Vulnerability Detection - Best Effort

Holistic Software Security

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Bits and pieces copied from: https://help.semmle.com/QL/ql-training/cpp

Best effort techniques

- We don’t need to find all the bugs, i.e., we do not need to be sound.
    - “Unsoundness was controversial in the research community, though it has since become almost a de facto tool bias for commercial products and many research projects.”
- Precision (i.e., no false positives is more important):
    - “False positives do matter. In our experience, more than 30% easily cause problems. People ignore the tool.”

*a-few-billion-lines-of-code-later.

Gen 1: User written patterns.

- METAL: Use compiler to check user written patterns.
- Custom language for checker:
  - Hard to write accurate patterns for common developers.
- False positives:
  - No field sensitivity and context sensitivity.

```
sm range_check {
  // Wild-card variables used in patterns.
  decl any_expr y, z, len; // match any expr
  decl any_pointer v;      // match any pointer
  state decl any_expr x;   // bind state to x

 // Start state. Matches any copy_from_user
 // call and puts parameter x in tainted state.
 start: { copy_from_user(x, y, len) }
        ==> x.tainted
 ;
 // Catch operations illegal on unsafe values.
 x.tainted, x.need_ub, x.need_lb:
    { v[x] } ==>{ err("Dangerous index!"); }
 | { copy_from_user(y, z, x) }
 | { copy_to_user(y, z, x) }
     ==> { err("Dangerous length arg!"); }
 ;
 // Named patterns that match upper-bound
 // (ub) and lower-bound checks (lb).
 pat ub = { x < y } | { x <= y };
 pat lb = { x > y } | { x >= y };
```

```
 ;
 x.need_lb:
  lb ==> true=x.stop, false=x.need_lb
 | ub ==> true=x.need_lb, false=x.stop
 | { x == y } ==> true=x.stop, false=x.need_lb
 | { x != y } ==> true=x.need_lb, false=x.stop
 ;
}
```

Gen 2: Make the patterns easier.

- Microgrammers:
  - Only parse required language features => Custom parsers for each checker.
- To detect Null ptr dereference:
  - We need to parse “if” and pointer-dereference.
- **No need to have full compiler front-end.**

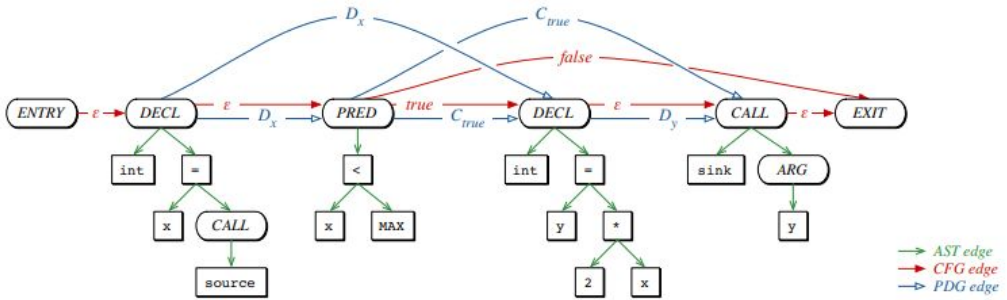
```
S          → Function
Function   → Ident ('(') FnArgs SkipTo('{') Body '}'
FnArgs     → SkipTo(',' FnArgs | ')')

Body       → '{' Statements '}' | Statement
Statements → Statement Statements | ϵ
Statement  → IfStmt | WhileStmt Body | ... | Line
IfStmt     → if Balanced('(', ')') Body [Else]
Else       → else Body
... // more constructs
Line       → SkipTo(';')
```

Gen 3: Make patterns even easier.

- Code Property Graphs:
  - Queries using Gremlin: Graph query over code property graph.

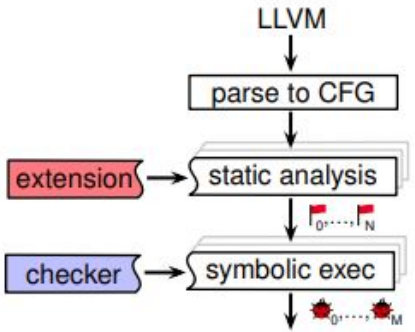
```
void foo()                          1
{                                   2
    int x = source();               3
    if (x < MAX)                    4
    {                               5
        int y = 2 * x;              6
        sink(y);                    7
    }                               8
}                                   9
```



Modeling and Discovering Vulnerabilities with Code Property Graphs

Gen 4: Reduce false positives.

- Sys: static/symbolic tool:
  - Use static extensions to find potential flows and then use symbolic checker to filter out false positives.



Sys: a Static/Symbolic Tool for Finding Good Bugs in Good (Browser) Code

Sys: Static/Symbolic tool

- Sys: static/symbolic tool:
  - Use static extension to save and report paths and symbolic checker to accurately find the bugs.

Static Extension

```
check :: Named Instruction -> Checker ()
check instr = case instr of

  -- Save the size of the object
  name := Call fName args | isAllocation fName -> do
    let allocSize = args !! 0
    saveSize name allocSize

  -- Keep track of dependencies between LHS and RHS
  -- variables of arithmatic instructions.
  name := _ | isArith instr -> do
    operands <- getOperands instr
    forM_ operands $ addDep name

  -- If an array index has some dependency on
  -- an object's allocated size, report the path
  name := GetElementPtr addr (arrInd:_) -> do
    let addrName = nameOf addr
    addrSize <- findSize addrName
    when (isDep addrSize arrInd) $
      reportPath arrSize arrInd

  -- Otherwise do nothing
  _ -> return ()
```

- False positives

Sys: Static/Symbolic tool

- Sys: static/symbolic tool:
  - Use static extension to save and report paths and symbolic checker to accurately find the bugs.

Static Extension

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    when (isDep addrSize arrInd) $
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  -- Otherwise do nothing
  _ -> return ()
```

Symbolic Checker

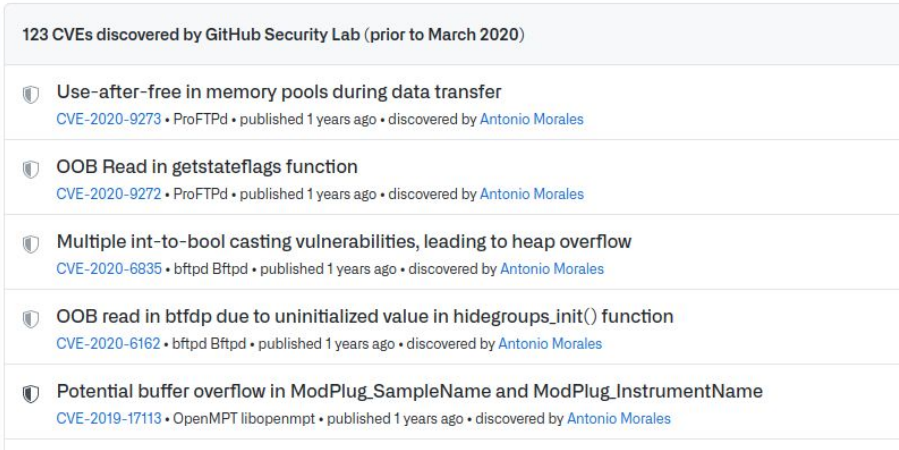
```
symexCheck :: Name -> Name -> Symex ()
symexCheck arrSize arrInd = do

    -- Turn the size into a symbolic bitvector
    arrSizeSym <- getName arrSize
    -- Turn the index into a symbolic bitvector
    let indTy = typeOf arrInd
    arrIndSym <- getName arrInd
    arrIndSize <- toBytes indTy arrInd

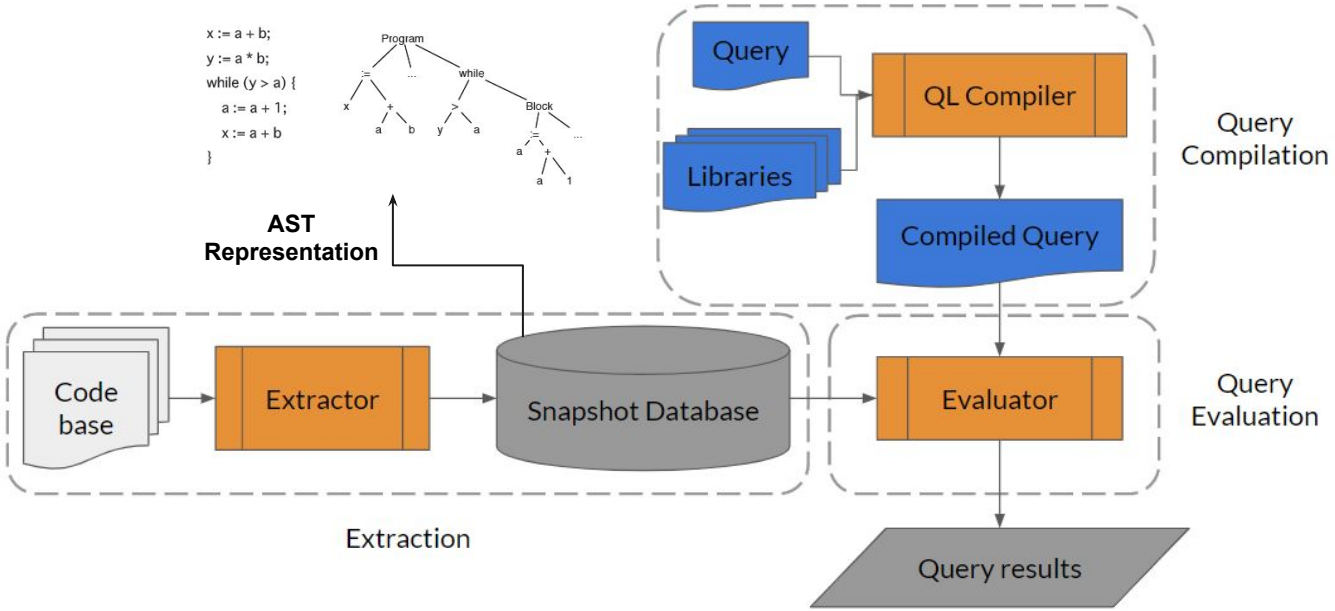
    -- Report a bug if the index size can be
    -- larger than the allocation size
    assert $ isUge byte arrIndSize arrSizeSym
```

CodeQL: State of the art (Pattern based)

- Logical query language similar to SQL.
- Modular and extensible:
  - Support for custom classes.
  - Libraries.
- Well maintained by Microsoft and its open source.



CodeQL


x := a + b;
y := a * b;
while (y > a) {
a := a + 1;
x := a + b
}
Program
while
Block
AST
Representation
Query
QL Compiler
Libraries
Compiled Query
Query
Compilation
Code
base
Extractor
Snapshot Database
Evaluator
Query
Evaluation
Extraction
Query results

CodeQL : Example

```
void fire_thrusters(double vectors[12]) {

  for (int i = 0; i < 12; i++) {

    ... vectors[i] ...

  }

}

...

double thruster[3] = ... ;

fire_thrusters(thruster);
```

- What is the problem with the code?

CodeQL : Example

```
void fire_thrusters(double vectors[12]) {

  for (int i = 0; i < 12; i++) {

    ... vectors[i] ...

  }

}

...

double thruster[3] = ... ;

fire_thrusters(thruster);
```

- What is the problem with the code?
- In C, array types of parameters degrade to pointer types.
- The size is ignored!

Finding using CodeQL

```
void fire_thrusters(double vectors[12]) {

  for (int i = 0; i < 12; i++) {

    ... vectors[i] ...

  }

}

...

double thruster[3] = ... ;

fire_thrusters(thruster);
```

- Basic Query Structure:

import <language library>

from <entities and types>

where <queries on entities>

select <entities to select>

Finding using CodeQL

```
void fire_thrusters(double vectors[12]) {

  for (int i = 0; i < 12; i++) {

    ... vectors[i] ...

  }

}

...

double thruster[3] = ... ;

fire_thrusters(thruster);
```

- First, let's find function calls.

```
import cpp

from Function f, FunctionCall c

where f = c.getTarget()

select "Found call to " + f.getName()
```

Finding using CodeQL

```
void fire_thrusters(double vectors[12]) {
  for (int i = 0; i < 12; i++) {
    ... vectors[i] ...
  }
}
...
double thruster[3] = ... ;
fire_thrusters(thruster);
```

- Argument should be constant array.

```
import cpp
from Function f, FunctionCall c, int i
where f = c.getTarget()
 and (f.getParameter(i).getType() instanceof ArrayType)
select "Found call to " + f.getName()
```

Finding using CodeQL

```
void fire_thrusters(double vectors[12]) {
  for (int i = 0; i < 12; i++) {
    ... vectors[i] ...
  }
}
...
double thruster[3] = ... ;
fire_thrusters(thruster);
```

Checking size of parameter and argument:

```
import cpp
from Function f, FunctionCall c, int i, int a, int b
where f = c.getTarget()
 and a = c.getArgument(i).getType().(ArrayType).getArraySize()
 and b = f.getParameter(i).getType().(ArrayType).getArraySize()
 and a < b
select c.getArgument(i), f, “Found vulnerability”
```

Finding using CodeQL

```
void fire_thrusters(double vectors[12]) {
  for (int i = 0; i < 12; i++) {
    ... vectors[i] ...
  }
}
...
double thruster[3] = ... ;
fire_thrusters(thruster);
```

Argument size < parameter size

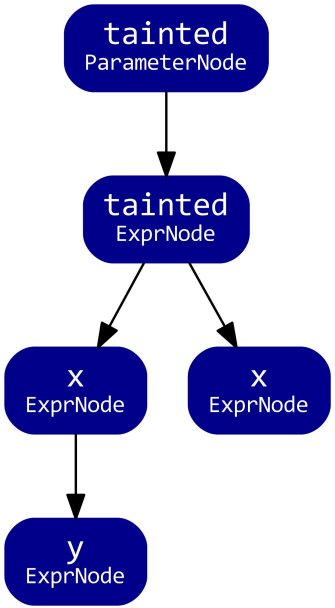
Checking size of parameter and argument:

Characteristic predicate

```
import cpp
from Function f, FunctionCall c, int i, int a, int b
where f = c.getTarget()
 and a = c.getArgument(i).getType().(ArrayType).getArraySize()
 and b = f.getParameter(i).getType().(ArrayType).getArraySize()
 and a < b
select c.getArgument(i), f, “Found vulnerability”
```

CodeQL : Data flow analysis

```
int func(int tainted) {
   int x = tainted;
   if (someCondition) {
     int y = x;
     callFoo(y);
   } else {
     return x;
   }
  return -1;
}
```



CodeQL : Data flow example

Format string checker: Use of externally controlled format string.

```
printf(userControlledString, arg1);
```

Goal: Find uses of printf (or similar) where the format string can be controlled by an attacker.

CodeQL : format string checker

```
import cpp
import semmle.code.cpp.dataflow.DataFlow
import semmle.code.cpp.commons.Printf
class SourceNode extends DataFlow::Node {
    SourceNode() {
      not DataFlow::localFlowStep(_, this)
    }
}
from FormattingFunction f, Call c, SourceNode src, DataFlow::Node  arg
where c.getTarget() = f and arg.asExpr() = c.getArgument(f.getFormatParameterIndex()) and
      DataFlow::localFlow(src, arg) and not src.asExpr() instanceof StringLiteral
select arg, "Non-constant format string."
```

CodeQL : format string checker

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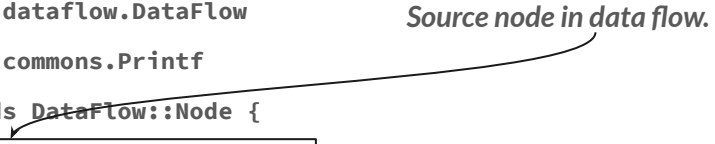

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Source node in data flow.

Flows from src to arg.

CodeQL : format string checker

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select arg, "Non-constant format string."
```

Source node in data flow.

Flows from src to arg.

Src is not a constant string.

CodeQL: Other features

- Taint analysis:
  - Custom taint source functions and taint sinks.

- LGTM -> Can run various checkers on open source codebases.

- Also, supports various other languages: C++, Java, JavaScript, etc.

CodeQL: Drawbacks

- AST representation (v/s IR representation):
  - Depends on coding pattern.

- Not suitable for complex analysis involving fine-grained data flow.

Pattern based methods

- Fine-grained patterns (e.g., CodeQL, Sys):
  - Hard to write => Need skill.
  - Require build system.
  - Precise.
- Coarse-grained patterns (e.g., Microgrammers, Metal):
  - Relatively easy to write.
  - Does not depend on build system (i.e., no compilation needed).
  - False positives.

Can we automatically generate fine-grained pattern (maybe with small help from developer)?

Best effort: Machine learning

- Category 1: Learn vulnerable code patterns from given dataset.
- Category 2: Bugs as a deviant behavior => Less frequently used pattern most probably suggests a bug.
- Category 3: Assist developers and other techniques to focus on potentially vulnerable code.
- Category 4: Active learning => Interact with users to know how a bug should look like.

General Principle of ML based Detectors

```
#!/bin/bash

# Verifie la validité d'une date
function dateValide()
{
    local  a=`echo $1 | grep ^[0-3][0-9]\/[0-1][0-9]\/[0-9]{4}$`
    if [ "$a" != 0 ];then
        j=`echo $1 | cut -d'/' -f1`
        m=`echo $1 | cut -d'/' -f2`
        a=`echo $1 | cut -d'/' -f3`

        [ $j -le 31 -a $j -ge 1 -a $m -le 12 -a $m -ge 1 ]
        echo $?
    else
        echo 1
    fi
}

# Verifie si une plage horaire $1 est bien comprise dans la plage horaire $2
function appartientPlage()
{
    if [ "`valideHoraire $1`" == "0" -a "`valideHoraire $2`" == "0" ];then
        local h1=`echo $1 | cut -d'-' -f1 | sed s/://`
        local h2=`echo $1 | cut -d'-' -f2 | sed s/://`
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Source Representation

AST, CFG, Program Dependency Graph (PDG), Symbolic Trace, etc.

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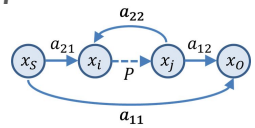
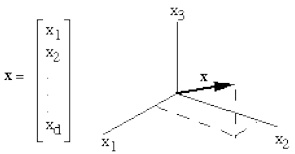
Source Representation



AST, CFG, Program Dependency Graph (PDG), Symbolic Trace, etc.

Vectorization



Bag of words, Word2Vec, Custom Boolean vector, etc

General Principle of ML based Detectors

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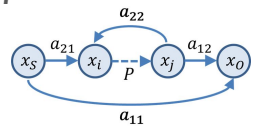
Source Representation



AST, CFG, Program Dependency Graph (PDG), Symbolic Trace, etc.

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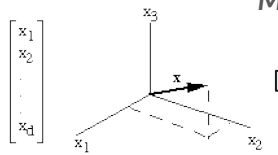
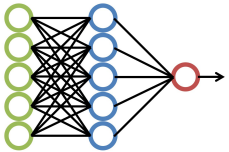


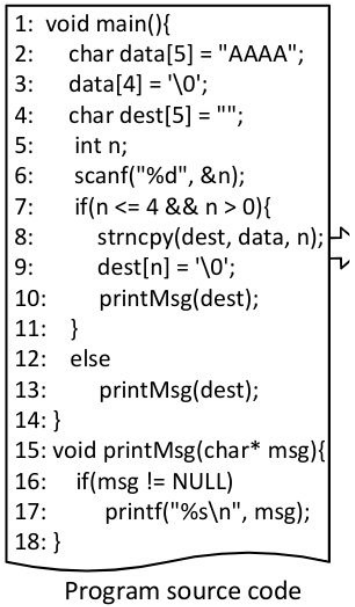
Bag of words, Word2Vec, Custom Boolean vector, etc

Model Training



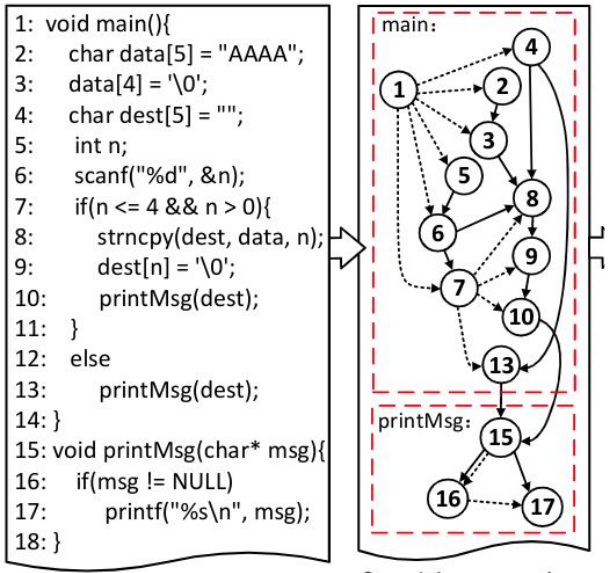
RNN, LSTM, SVM, Clustering, etc.

Category 1: μVulDeePecker



Program source code

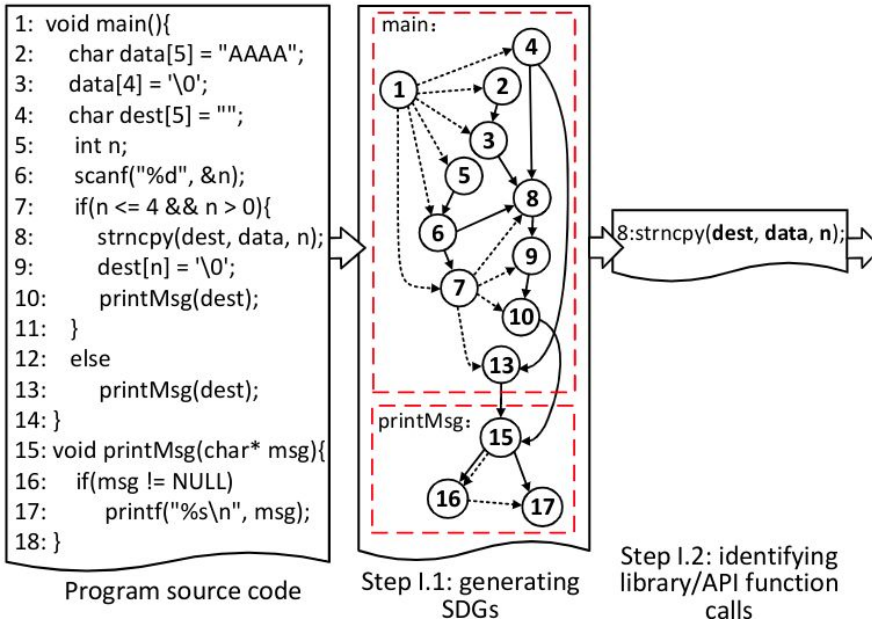
Category 1: μVulDeePecker



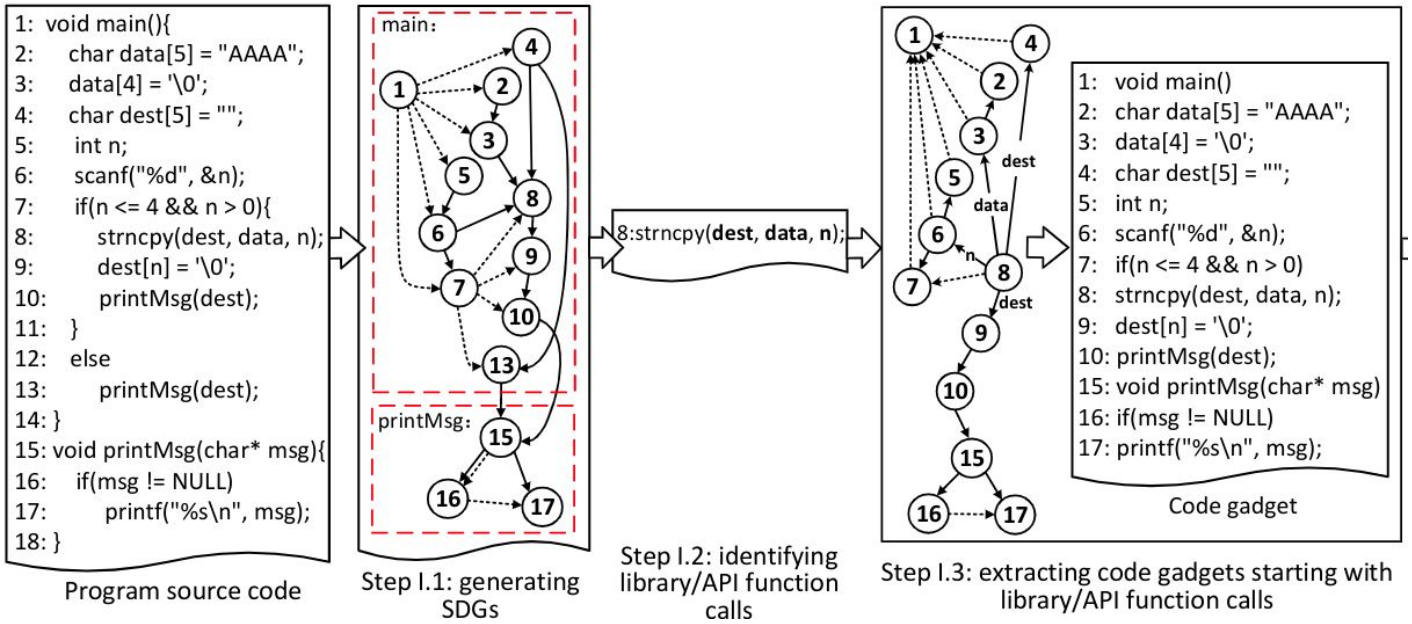
Program source code

Step I.1: generating SDGs

Category 1: μVulDeePecker



Category 1: μVulDeePecker



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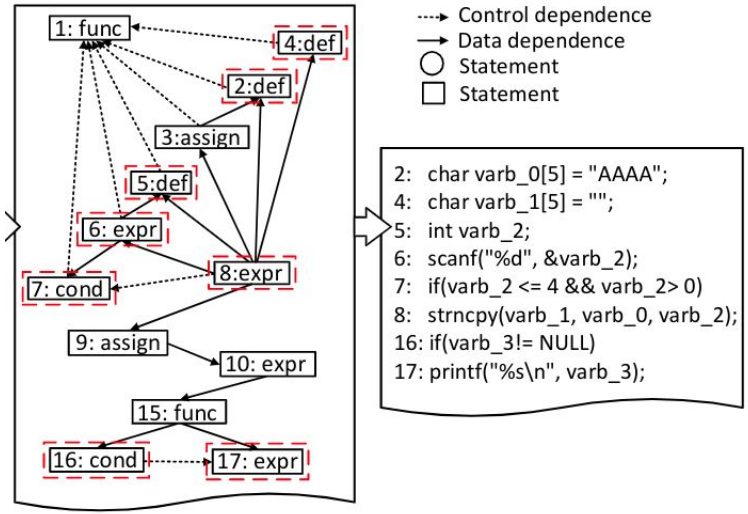


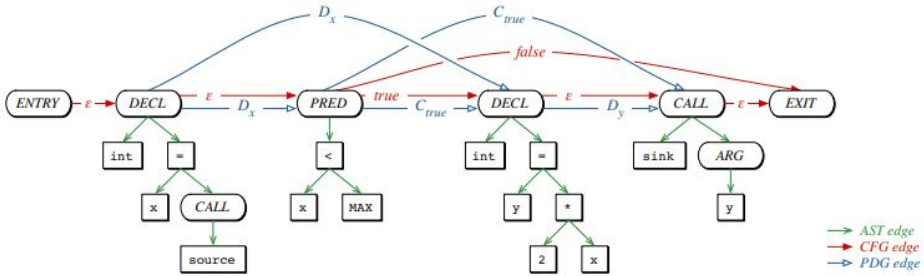
Step IV: generating code attentions corresponding to code gadgets

(b) generating code attentions

Category 2: Automatic Inference of Taint Style Vulnerabilities

- Based on Code Property Graphs.

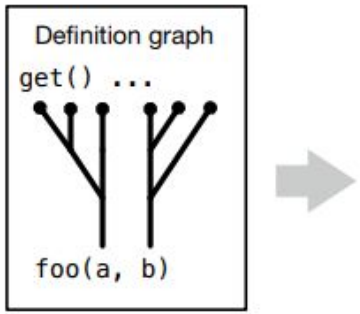
```
void foo()
{
    int x = source();
    if (x < MAX)
    {
        int y = 2 * x;
        sink(y);
    }
}
```



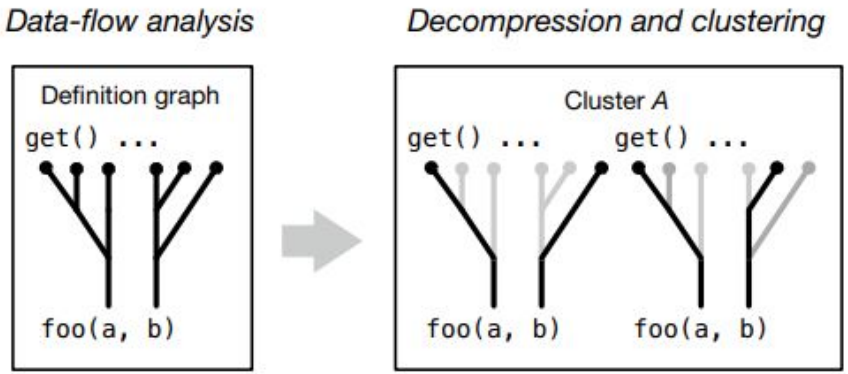
- For each sensitive sink -> Infer the “most common way” the arguments are passed -> create *an inverse pattern* of the most common way.

Category 2: Automatic Inference of Taint Style Vulnerabilities

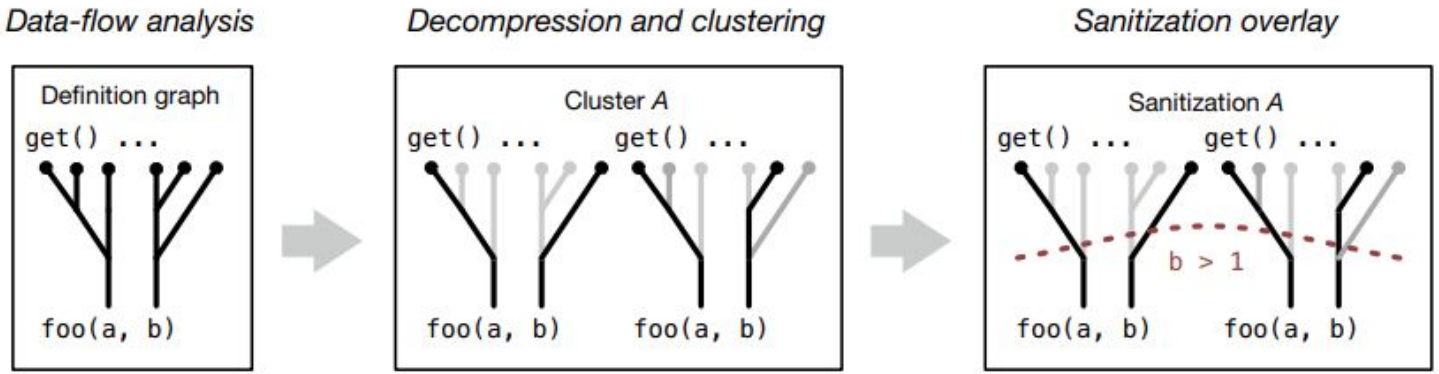
Data-flow analysis



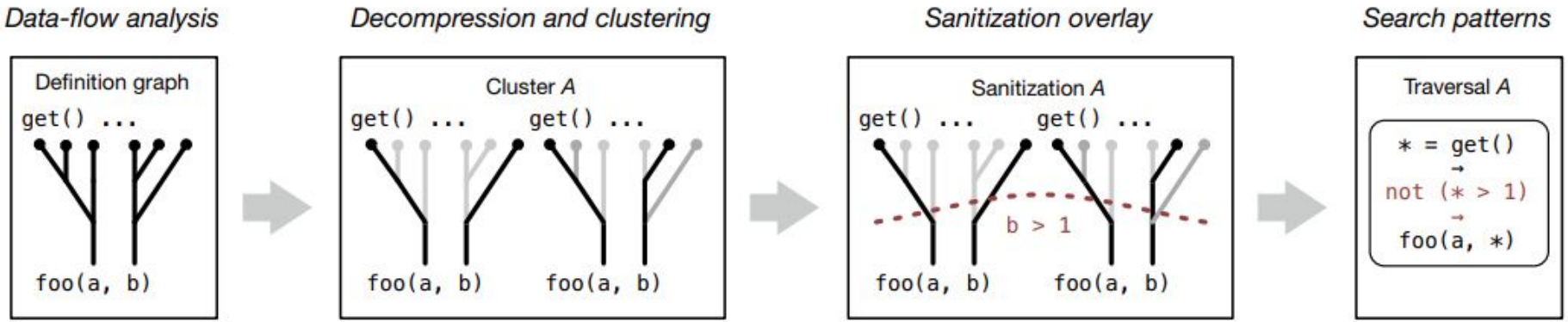
Category 2: Automatic Inference of Taint Style Vulnerabilities



Category 2: Automatic Inference of Taint Style Vulnerabilities



Category 2: Automatic Inference of Taint Style Vulnerabilities



Category 3: Assist Developers in finding Potentially vulnerable code

- BRAN: Finds potentially vulnerable functions:
  - Can direct the attention of developer or other tools (E.g., fuzzing) towards these functions.

- Uses representation based features and commit metadata:
  - Size of function, number of pointer accesses, Loops, etc.
  - Number of commits to the function, Reputation of the developer, etc.

- Trains RandomForest to detect vulnerable functions.

Category 4: Active learning

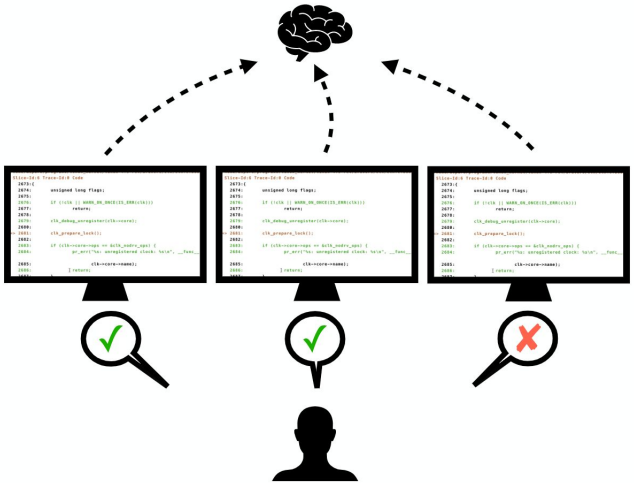
- Existing tools require a lot of effort by the developers.
  - Write precise patterns (CodeQL)
    - Hard -> GitHub pays money to write a good CodeQL query.

1. Write a CodeQL query that models a vulnerability you're interested in.
2. Run your query on real world open source software and find at least four vulnerabilities, preferably across multiple projects. Please note that projects which purposely include a vulnerability pattern for testing purposes are considered out of scope.
3. Report the vulnerabilities to the projects' maintainers, help them fix them, and have them obtain CVEs for each one. Remember that for most open source projects, maintainers can now get a CVE directly from GitHub via Security Advisories. **To be eligible for a bounty, you must first coordinate disclosure of the vulnerabilities with the maintainers of the projects.**
4. Open a pull request in the CodeQL repo with your CodeQL query. See the contribution guidelines for more details.
5. Create an issue using the bug slayer template. The issue should link to your pull request and contain a detailed report of the vulnerabilities your query finds. **Mention only the vulnerabilities that have been publicly disclosed and fixed.** It should include a description of the vulnerabilities, their associated CVEs, and how the query allowed you to find them. Pull requests without an accompanying issue cannot be considered.
6. An award of up to **$5000 USD** will be granted. We consider the impact and risk associated with the vulnerability and the quality of your query when determining the award amount.

https://securitylab.github.com/bounties/

Category 4: Active learning

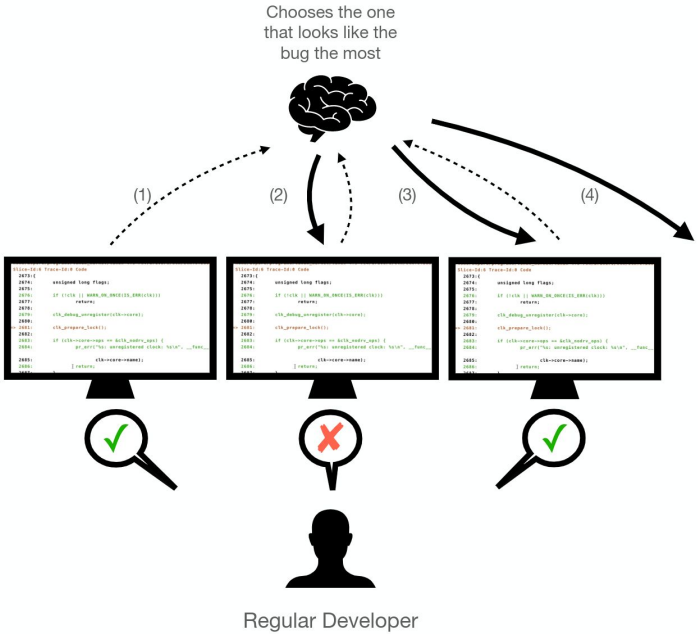
- What do developers know?
  - Given a warning, they can say whether the warning is true or not.



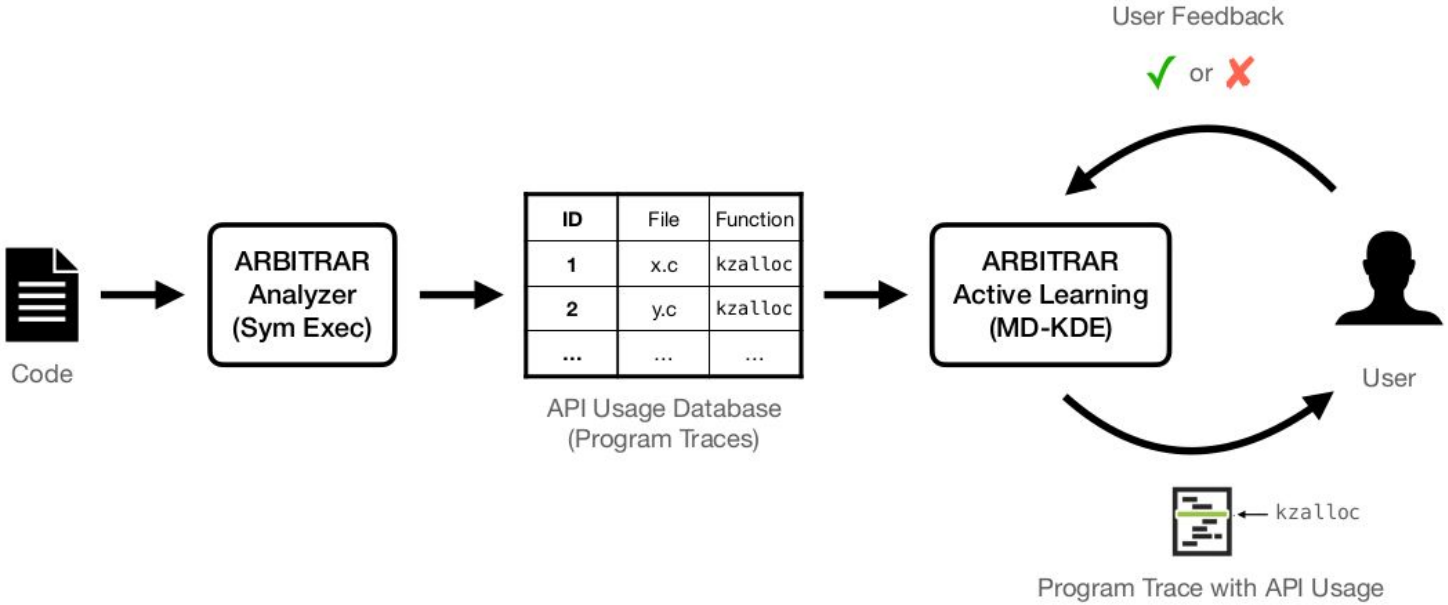
Regular Developer

Category 4: Active learning

- Can we learn from it?



Category 4: ARBITRAR: User-Guided API Misuse Detection!



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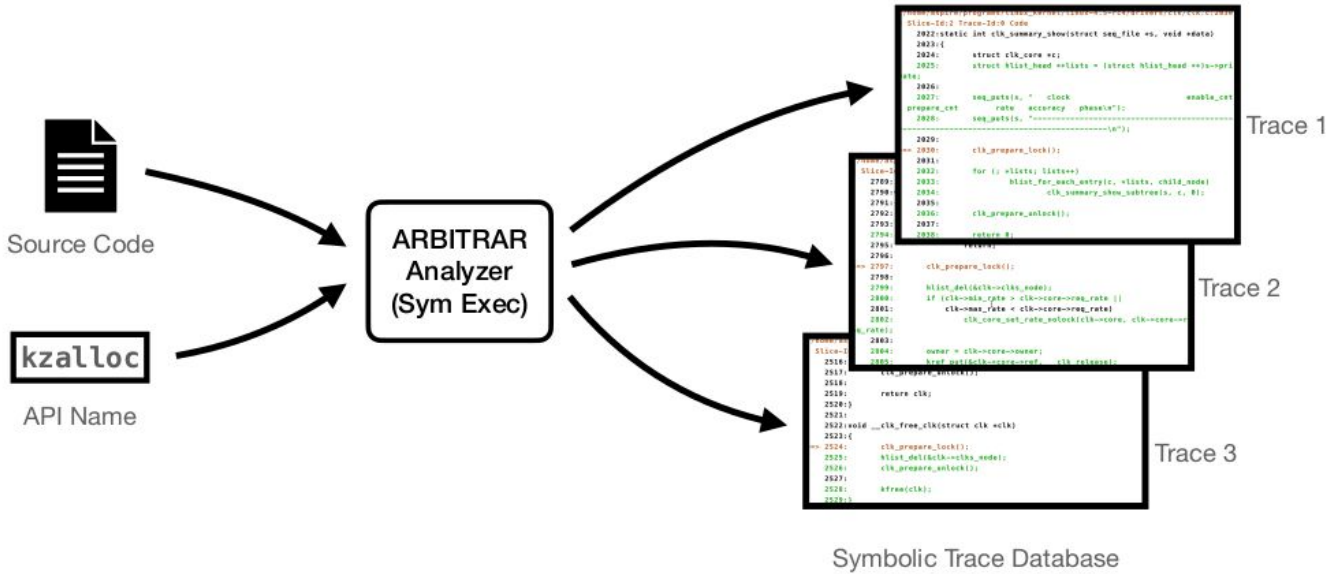

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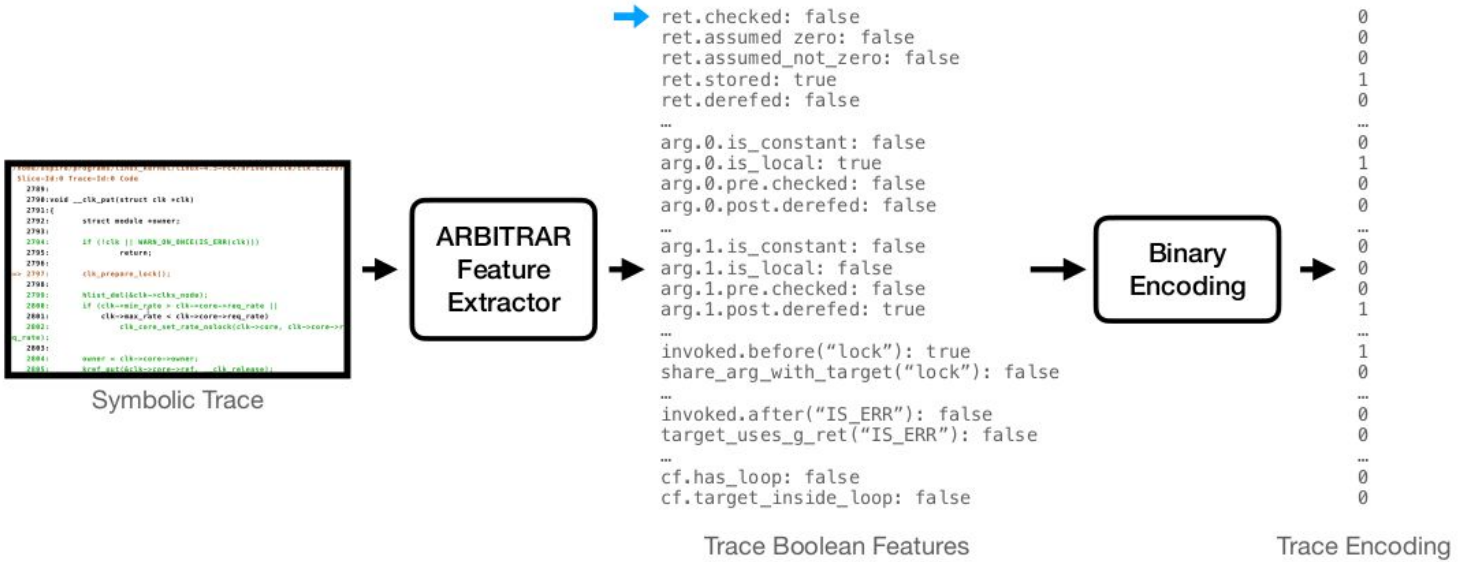

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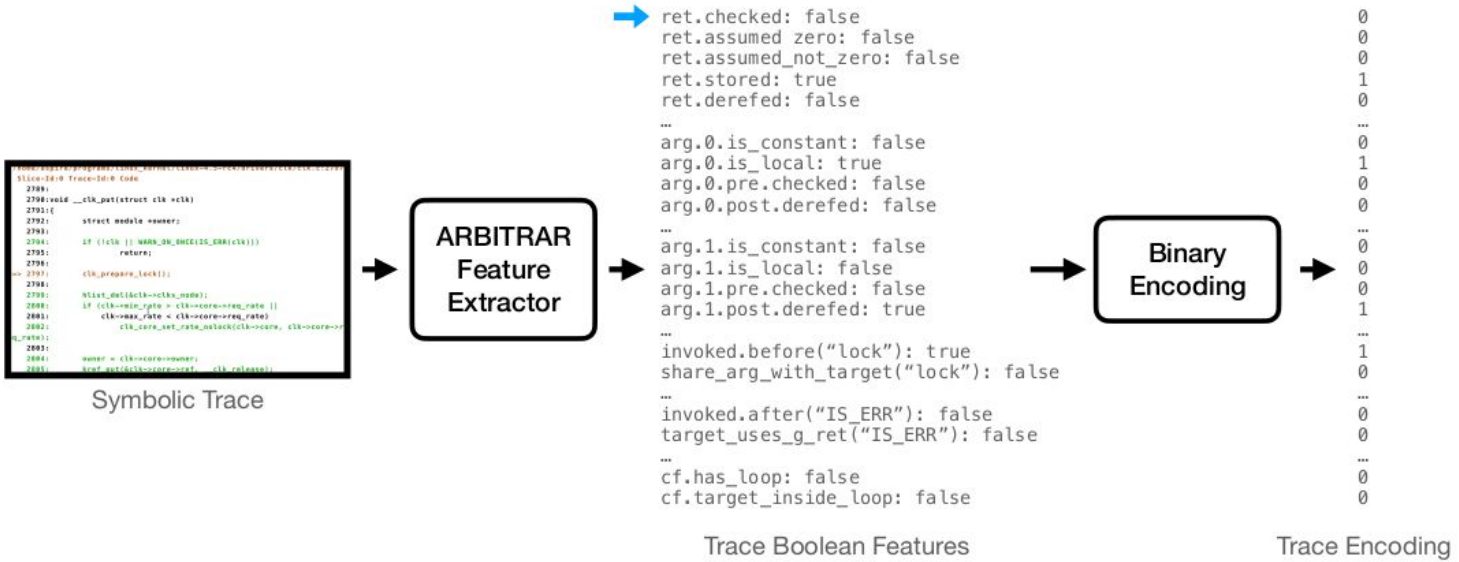

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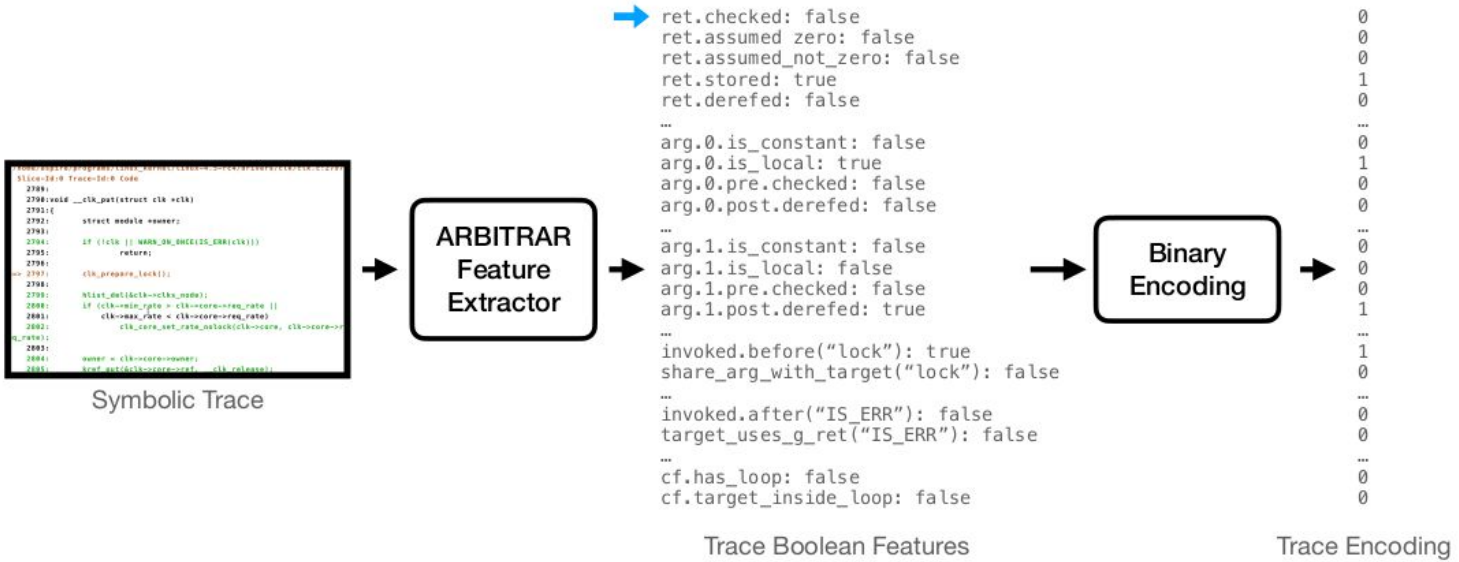

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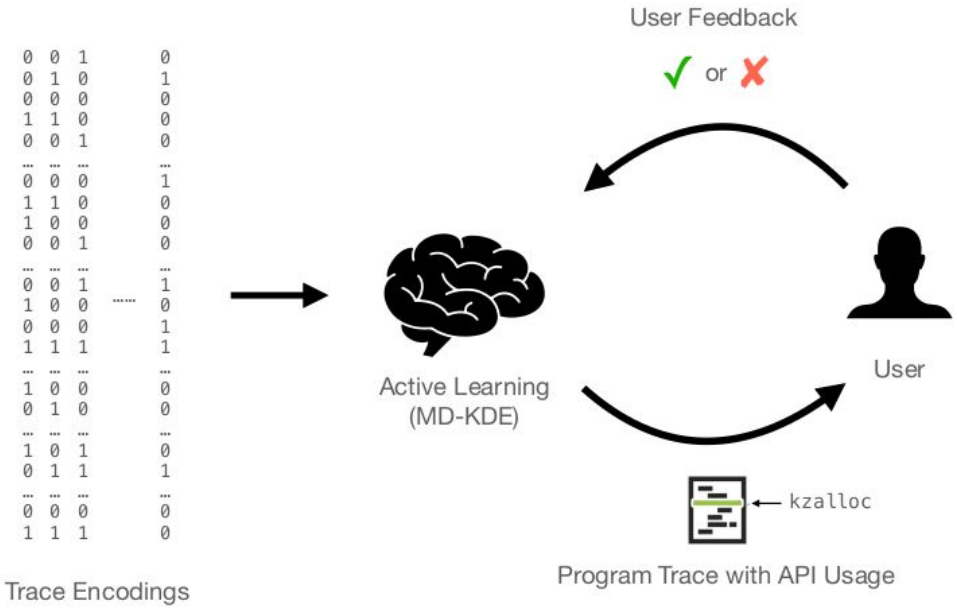

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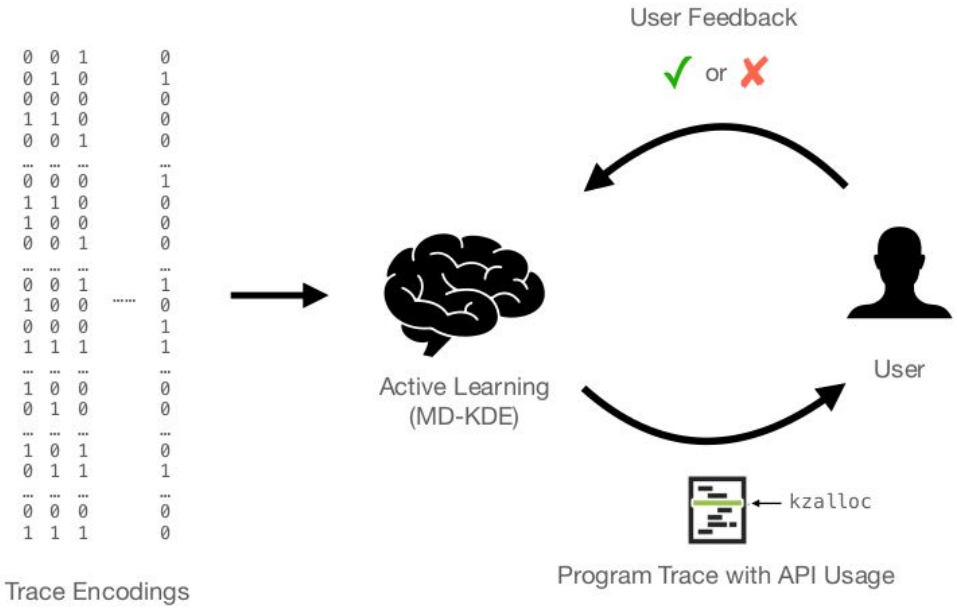
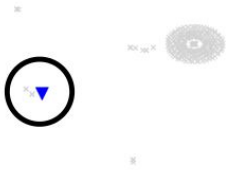
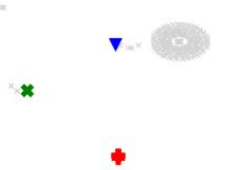
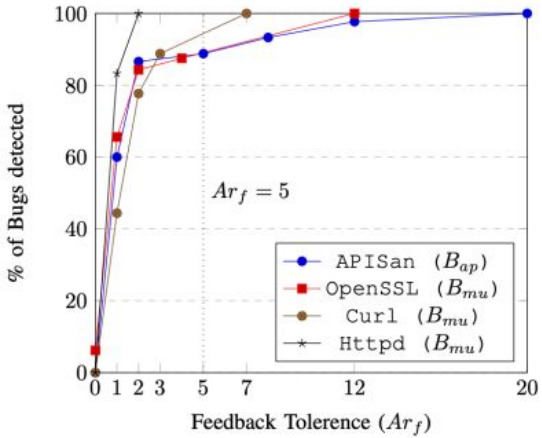


Category 4: ARBITRAR: User-Guided API Misuse Detection!

Iteration	1^{st}	2^{nd}	3^{rd}	4^{th}
Trace	libpng/png.c:4577 →png_destroy_read_struct(&c.png_ptr, &c.info_ptr, NULL); fclose(fp); return sng_error;	pngtools/pngread.c:43 →png_destroy_read_struct(&png_ptr, &info_ptr, ... png_destroy_read_struct(&png_ptr, &info_ptr,	apngasm/apngasm.c:187 →png_destroy_read_struct(&png_ptr, &info_ptr, ... png_destroy_read_struct(&png_ptr, &info_ptr,	apngasm/apngasm.c:195 →png_destroy_read_struct(&png_ptr, &info_ptr,
Info	Correct Usage: As the png_ptr and info_ptr are passed in from arguments	Invalid Usage : Double free because of multiple calls to png_destroy_read_struct	Invalid Usage : Double free because of multiple calls to png_destroy_read_struct	Normal trace
User Feedback	Not a Bug	Bug	Bug	Not a Bug
2D TSNE Plot				
Trace Acquisition	Pick a trace at random.	Pick a trace that is furthest from the previous negative trace.	Pick a trace that is closest to the known positive trace.	Pick a trace that is furthest from the negative trace and closest to the positive trace.

Category 4: ARBITRAR: User-Guided API Misuse Detection!

How quickly did we find bugs? **85% of the bugs were found with first 2 tries.**



Machine Learning Based Methods

- Features depends on bug types:
  - Syntactic v/s semantic features.
- Need large labelled dataset.
- Should have explainable results.
- Interactive techniques should be explored.