of-service
CVE-2016-2180	OpenSSL	Out-of-bounds read
CVE-2016-2178	OpenSSL	Leak DSA private key
CVE-2016-2176	OpenSSL	Buffer over-read
CVE-2016-2109	OpenSSL	Allows denial-of-service
CVE-2016-2106	OpenSSL	Integer overflow
CVE-2016-2105	OpenSSL	Integer overflow
CVE-2016-0799	OpenSSL	Out-of-bounds read
CVE-2016-0798	OpenSSL	Allows denial-of-service
CVE-2016-0797	OpenSSL	NULL pointer dereference
CVE-2016-0705	OpenSSL	Memory corruption

16 Vulnerabilities (Compiled in x86)

Search →

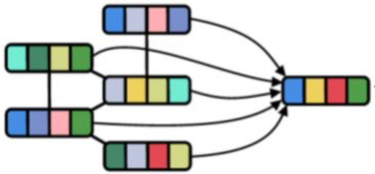
Firmware Images: `Arm`, `MIPS` with unknown compiler flags

Ubiquiti sunMax → 15 CVEs

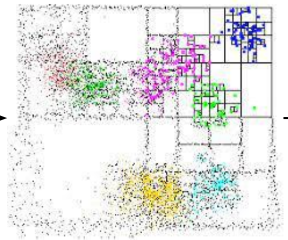
TP-Link Deco-M4 → 16 CVEs

NETGEAR R7000 → 7 CVEs

Linksys RE7000 → 14 CVEs



Learned Function Embeddings

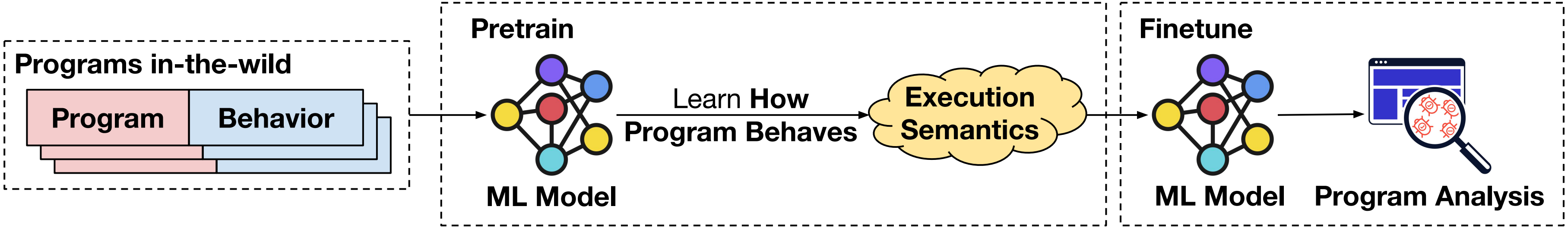


Approximate Nearest Neighbors

Search over **1.4M** functions within **6.3 seconds**

Pei, Xuan, Yang, Jana, Ray. Trex: Learning Execution Semantics from Micro-traces for Binary Similarity. TSE'22

Summary: Learning **Program Semantics** via **Execution-Aware Pre-training** Improves Program Analysis



Precise: Outperforms the state-of-the-art by up to **118%**

Efficient: Speedup over the off-the-shelf tool by up to **98.1x**

Generalizable and Robust: Remains accurate across

GCC Visual C++ — Compilers

x64 x86 — Architectures

-O0 -O1 -O2 -O3 -Od Ox — Optimizations

Obfuscations

Broad Application

- Detecting Semantically Similar Binary Code [1]
- Type Inference and Data Structure Recovery [2]
- Binary Memory Dependence Analysis [3]
- Inferring Program Invariance for Source Code [4]
- Source Code Vulnerability Detection [5]

[1] Pei et al. Trex: Learning Execution Semantics from Micro-traces for Binary Similarity. TSE'22
[2] Pei et al. StateFormer: Fine-grained type recovery from binaries using generative state modeling. ESEC/FSE'21
[3] Pei et al. NeuDep: neural binary memory dependence analysis. ESEC/FSE'22
[4] Pei et al. Can Large Language Models Reason about Program Invariants. ICML'23
[5] Ding et al. TRACED: Execution-aware Pre-training for Source Code. ICSE'24.