Static Program Analysis Meets Test Case Generation

Maria Christakis

MPI-SWS, Germany

About me

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Greece

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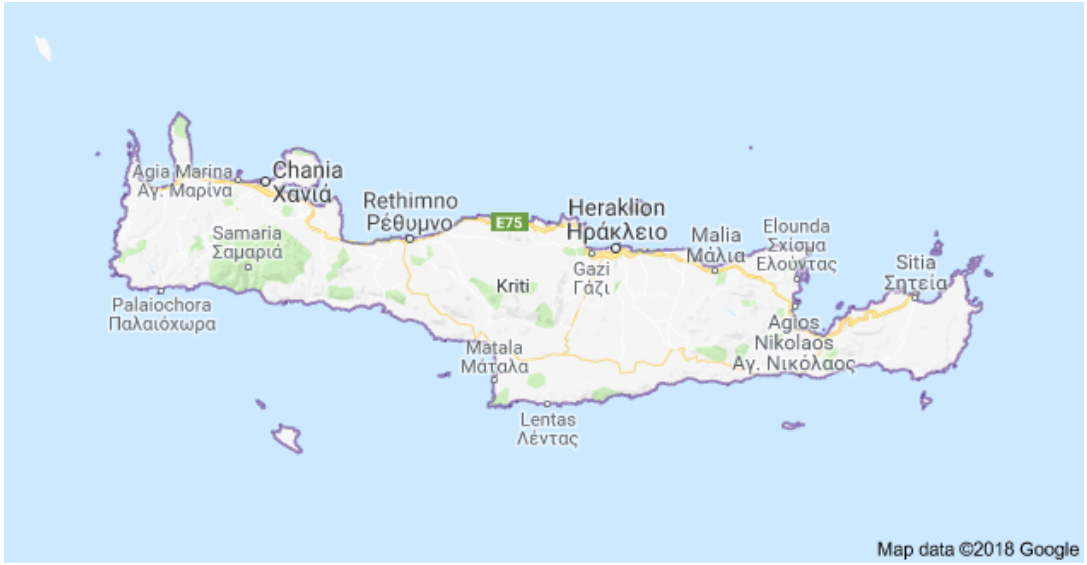

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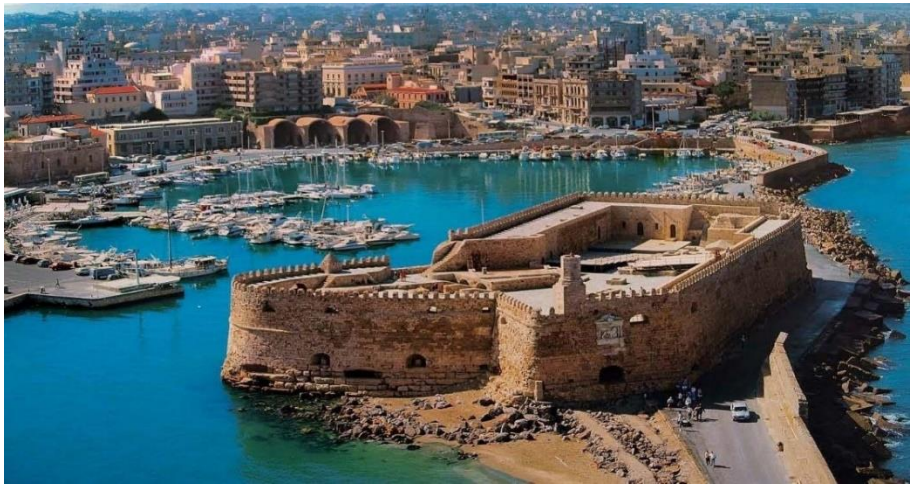

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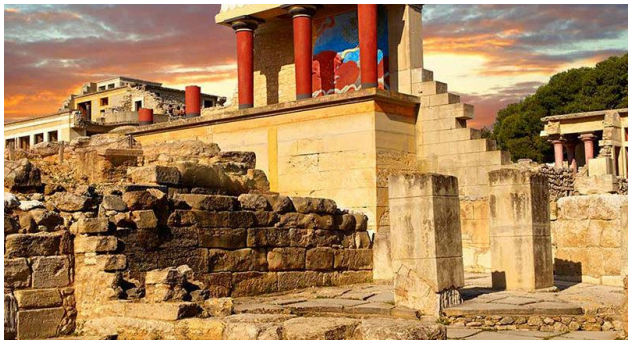

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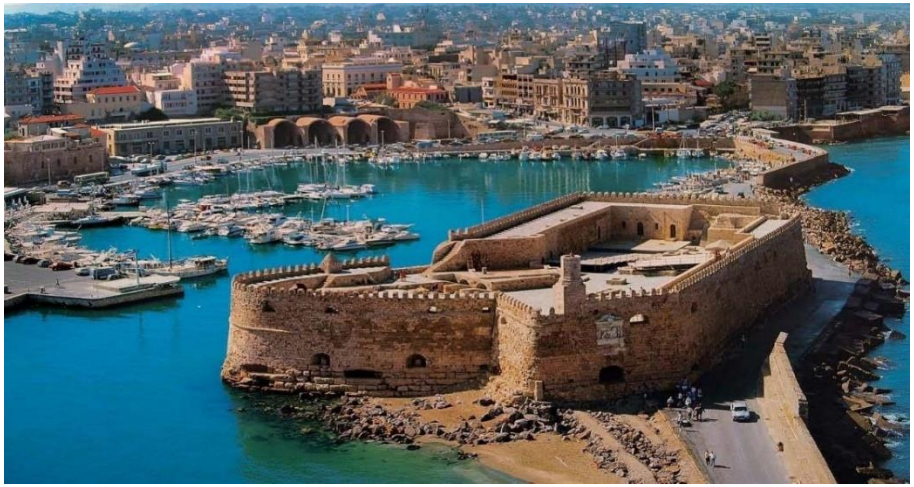

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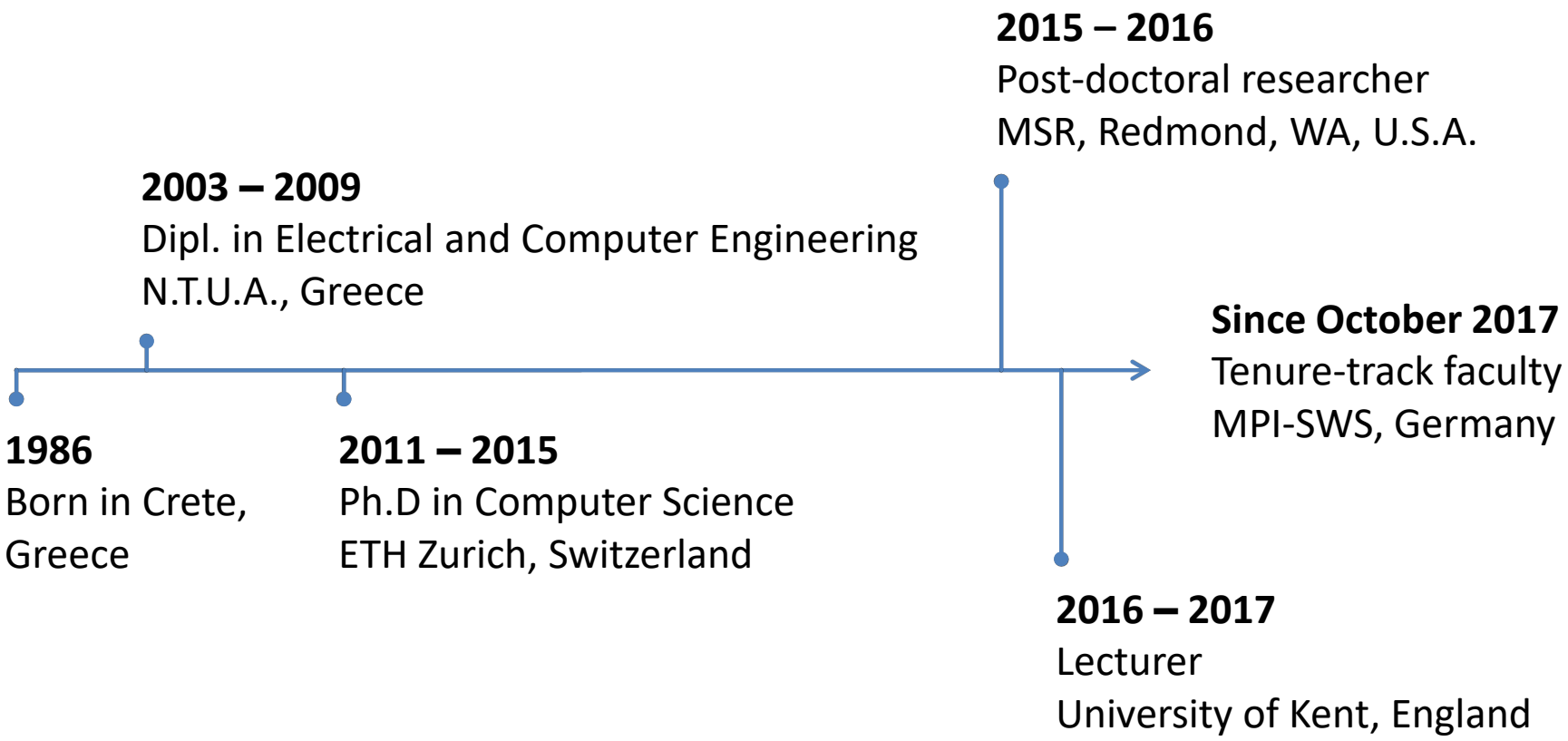
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Practical formal methods

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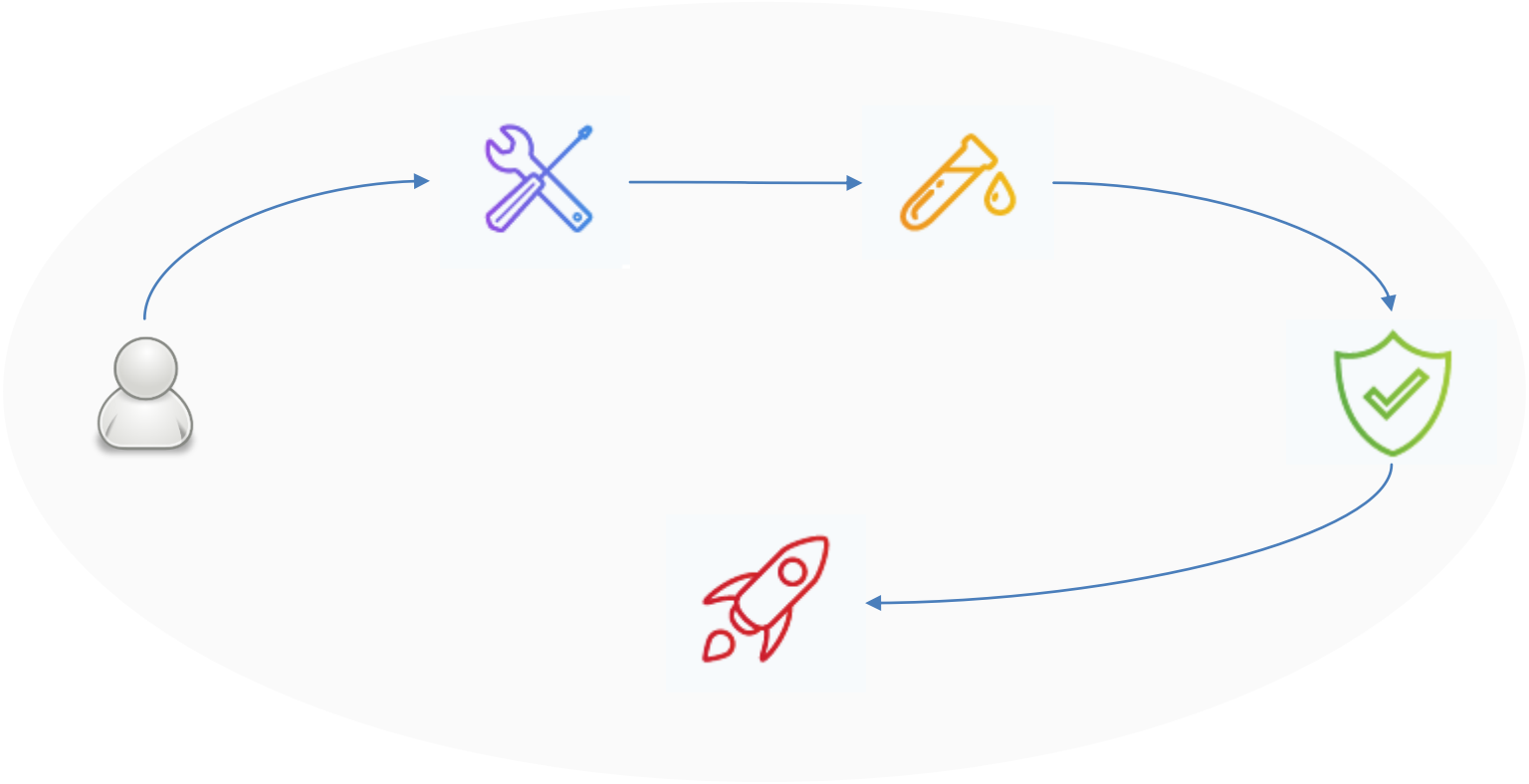
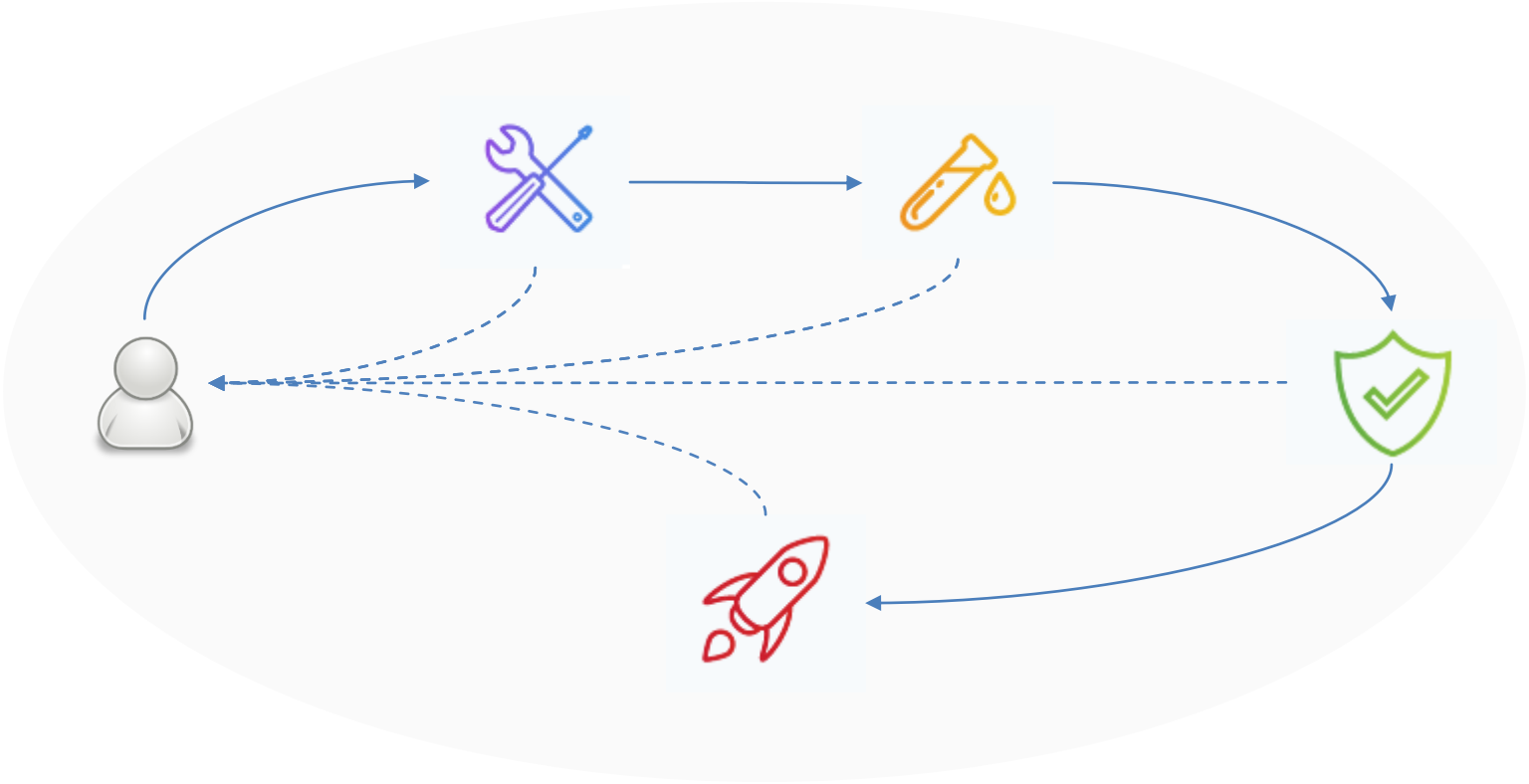


Practical formal methods



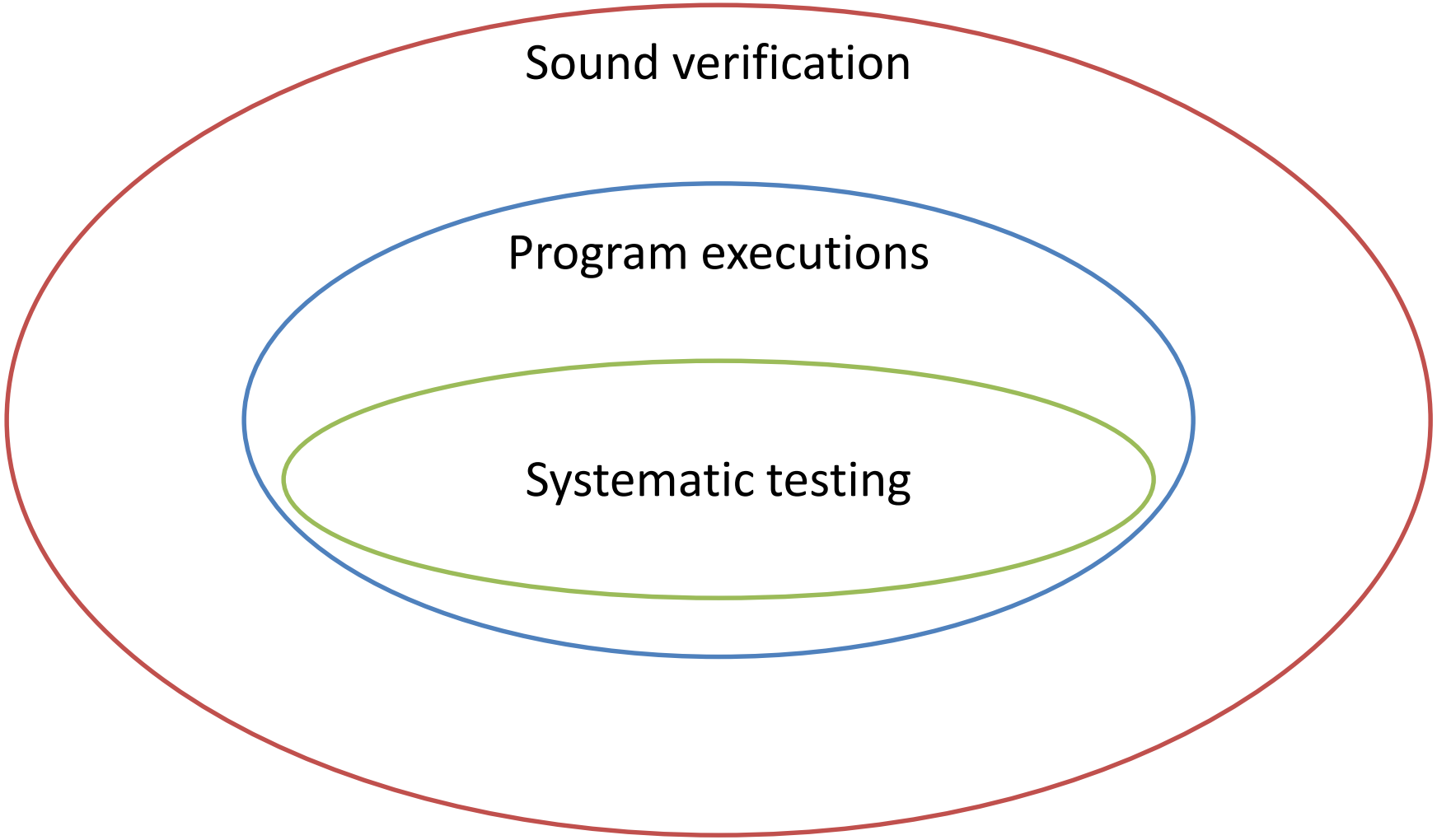
Our research mission

- Build more reliable software while increasing developer productivity
  - Formal foundation
  - Wide applicability
  - Strong practical impact

Our methodology

- Software engineering and formal methods
  - Automatic test generation
  - Program analysis and verification
  - Human-computer interaction
  - Empirical evaluation

Verification and testing



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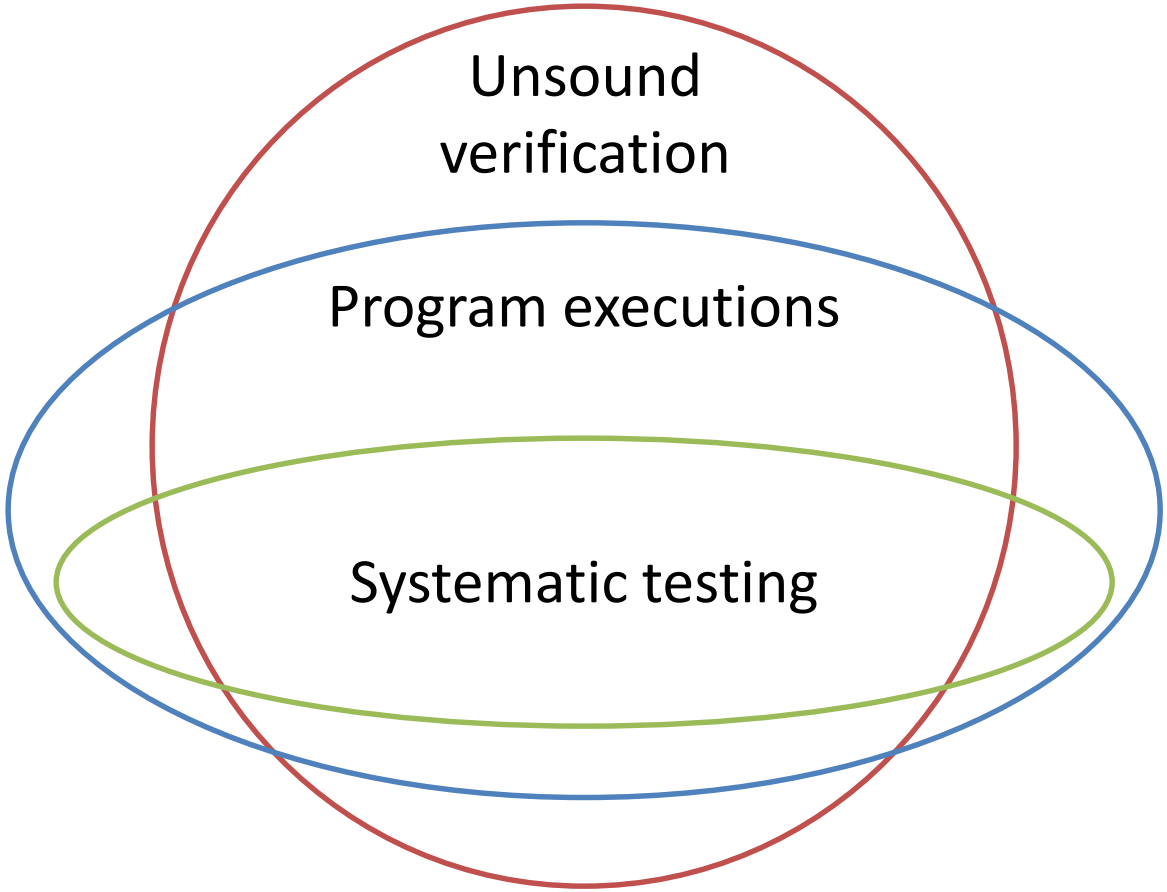
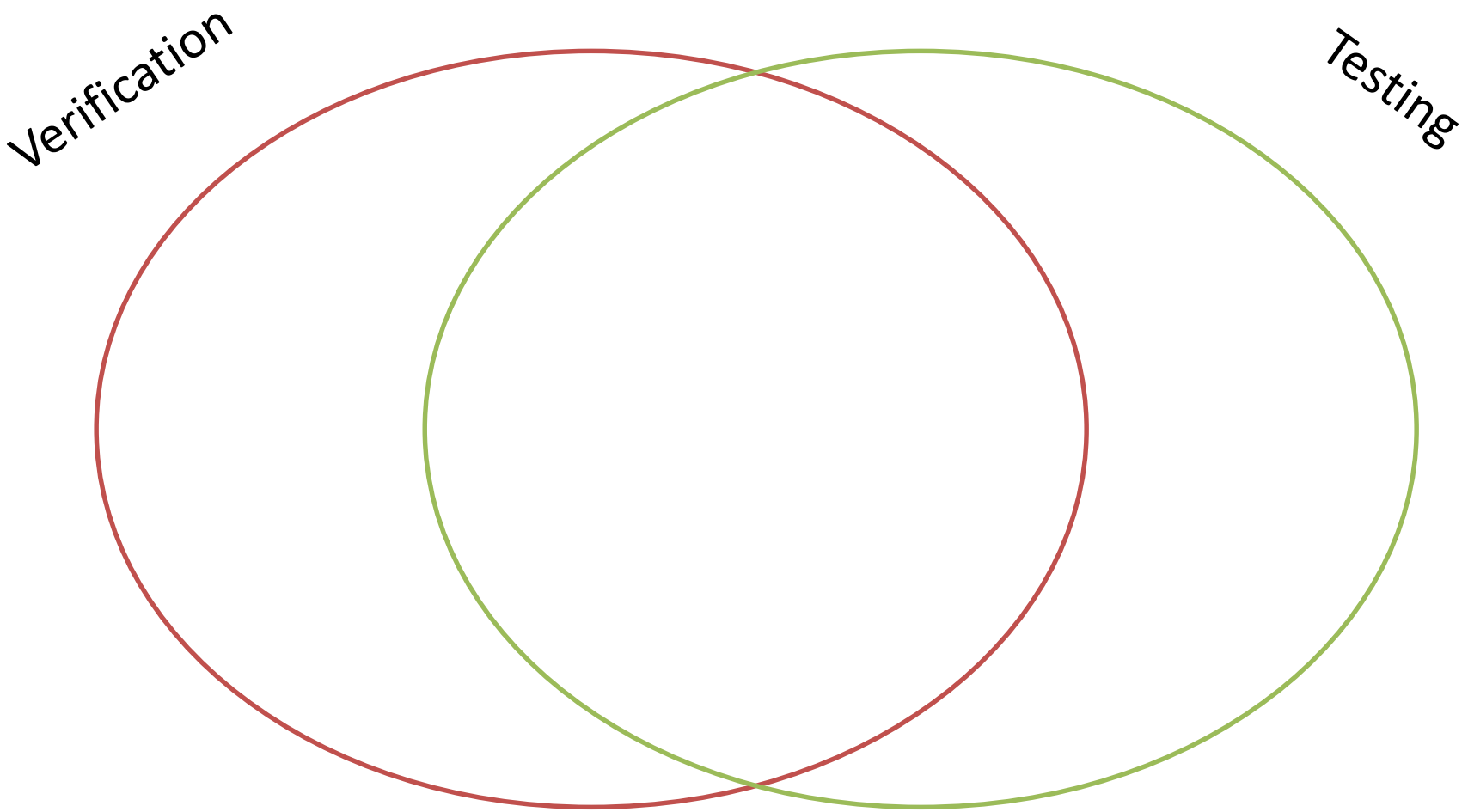
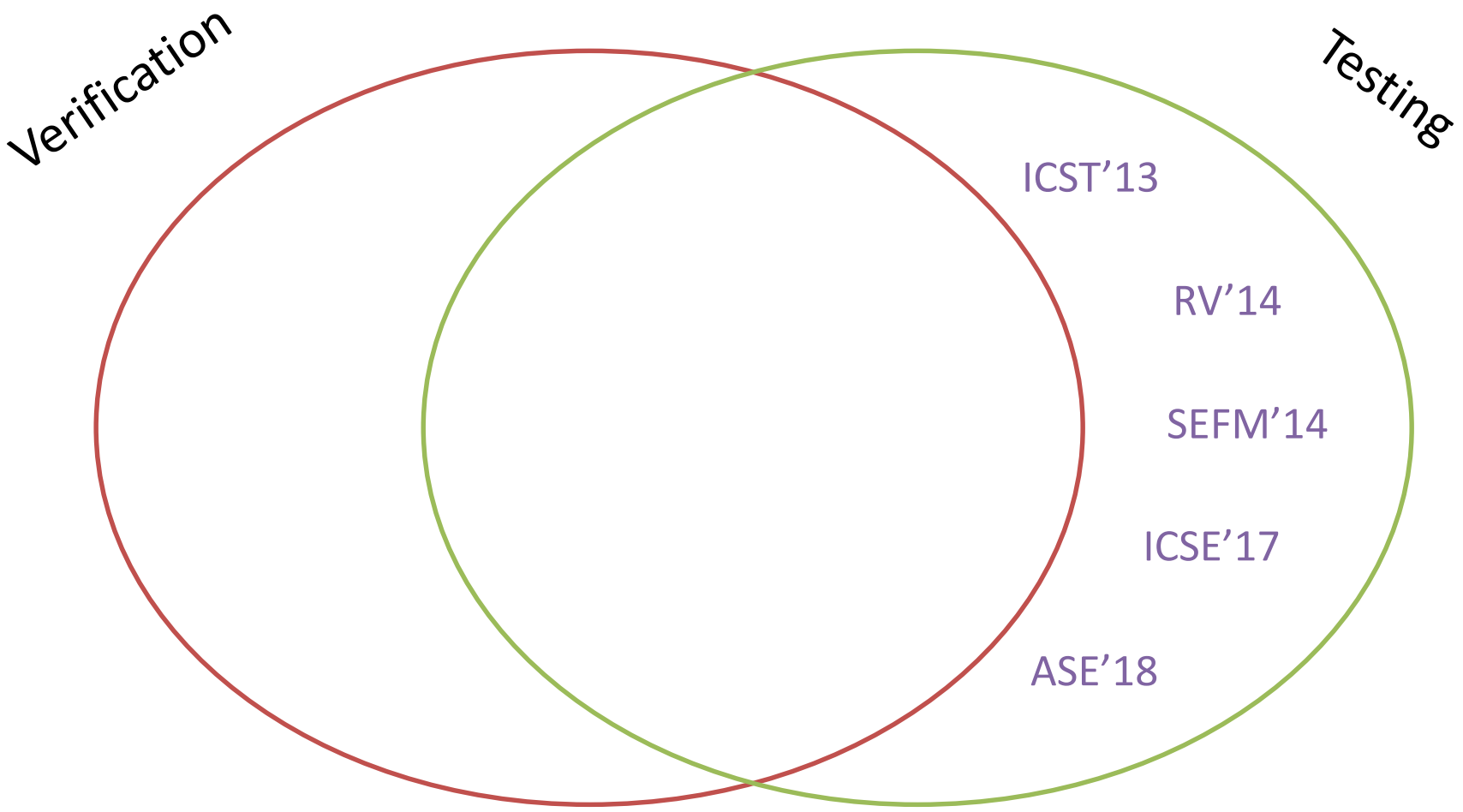
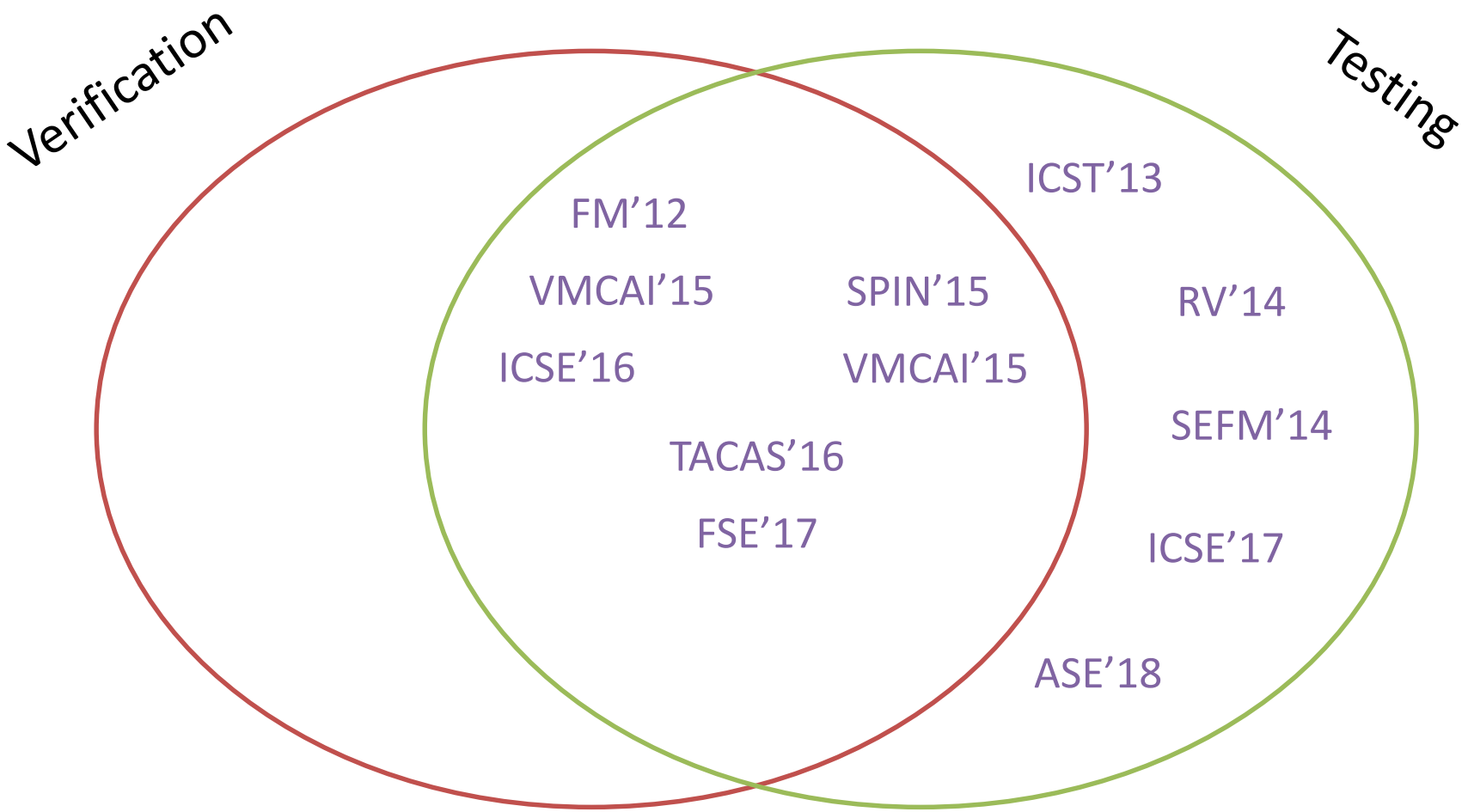



Verification
Testing


Verification
Testing
ICST'13
RV'14
SEFM'14
ICSE'17
ASE'18


Verification
Testing
FM'12
VMCAI'15
ICSE'16
SPIN'15
VMCAI'15
TACAS'16
FSE'17
ICST'13
RV'14
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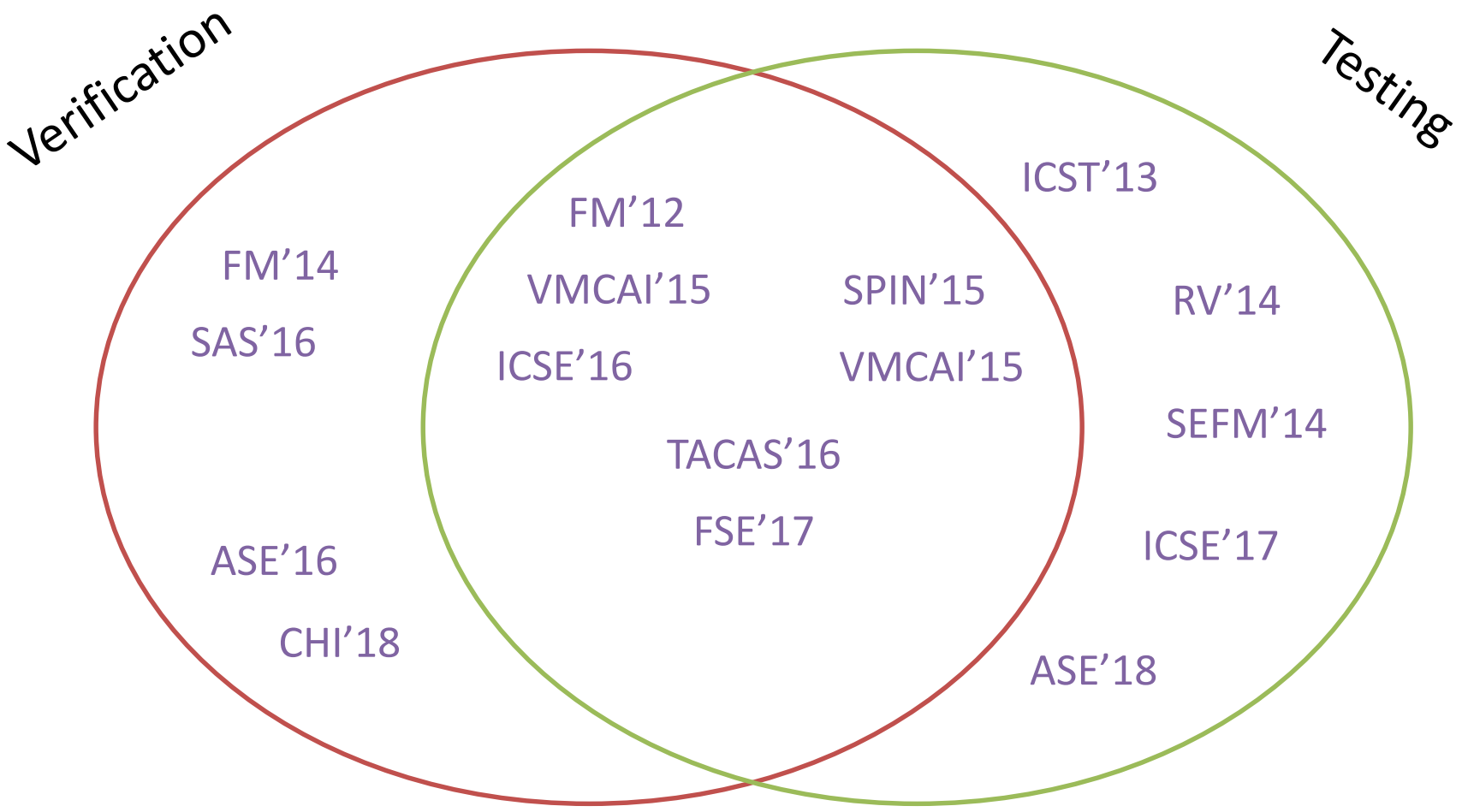
Verification
Testing
FM'14
SAS'16
ASE'16
CHI'18
FM'12
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RV'14
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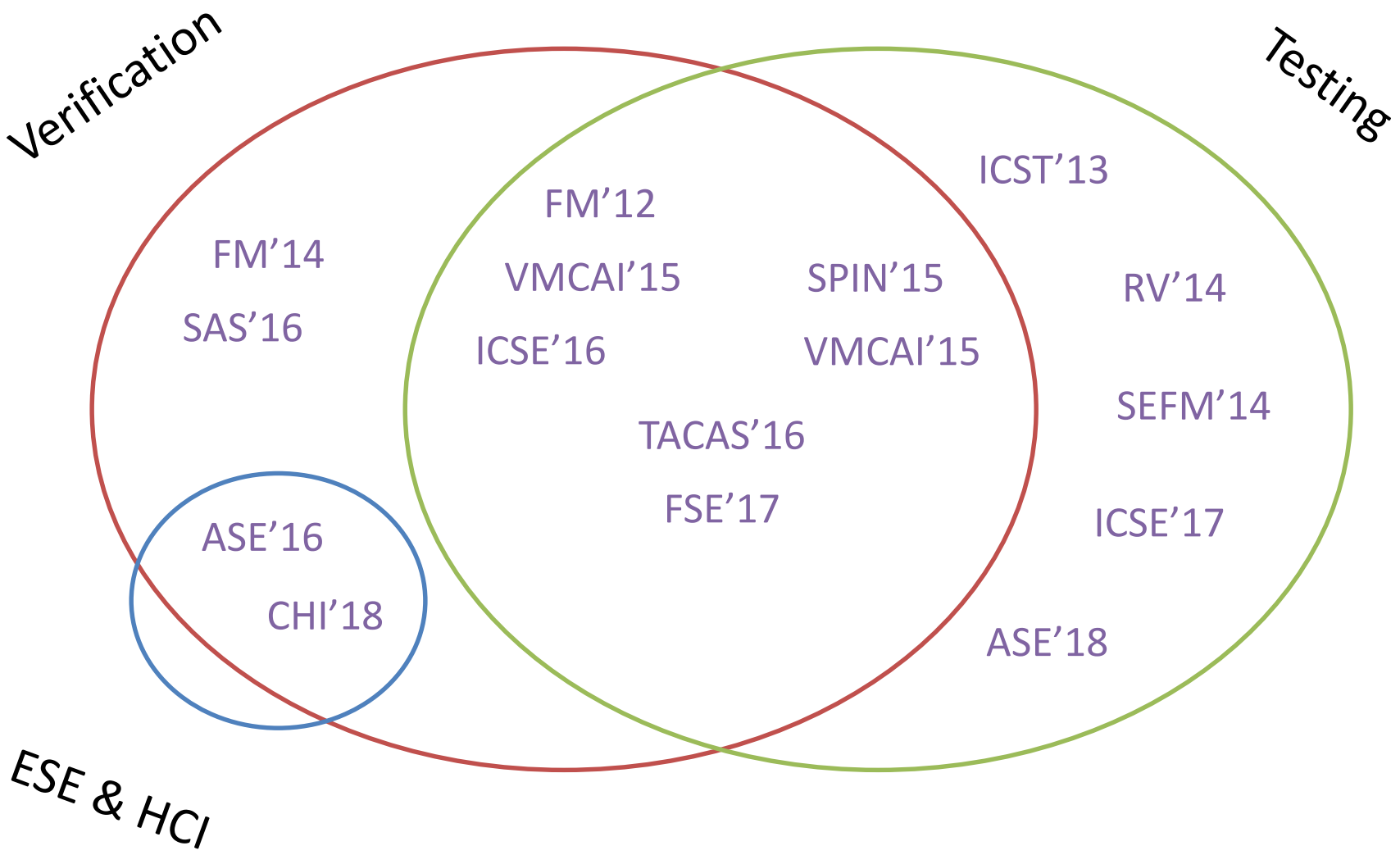
Verification
Testing
ESE & HCI
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SAS'16
FM'12
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Static Program Analysis Meets *Test Case Generation*
Lecture 1

Textbook:
Test Case Generation

Test case generation

- Detects bugs and security vulnerabilities
- Improves software quality
- Is cumbersome when done manually

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- Improves software quality
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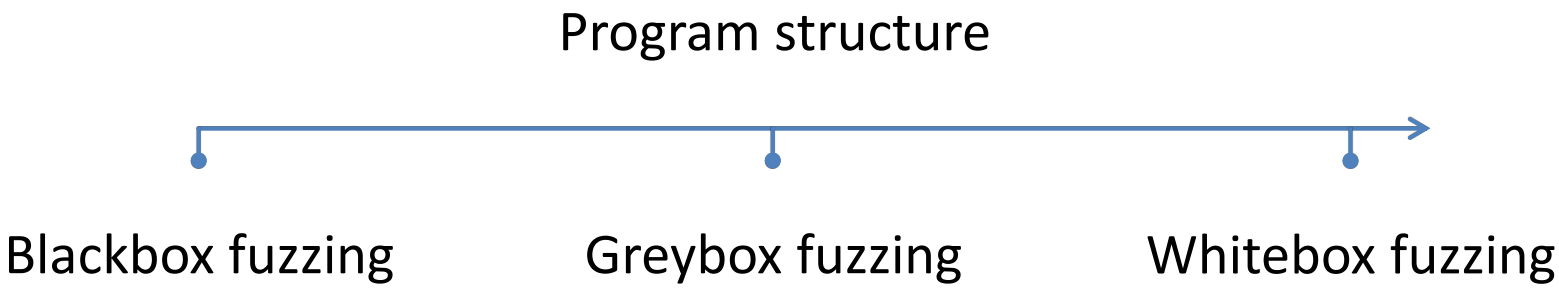
Characteristics

- Does not cover all program executions
- Does not generate false positives

Test case generation

- Detects bugs and security vulnerabilities
- Improves software quality
- Is cumbersome when done manually



Textbook:
Blackbox Fuzzing

Blackbox fuzzing

- Also called random testing

Blackbox fuzzing

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Algorithm

- Generates random inputs to a program
- Runs the program with these inputs
- Checks whether any bugs were found

Blackbox fuzzing: Discussion

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- Practical
- Very efficient

Blackbox fuzzing: Discussion

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but…

- Very ineffective in exploring new paths

Exercise

What is the probability of a blackbox fuzzer detecting the bug?

```
void foo(int x) {
  if x == 42 { bug(); }
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$2^{32}!$

Fun:
A General Framework for Dynamic Stub Injection

Background: Stub testing

- A technique to simulate dependencies of an application

Background: Stub testing

- A technique to simulate dependencies of an application

1. Decide which functions to replace by stubs
2. For each such function, implement one or more stubs
3. For each call to such functions, decide whether to call a stub
4. For each chosen call, perform the stub injection

Our framework

- Provides a domain specific language
  - Arbitrary stub behavior and flexible injection strategies
  - Stub reuse across programming languages
- Dynamically alters any executable program
  - No need for source code
- Detected 176 crashes in 10 commercial applications

A stub injection rule

```
kernel32.dll!GetModuleFileNameW(
    hModule, lpFileName, nSize)
```

A stub injection rule

```
rule kernel32.dll!GetModuleFileNameW(
          hModule, lpFileName, nSize)
  frequency every(2);
  after {
    if (nSize < 32767) {
      SetLastError(ERROR_INSUFFICIENT_BUFFER);
      result = nSize;
    }
  }
```

A stub injection rule

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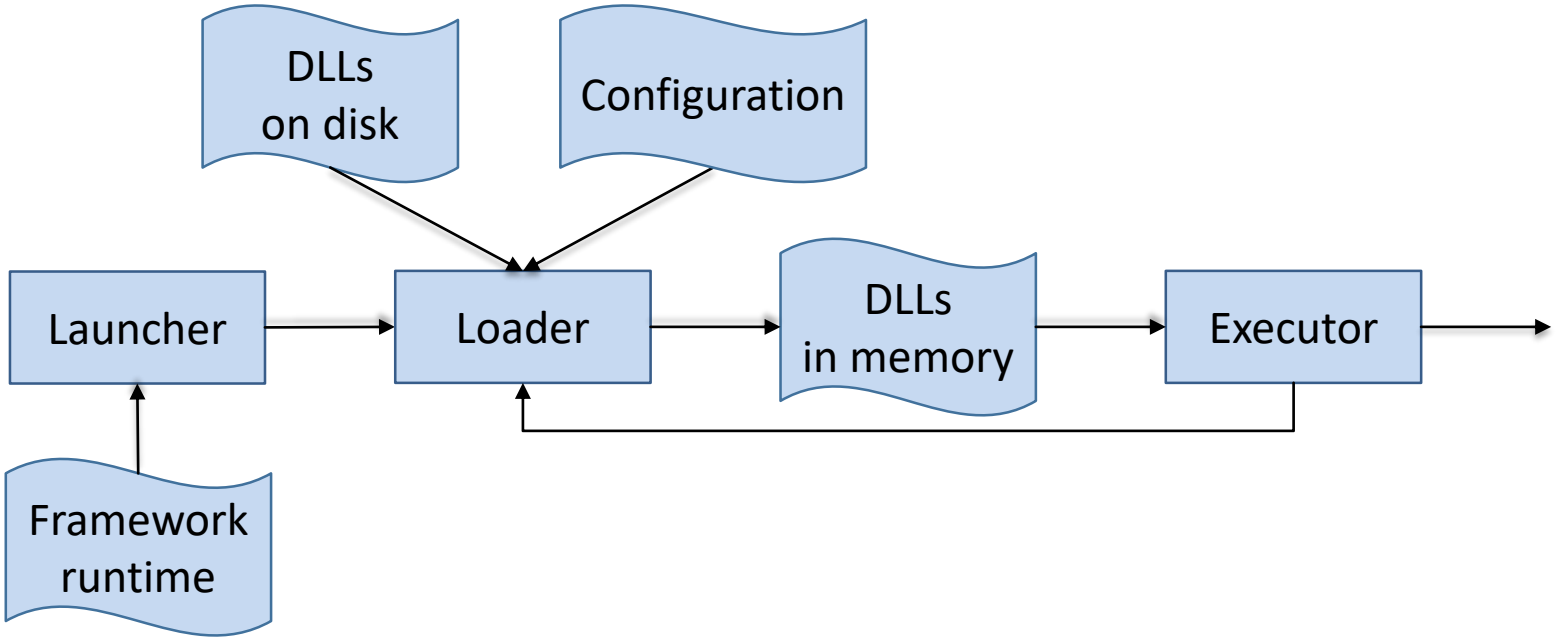
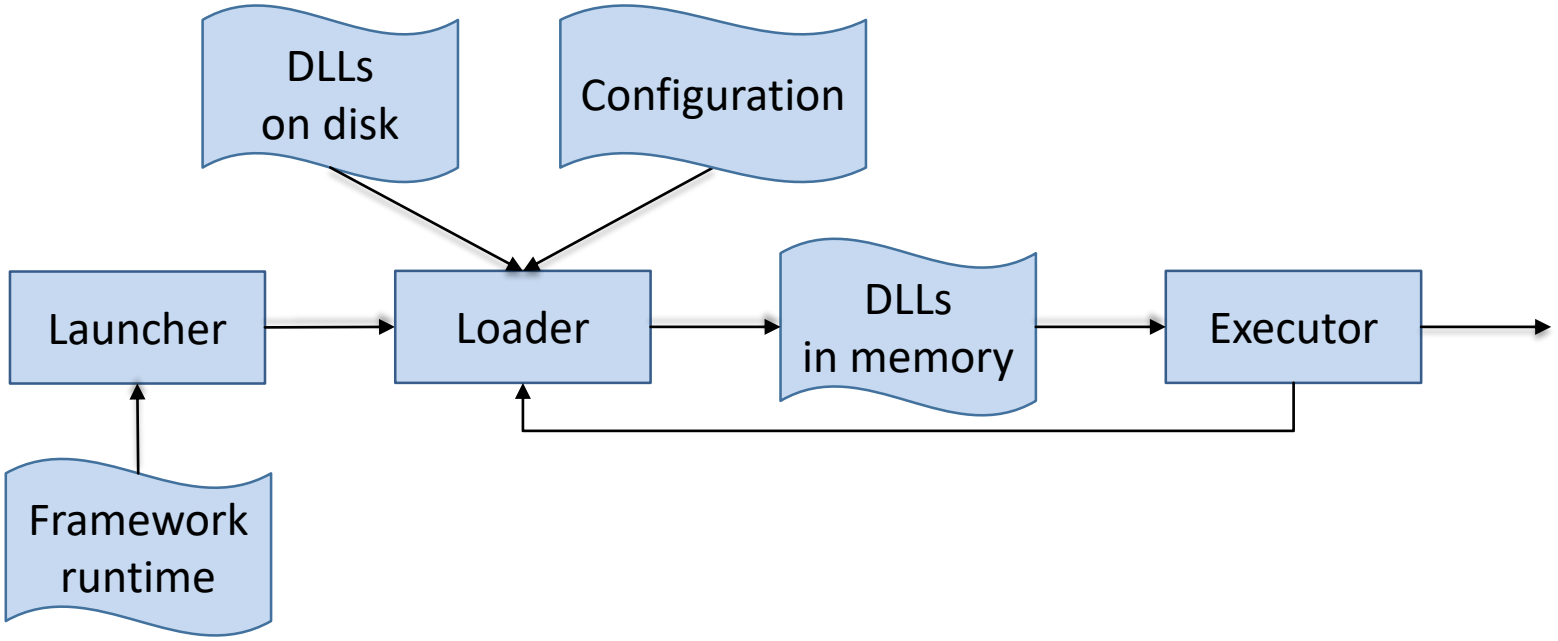
```

- A stub can have non-trivial behavior
- A rule is language independent
- A stub can replace or augment the function behavior

The stub injection workflow



The stub injection workflow



- The instrumentation happens on the deployed code
- No need to know in advance which DLLs will be loaded
- Complex invocation schemes are easily handled

Experiment design: Fault injection

- Applications under test
- Test scenarios
- Stub injection rules

Experiment design: Fault injection

- Applications under test
- Test scenarios
- Stub injection rules

Internet Explorer Microsoft Excel

Microsoft Notepad

Microsoft OneNote Launcher

Microsoft Outlook Microsoft Paint

Microsoft PowerPoint

Microsoft Publisher

Microsoft Visio Microsoft Word

Notepad++ Skype for Business

Experiment design: Fault injection

- Applications under test
- Test scenarios

Start → Wait → Close

- Stub injection rules

Design: Stub injection rules

- Target functions
  - Requesting new resources
  - Accessing external resources
- Injection strategy
- Stub behavior

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Always
Once
EveryOtherCall
FiftyFifty

Design: Stub injection rules

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MSDN StackOverflow

Result highlights

- 160 rules (40 target functions x 4 injection strategies)
- 1,920 runs (160 rules x 12 applications)

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- 160 rules (40 target functions x 4 injection strategies)
- 1,920 runs (160 rules x 12 applications)
- 176 crashes in 10 applications
- 390,571 instrumented calls
- 140,621 stubbed calls

Results: Injection strategies

- All injection strategies detected crashes
- Always detects the most crashes, and Once the least
- Always may inject fewer stubs than EveryOtherCall and FiftyFifty
- Once detects by far the most crashes per 1,000 stubbed calls

Results: From crashes to bugs

$$rbi_i = 1 - \frac{\text{number of crashes by stubbing } f_i}{\text{number of stubbed calls to } f_i}$$

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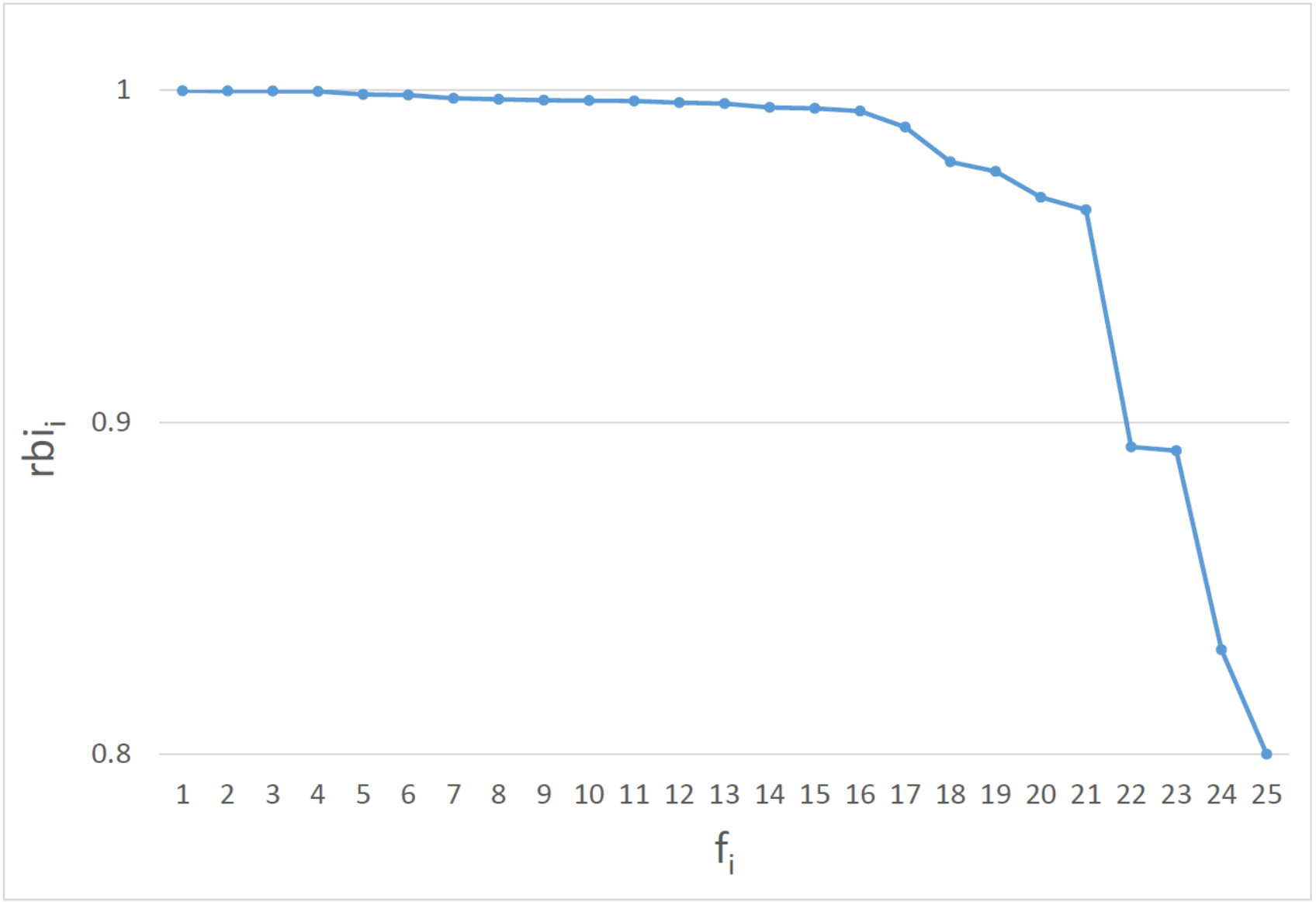
- Rules with a low rbi_i should be revised
- Developers should prioritize crashes by rules with high rbi_i
- New applications should be tested with rules with high rbi_i

Results: The real-bug indicator



Results: Bug in Excel

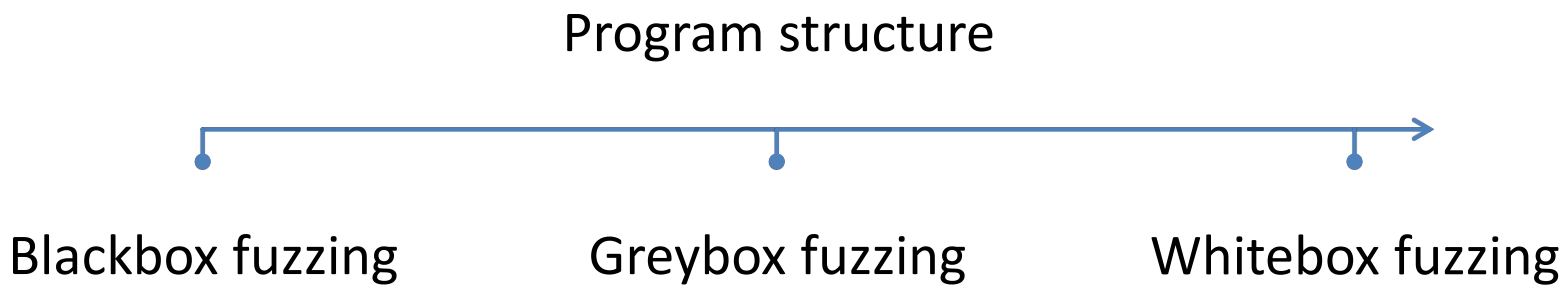
```
for (int c = 0; c < 2; c++) {
  error = RegQueryValueExW(key, /* ... */,
                           buffer, &buffer_size);
  if (ERROR_SUCCESS == error) {
    value_ptr = buffer;
    break;
  }
  else if (ERROR_MORE_DATA == error) {
    buffer.resize(buffer_size)
  }
}
assert(error == ERROR_SUCCESS);
```

Results: Rule for bug in Excel

```
rule ADVAPI32.dll!RegQueryValueExW(hKey,
            /* ... */, lpData, lpcbData)
  before {
    if (last_key != hKey) {
      last_key = hKey;
      counter = 0;
    } else {
      counter++;
    }
  }
  after {
    if (counter < 2) {
      (*lpcbData)++;
      SetLastError(ERROR_MORE_DATA);
      result = ERROR_MORE_DATA;
    }
  }
```

Textbook:
Greybox Fuzzing

Greybox fuzzing



Greybox fuzzing: Algorithm

- Runs the program with an input
- Computes the identifier of the explored path
- Mutates the input and runs the program again
- Adds the new input to the test suite,
  if a new path was explored
- Picks a new input from the test suite

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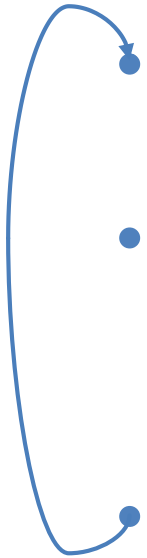

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a = -1, b = 0, c = -5
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a =  0, b = 0, c =  5
a = -1, b = 7, c = -5
```

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a =  0, b = 0, c =  5
a = -1, b = 7, c = -5
a = -1, b = 7, c = 64
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4 out of 5 paths
covered in 12 hours!

Greybox fuzzing: Discussion

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- Very practical
- Efficient

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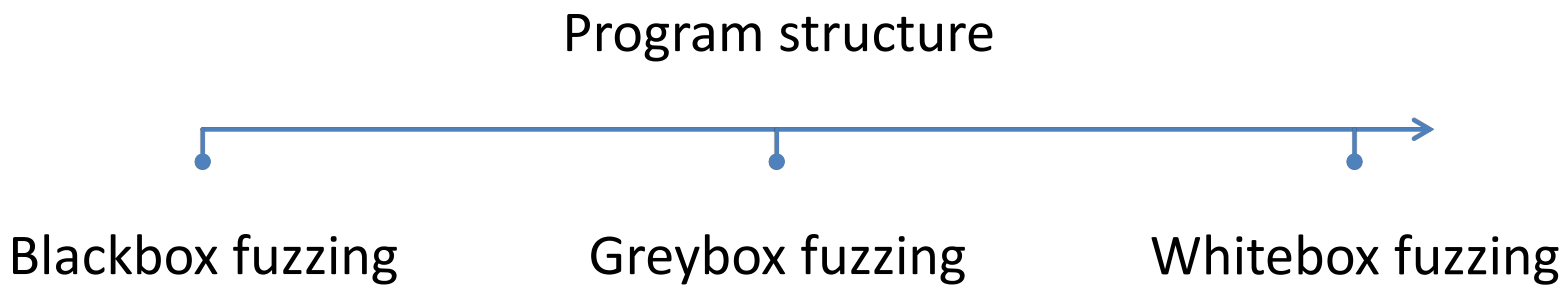
but…

- Ineffective in exploring new paths
  (Inputs are still randomly mutated)

Greybox fuzzing: Discussion



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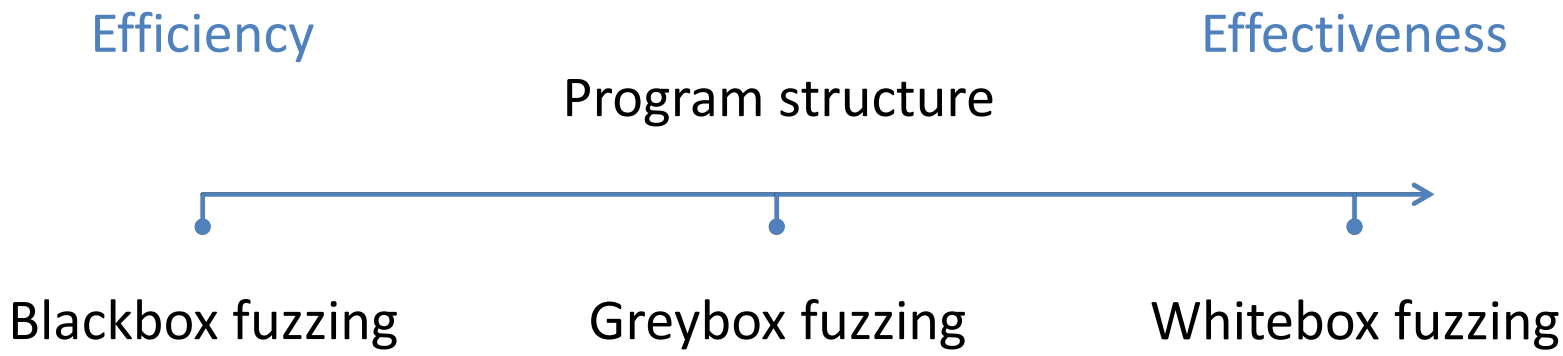
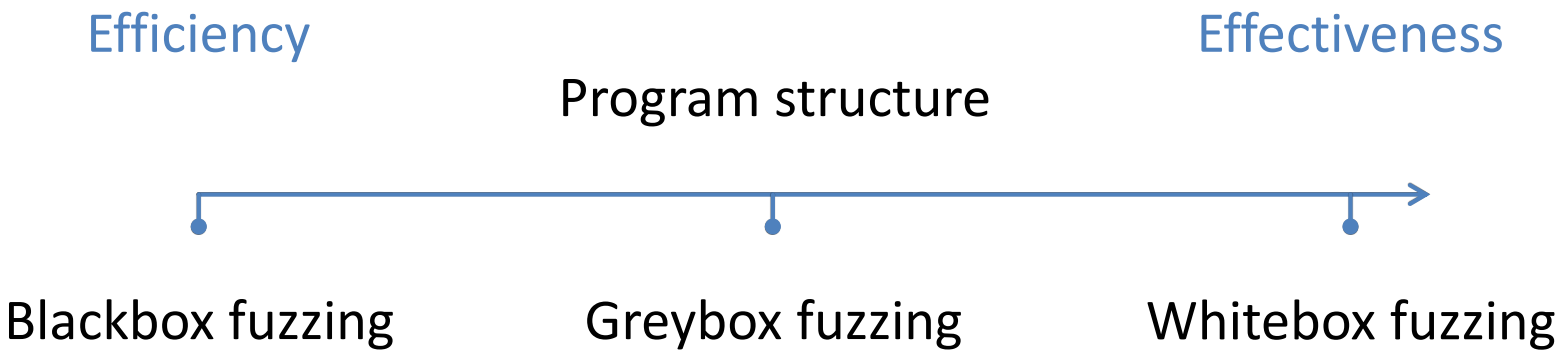
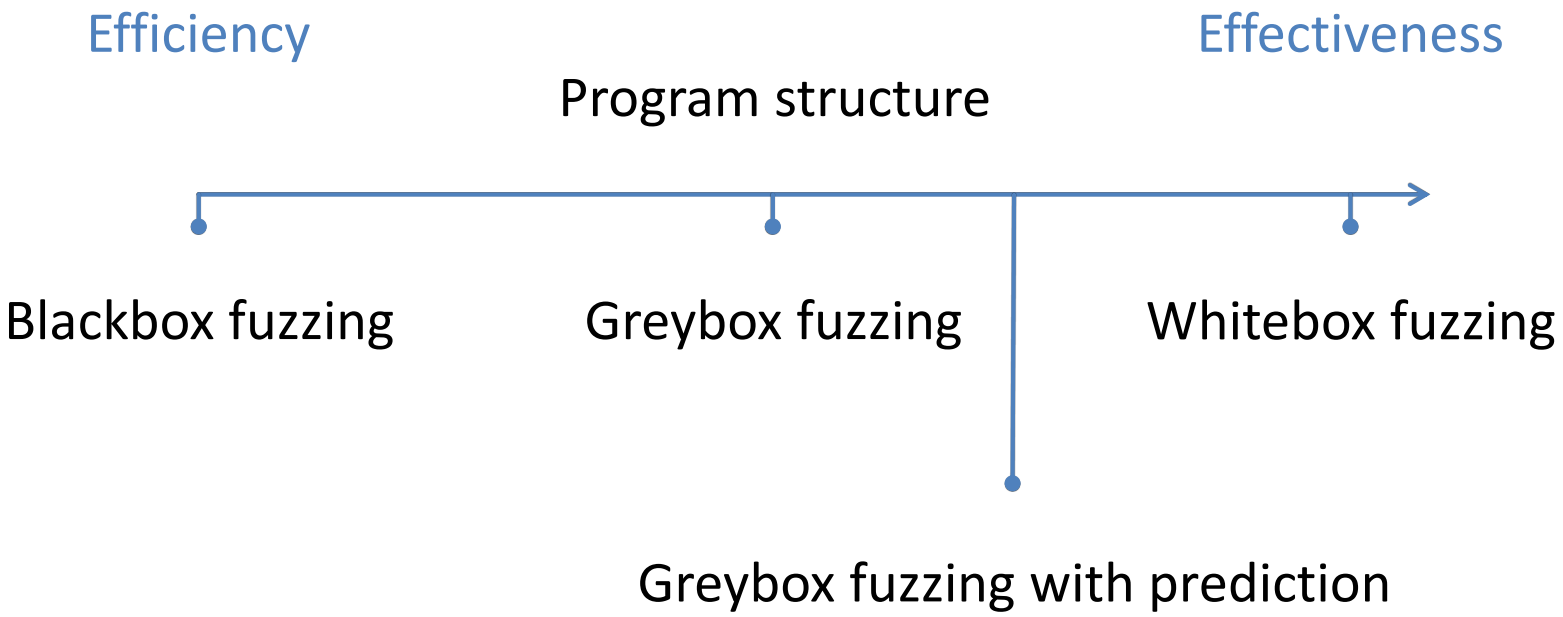


Fun:
Greybox Fuzzing with Cost-Directed Input Prediction

Greybox fuzzing



Greybox fuzzing: Input prediction



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1 - d

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1 - d

d

Input prediction: Example

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3 - b

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1) a = -1, b = 0, c = -5

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1 - d c1:6

3 - b

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`1 - d` c1:6

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```
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1 - d c1:6

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```

1 - d c1:6 c2:9

3 - b c1:3

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1 - d c1:6 c2:9

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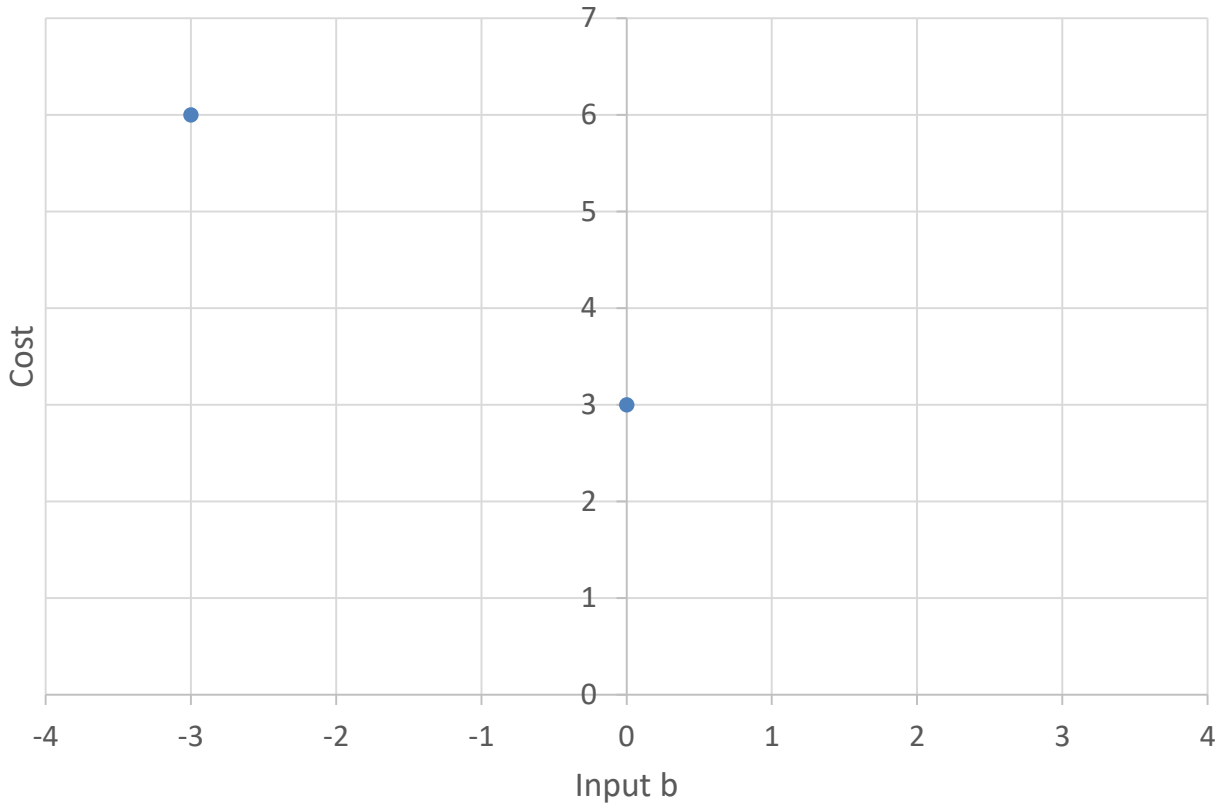

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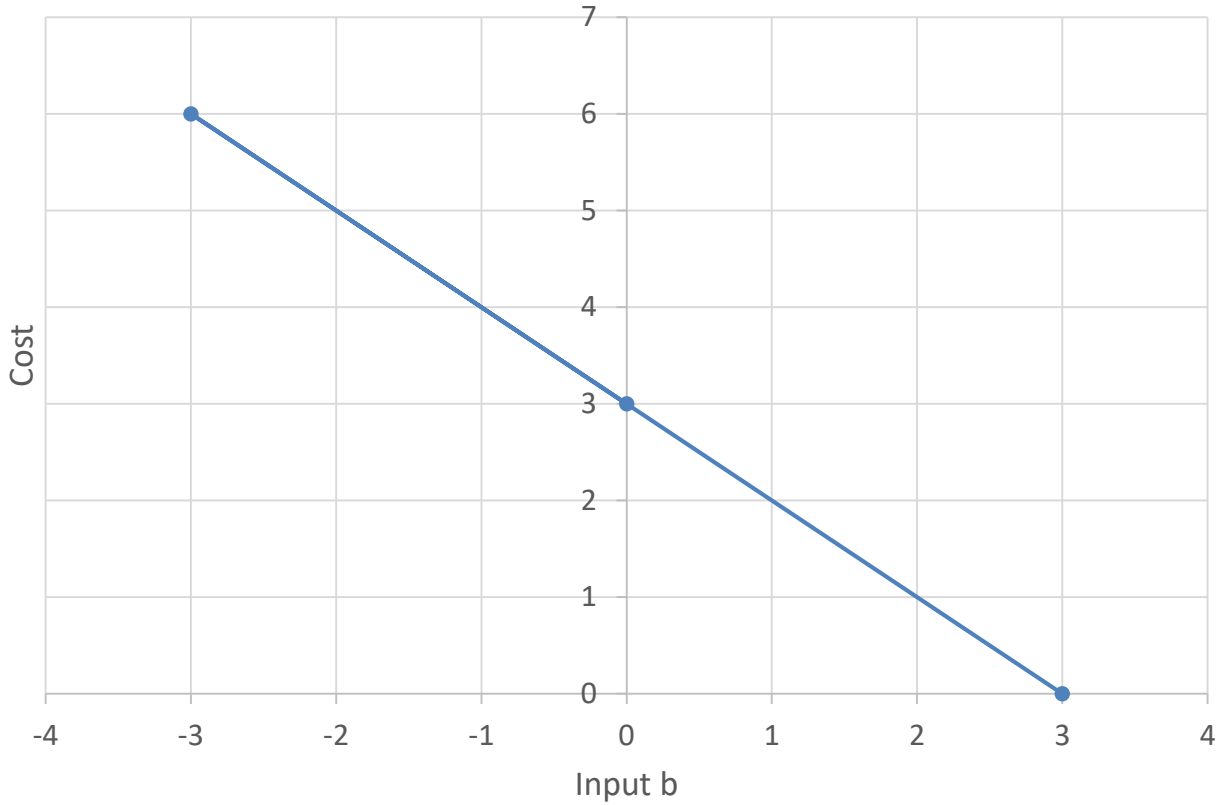

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Only 8 tests
for full path coverage!

Evaluation highlights

- Run on 26 applications, totaling 12’000 LOC
- Increased path coverage by up to 4X
- Found up to 77% more vulnerabilites, often orders-of-magnitude faster

Input prediction: Discussion

Input prediction: Discussion

- Very practical
- Efficient
- Effective in exploring new paths

Input prediction: Discussion

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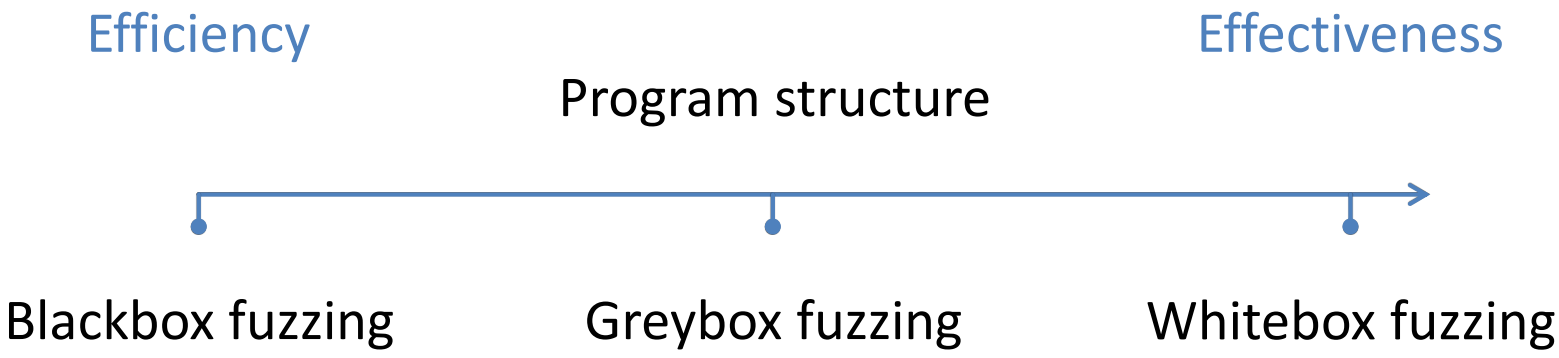
but…

- Approximate!

Textbook:
Whitebox Fuzzing

Whitebox fuzzing



Whitebox fuzzing

- Also called dynamic symbolic execution

Whitebox fuzzing

- Also called dynamic symbolic execution

Algorithm

- Runs the program concretely and symbolically
- Collects constraints on inputs at branches
- Uses a constraint solver to generate new inputs

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$b + c < 1 \wedge b < 3$

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$$b + c < 1 \wedge b \geq 3 \wedge \neg(a = 42)$$

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$b + c \geq 1 \wedge c \geq 42$

Whitebox fuzzing: Example

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but…

- Very effective in exploring new paths

Exercise

Encode the path constraints to determine the feasible paths.

```
int bar(int a, int b) {
  var c = a * b;
  if c >= 0 && b > 0 {
    var d = c / 3 + a;
    if d < 0 {
      return 1;
    }
    return 2;
  }
  return 3;
}
```

Exercise

Encode the path constraints to determine the feasible paths.

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int bar(int a, int b) {
  var c = a * b;
  if c >= 0 && b > 0 {
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    if d < 0 {
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  }
  return 3;
}
```

2 feasible paths!

Exercise

How many paths are feasible?

```
void bar(int c) {
  var i = 0;
  while i < c {
    i++;
  }
}
```

Exercise

How many paths are feasible?

```
void bar(int c) {
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```

2,147,483,647 + 1!

Fun:
Proving Memory Safety of the ANI Image Parser

Contributions

- First application of systematic testing for proving attacker memory safety
- of a complex and security-critical image parser
- using only compositional exhaustive testing
- How big is the gap between systematic testing and verification?

Attacker memory safety

- Means no attacker-controllable buffer overflows
- Is weaker than traditional memory safety
- Ignores input-independent memory accesses

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```
void buggy(int x) {
  char buf[10];
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```

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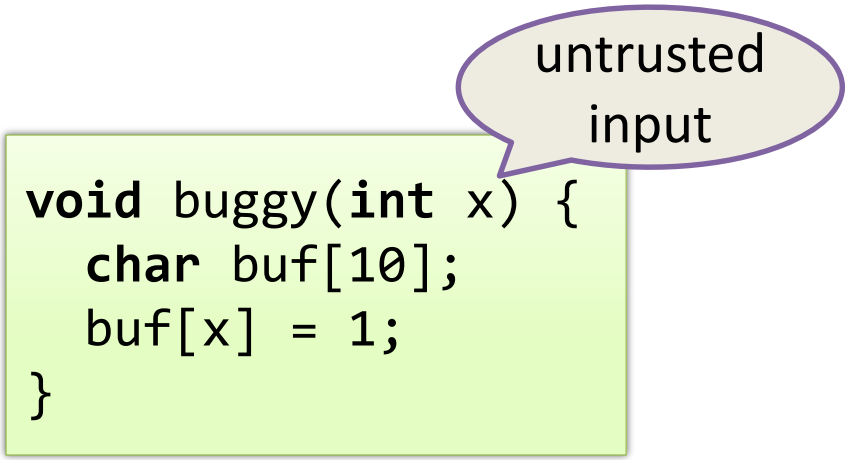

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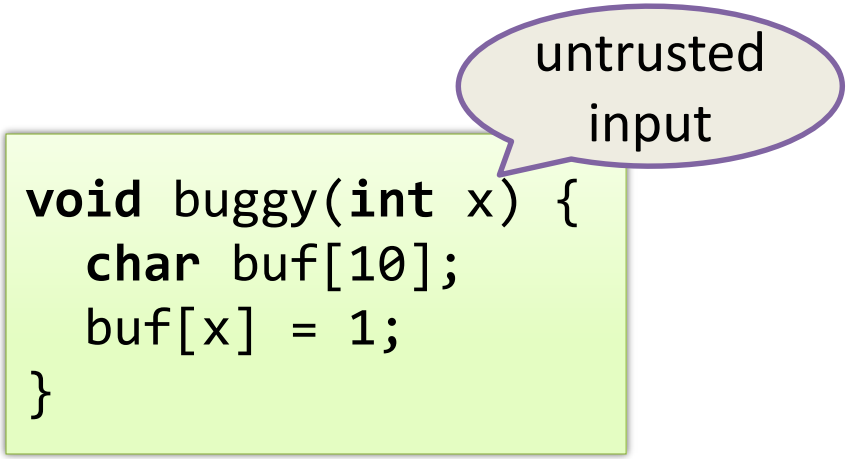

attacker memory unsafe

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untrusted input

```
void buggy(int x) {
  char buf[10];
  buf[x] = 1;
}
```

attacker memory unsafe

```
void buggy() {
  char* buf = malloc(10);
  buf[0] = 1;
}
```

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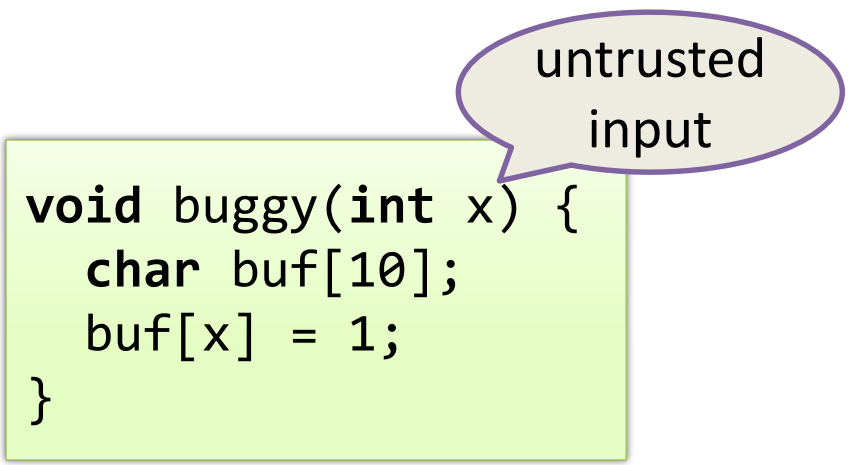

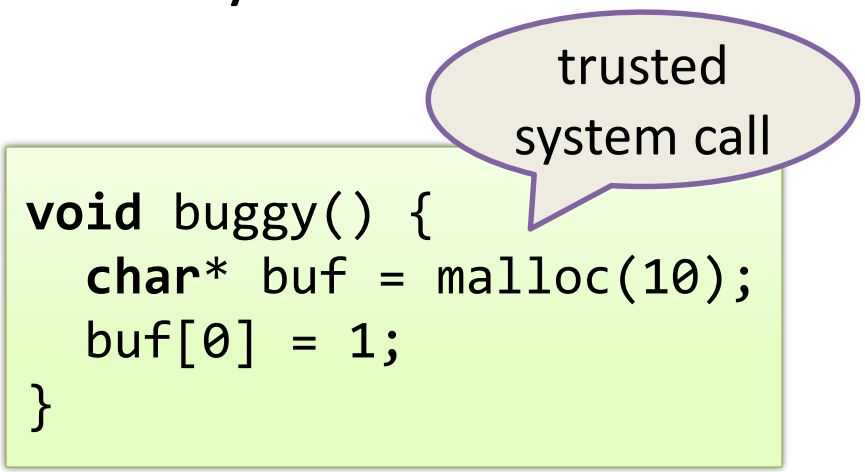

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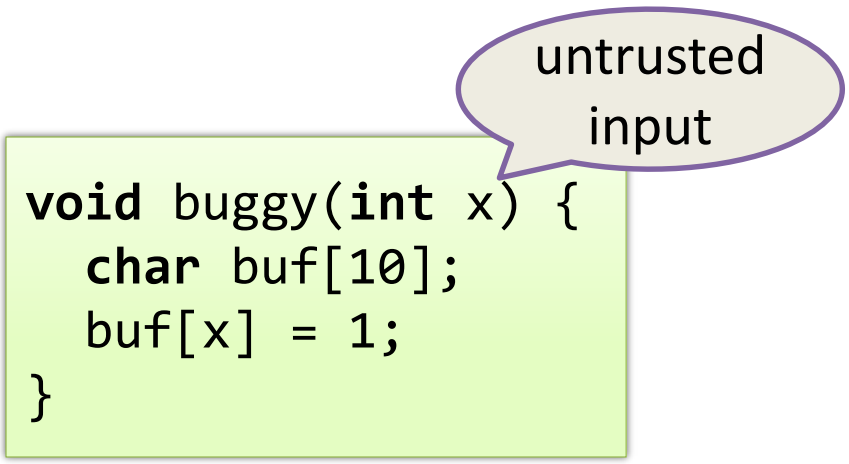
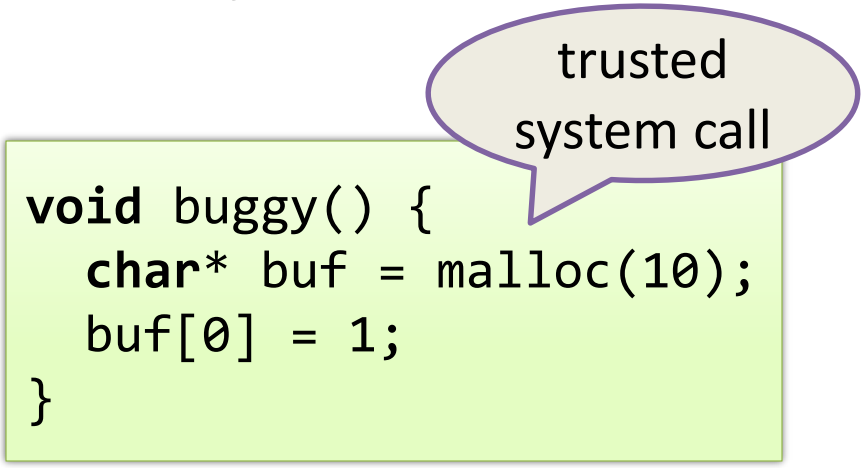
- Ignores input-independent memory accesses



attacker memory unsafe



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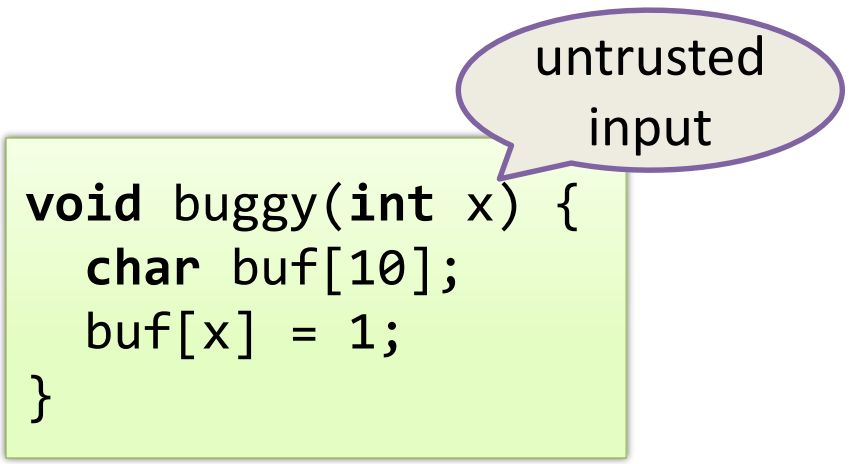

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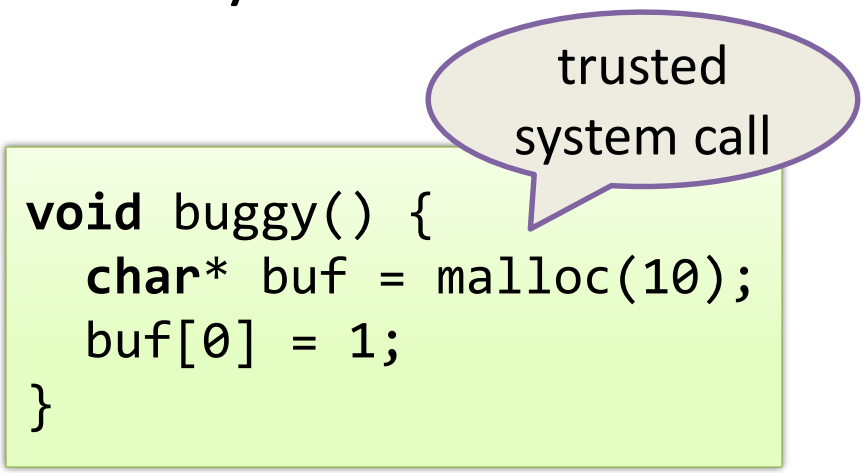


attacker memory safe
but memory unsafe

SAGE

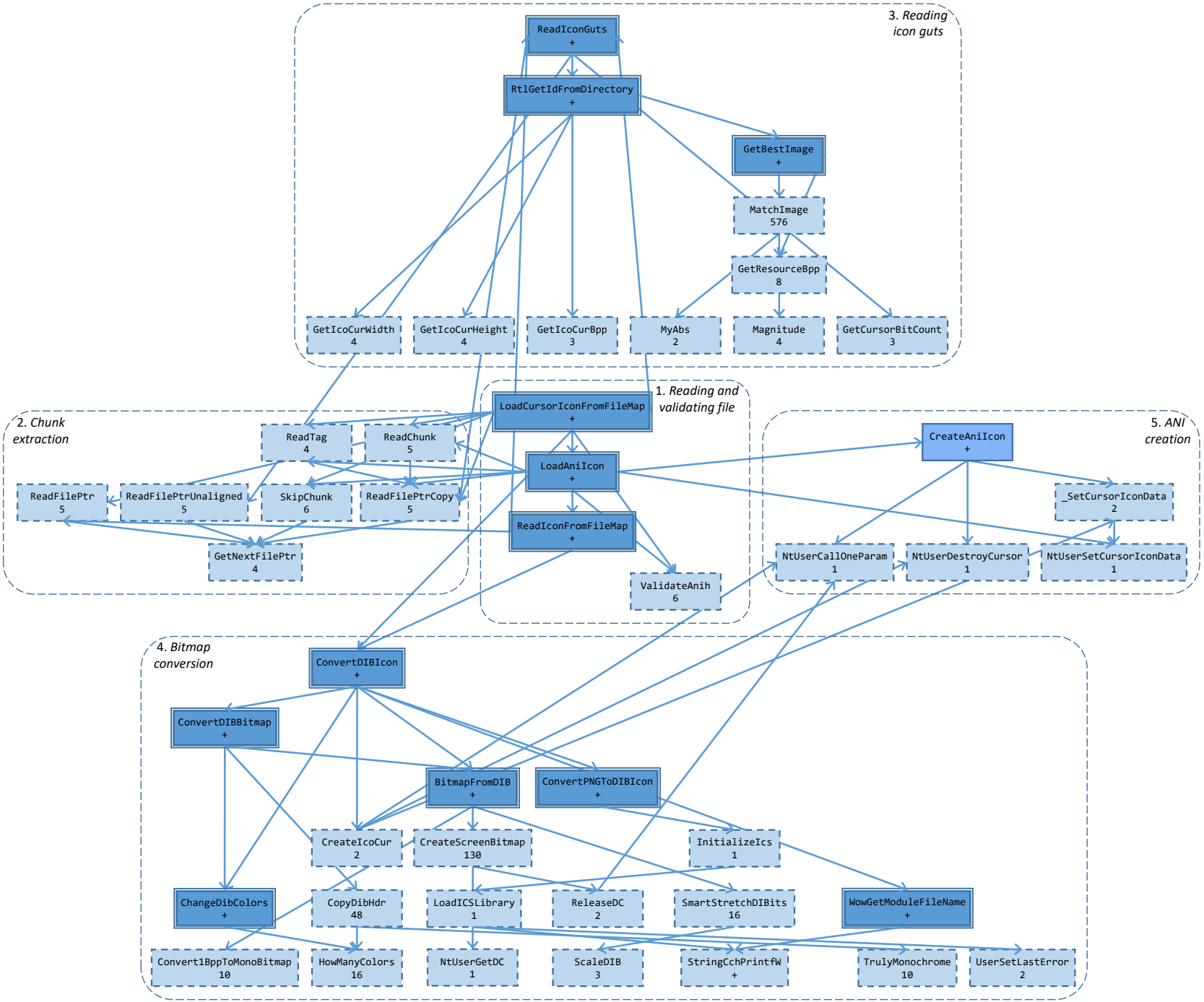
- Is a whitebox fuzzer for security testing
- Applies dynamic symbolic execution at the x86 level
- Is extensively used to fuzz several Microsoft products

Verification with testing?

- All program paths may be enumerated with dynamic symbolic execution when
  - there are finitely many paths
  - all feasible branches are explored
  - the constraint solver is sound and complete
- We turned maximum precision of SAGE on and any unsound pruning off

The ANI Windows image parser

- Implemented in C and x86 assembly
- At least 350 functions in 5 DLLs
- Testing untrusted inputs in at least 110 functions
- 47 top-level functions in `user32.dll`
- No recursion and no complex data structures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Strategies

- Stage 1: Bottom-up strategy
  - Exhaustive path enumeration and inlining
- Stage 2: Input-dependent loops
  - Restricting input-dependent loop bounds
- Stage 3: Top-down strategy
  - Summarization

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- Fixing or ignoring attacker-memory-safety bugs

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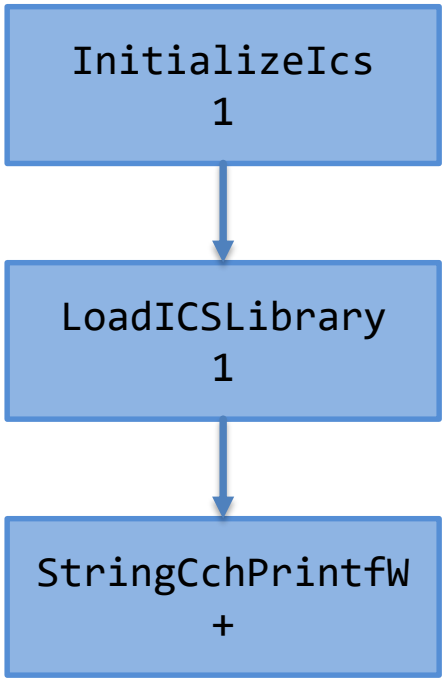

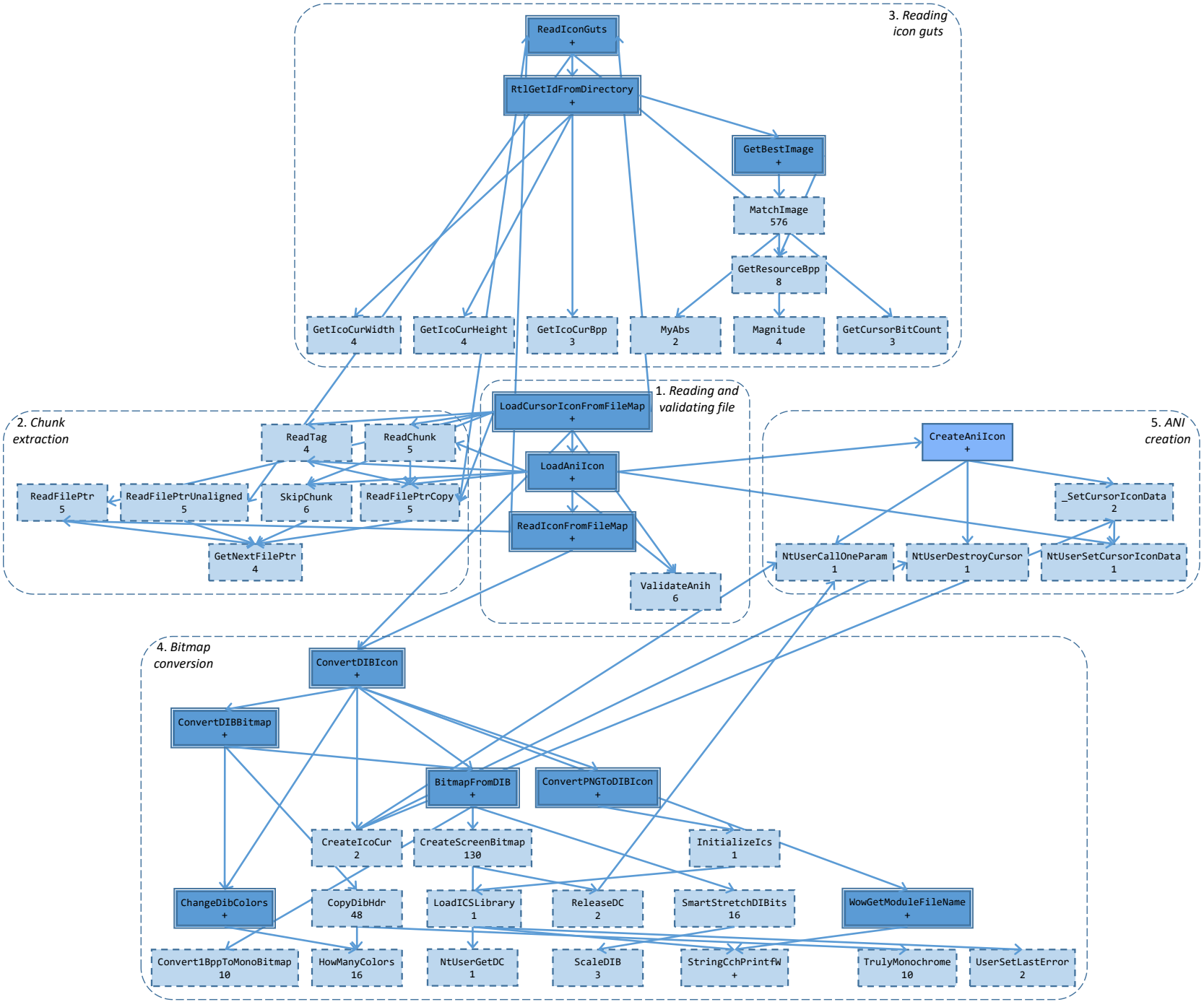
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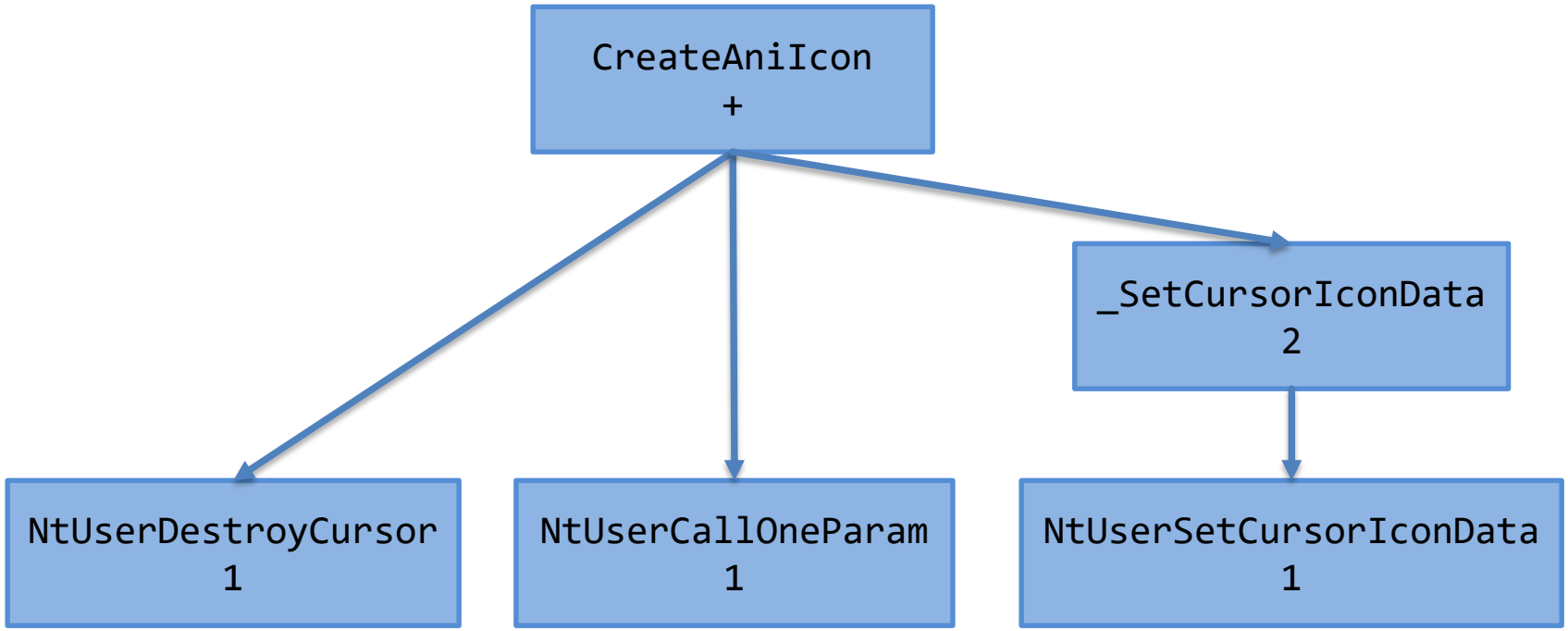
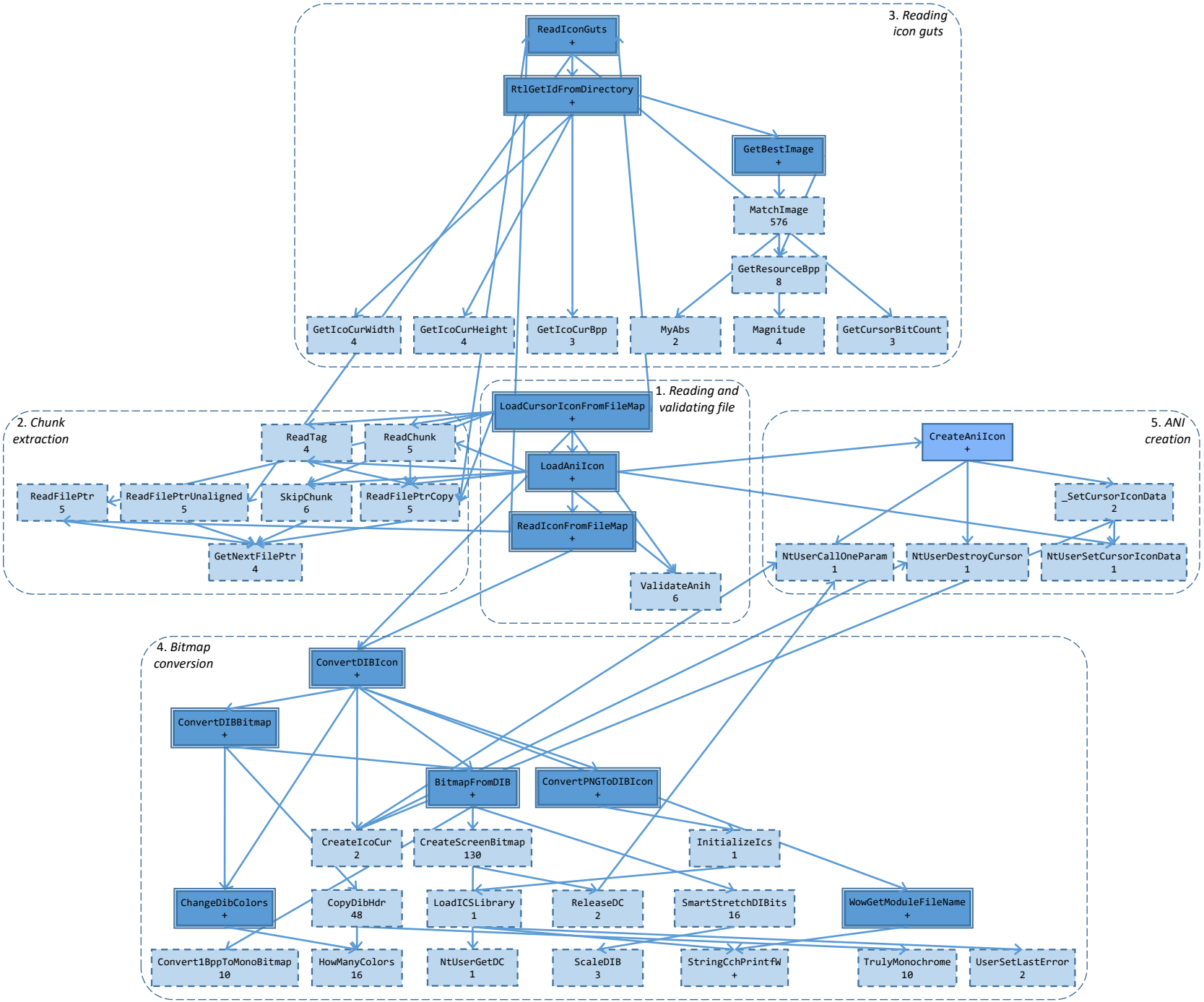


Stage 2: Input-dependent loops

- Manually restricting input-dependent loop bounds

```
for (i = 0; i < frames; i++)
  frameArrT[i] = frameArr[i];
for (i = 0; i < steps; i++) {
  if (rateArr == NULL)
    rateArrT[i] = rate;
  else
    rateArrT[i] = rateArr[i];
  if (stepArr == NULL)
    stepArrT[i] = i;
  else
    stepArrT[i] = stepArr[i];
}
```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- Manual program decomposition and summarization

Summarization

- Alleviates path explosion at the expense of computing logic representations of functions

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- Alleviates path explosion at the expense of computing logic representations of functions
- Is attractive only for functions
  - that contain many execution paths, and
  - whose inputs/outputs are easy to represent logically

Compositional memory safety

```
void bar(char* buf, int x) {
  if (0 <= x && x < 10) buf[x] = 1;
}
```

- Summary for bar:

$$\big((0 \le x) \wedge (x < 10) \wedge (0 \le x < \mathsf{buf}.size) \wedge (\mathsf{buf[x]=1})\big) \vee \big((x < 0) \wedge (10 \le x)\big)$$

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```
void foo(int x) {
  char* buf = malloc(5);
  bar(buf, x);
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5

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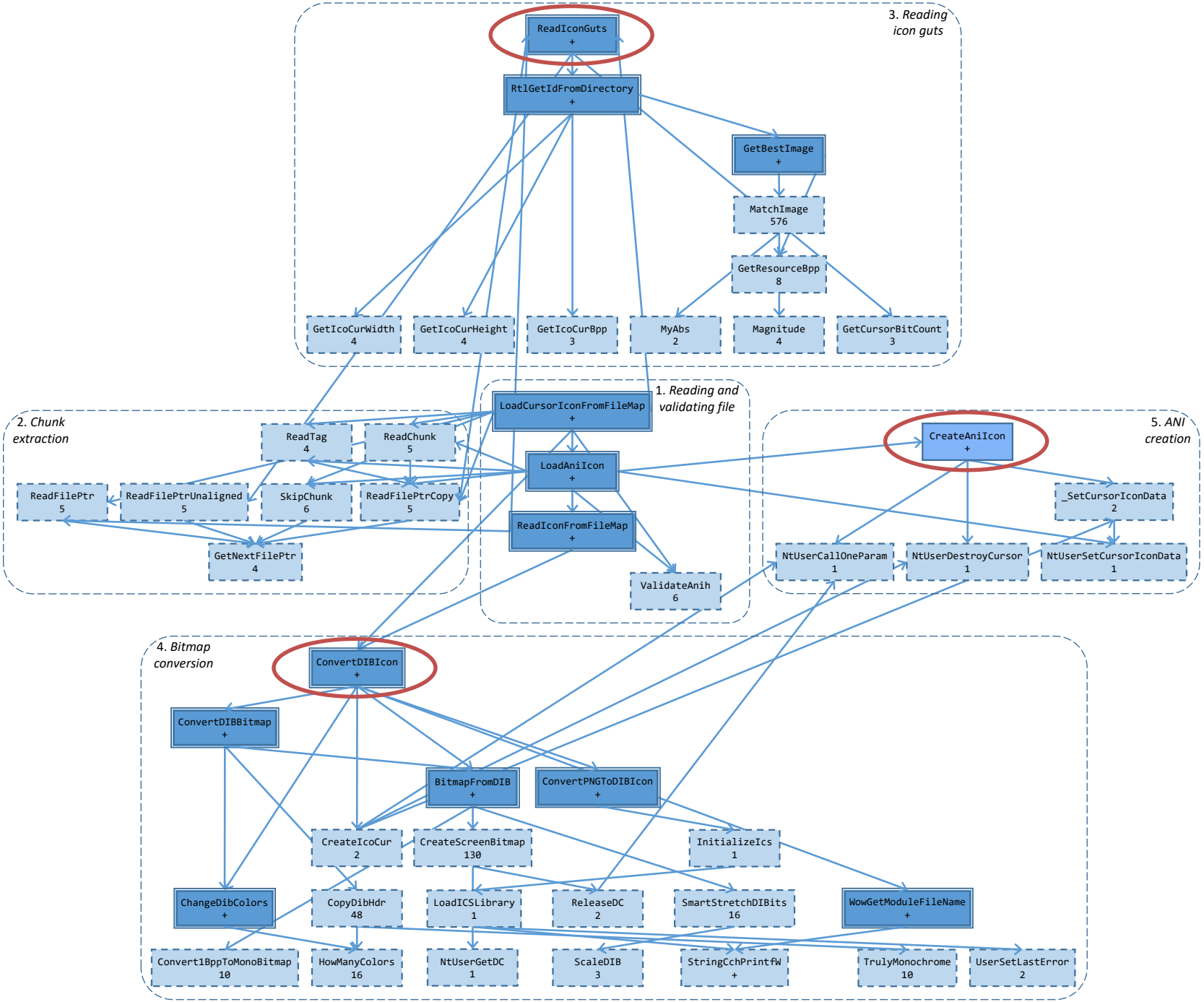
- Key observation:
  Architectural components of the parser typically return a single “success” or “failure” value

  - If “failure”, parsing aborts

  - If “success”, parsing proceeds with unconstrained inputs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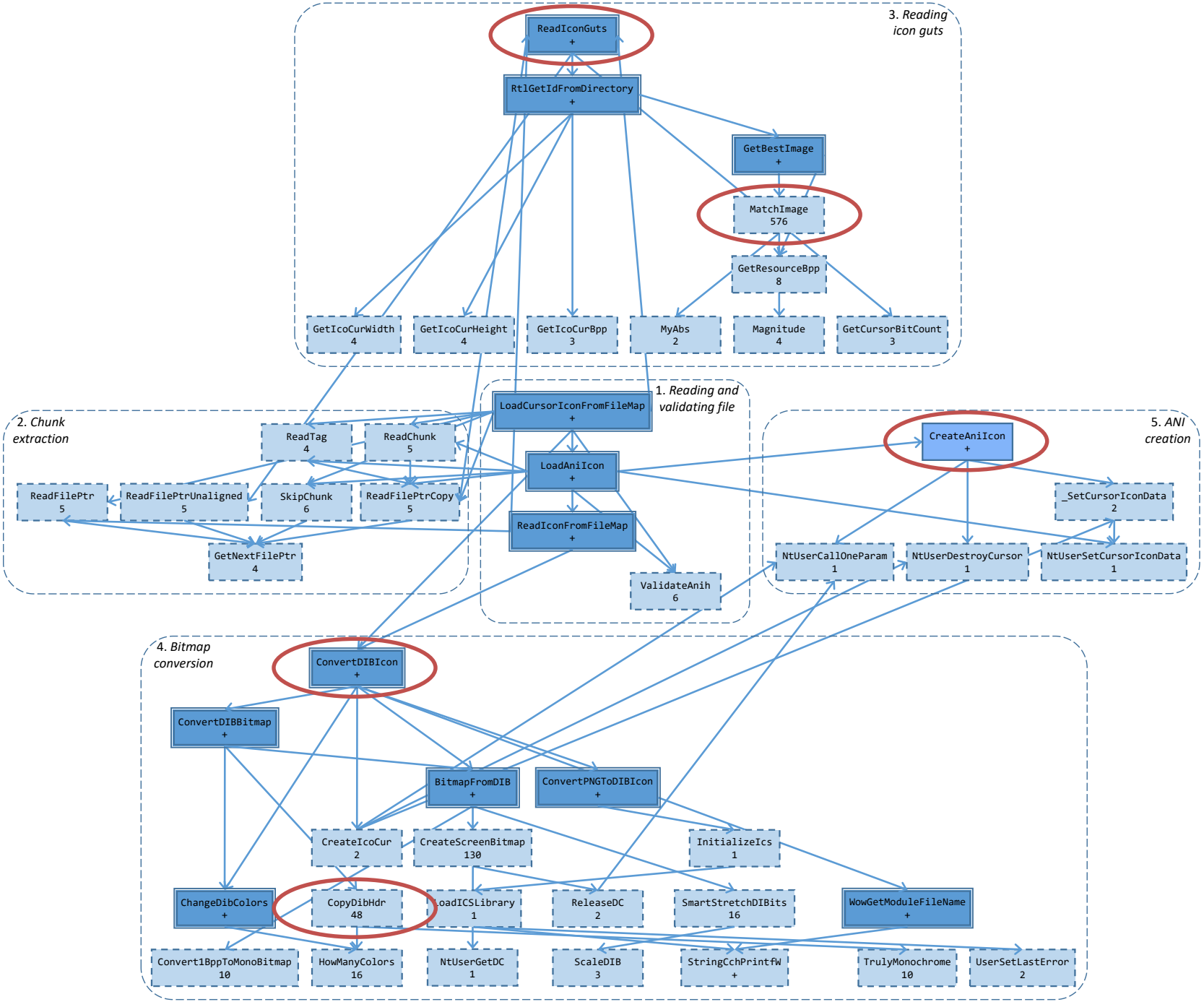
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Only 5 summaries were used!

Attacker-memory-safety bugs

- Real bugs (fixed in the latest version of Windows)
- Harmless (off-by-one) bugs
- Code parts not memory safe by design

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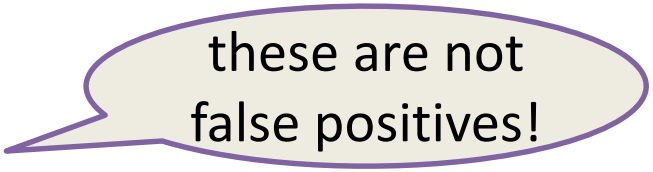

Shrinking the gap

- Interesting findings:
  - Many loop-free and easy-to-verify functions
  - Input-dependent loops controlled by about 10 bytes plus the file size
  - Path explosion controlled by 5 simple summaries

- Can we automate the manual steps?

Static Program Analysis Meets Test Case Generation Lecture 1

Maria Christakis

MPI-SWS, Germany