Static Program Analysis Meets Test Case Generation
Lecture 3

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Textbook:
Weakest Preconditions

Verification condition

- Logic formula reflecting the correctness of a program
- Typically checked by an automatic theorem prover
- Equivalent formulations can affect performance

Verification condition

- Logic formula reflecting the correctness of a program
- Typically checked by an automatic theorem prover
- Equivalent formulations can affect performance

A technique for computing verification conditions is

weakest preconditions

A simple language

$$S, T \ ::= \ \ Id \coloneqq Expr$$

A simple language

$$
\begin{array}{rcl}
S, T & ::= & Id \coloneqq Expr \\
& | & \textbf{assert}\ Expr
\end{array}
$$

A simple language

$$
\begin{aligned}
S, T \; ::= \quad & Id \coloneqq Expr \\
\mid \quad & \textbf{assert } Expr \\
\mid \quad & \textbf{assume } Expr
\end{aligned}
$$

A simple language

$$
\begin{aligned}
S, T \;::=\;& Id \coloneqq Expr \\
\mid\;& \textbf{assert}\ Expr \\
\mid\;& \textbf{assume}\ Expr \\
\mid\;& S\ ;\ T
\end{aligned}
$$

A simple language

$$
\begin{aligned}
S, T \;::=\; & \; Id \coloneqq Expr \\
\mid \; & \; \textbf{assert } Expr \\
\mid \; & \; \textbf{assume } Expr \\
\mid \; & \; S \; ; \; T \\
\mid \; & \; S \; \square \; T
\end{aligned}
$$

Exercise

Is this simple language rich enough to encode if-statements?

if *B* **then** *S* **else** *T* **end**

$$
\begin{array}{rcl}
S, T & ::= & Id \coloneqq Expr \\
& | & \textbf{assert}\ Expr \\
& | & \textbf{assume}\ Expr \\
& | & S\ ;\ T \\
& | & S\ \square\ T
\end{array}
$$

Exercise

Is this simple language rich enough to encode if-statements?

if B **then** S **else** T **end**

Yes!

$$(\textbf{assume}\ B\ ;\ S)\ \square\ (\textbf{assume}\ \neg B\ ;\ T)$$

Weakest precondition

$$wp(S, Q)$$

Weakest precondition

$$wp(S, Q)$$

characterizes all pre-states from which

Weakest precondition

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characterizes all pre-states from which every non-blocking execution of S

Weakest precondition

$$wp(S, Q)$$

characterizes all pre-states from which
every non-blocking execution of S
does not go wrong and terminates

Weakest precondition

$$wp(S, Q)$$

characterizes all pre-states from which
every non-blocking execution of S
does not go wrong and terminates
in a state satisfying Q

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

Weakest precondition

$$wp(x \coloneqq Expr, Q) \equiv Q[x \coloneqq Expr]$$

Example:

$$wp(x \coloneqq y, 0 < x) \equiv 0 < y$$

Weakest precondition

$$wp(x \coloneqq Expr, Q) \equiv Q[x \coloneqq Expr]$$

Exercise:

$$wp(x \coloneqq x + 1, 0 < x) \equiv$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

Exercise:

$$wp(x := x + 1, 0 < x) \equiv 0 < x + 1$$

Weakest precondition

$$wp(x \coloneqq Expr, Q) \equiv Q[x \coloneqq Expr]$$

Exercise:

$$wp(x \coloneqq x + 1, 0 < x) \equiv 0 < x + 1$$

$$wp(x \coloneqq x + 1, z - 2 < y) \equiv$$

Weakest precondition

$$wp(x \coloneqq Expr, Q) \equiv Q[x \coloneqq Expr]$$

Exercise:

$$wp(x \coloneqq x + 1, 0 < x) \equiv 0 < x + 1$$

$$wp(x \coloneqq x + 1, z \; - 2 < y) \equiv z \; - 2 < y$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\mathbf{assert}\ Expr, Q) \equiv Expr \land Q$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\textbf{assert}\ Expr, Q) \equiv Expr \wedge Q$$

Exercise:

$$wp(\textbf{assert false}, Q) \equiv$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\textbf{assert}\ Expr, Q) \equiv Expr \land Q$$

Exercise:

$$wp(\textbf{assert false}, Q) \equiv false$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\mathbf{assert}\ Expr, Q) \equiv Expr \wedge Q$$

$$wp(\mathbf{assume}\ Expr, Q) \equiv Expr \Rightarrow Q$$

Weakest precondition

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$$wp(S\ ;\ T, Q) \equiv wp(S, wp(T, Q))$$

Weakest precondition

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\textbf{assert}\ Expr, Q) \equiv Expr \land Q$$

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$$wp(S\ ;\ T, Q) \equiv wp(S, wp(T, Q))$$

$$wp(S \ \square\ T, Q) \equiv wp(S, Q) \land wp(T, Q)$$

Exercise

What is the weakest precondition of the if-statement?

```
if B then S else T end
```

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\textbf{assert}\ Expr, Q) \equiv Expr \wedge Q$$

$$wp(\textbf{assume}\ Expr, Q) \equiv Expr \Rightarrow Q$$

$$wp(S\ ;\ T, Q) \equiv wp(S, wp(T, Q))$$

$$wp(S \,\square\, T, Q) \equiv wp(S, Q) \wedge wp(T, Q)$$

Exercise

What is the weakest precondition of the if-statement?

$$(\textbf{assume}\ B\ ;\ S)\ \square\ (\textbf{assume}\ \neg B\ ;\ T)$$

$$wp(x := Expr, Q) \equiv Q[x := Expr]$$

$$wp(\textbf{assert}\ Expr, Q) \equiv Expr \land Q$$

$$wp(\textbf{assume}\ Expr, Q) \equiv Expr \Rightarrow Q$$

$$wp(S\ ;\ T, Q) \equiv wp(S, wp(T, Q))$$

$$wp(S\ \square\ T, Q) \equiv wp(S, Q) \land wp(T, Q)$$

Exercise

What is the weakest precondition of the if-statement?

$$(\textbf{assume}\ \ B\ ;\ S)\ \square\ (\textbf{assume}\ \neg B\ ;\ T)$$

$$B \Rightarrow wp(S, Q) \land \neg B \Rightarrow wp(T, Q)$$

Verification condition

For a given program *P*, the verification condition is

$$wp(P, true)$$

Verification condition

For a given program P, the verification condition is

$$wp(P, true)$$

This condition is valid if and only if P is free of errors

Exercise

What is the weakest precondition of the program?

$$(\textbf{assume}\ \ B\ ;\ x\ \ \coloneqq 1)\ \square\ (\textbf{assume}\ \neg B\ ;\ x\ \ \coloneqq -1)$$

Assume that Q is $x = 2$.

$$B \Rightarrow wp(S, Q) \wedge \neg B \Rightarrow wp(T, Q)$$

$$wp(x \coloneqq Expr, Q) \equiv Q[x \coloneqq Expr]$$

Exercise

What is the weakest precondition of the program?

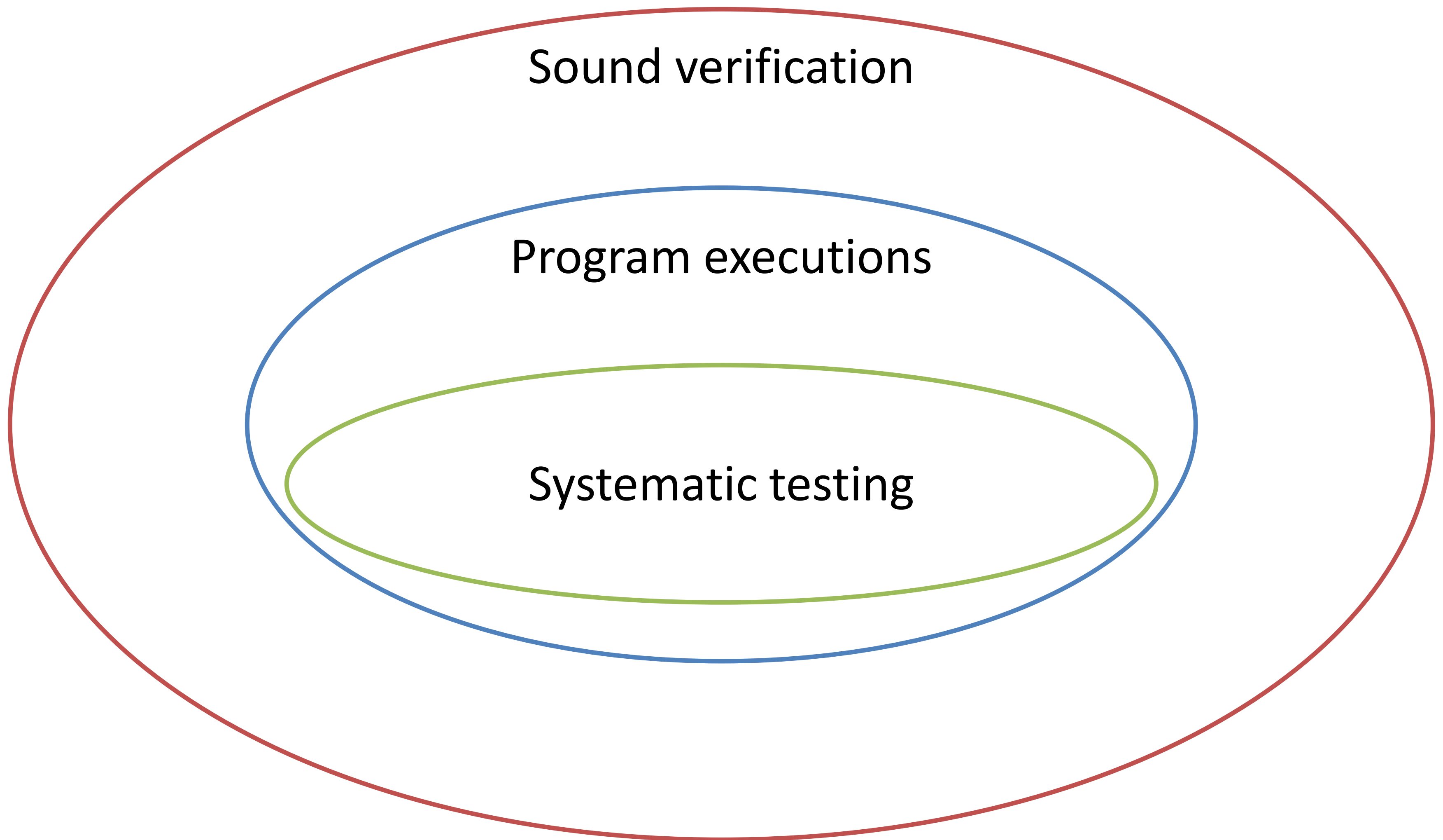
$$(\textbf{assume}\ \ B\ ;\ x\ \ \coloneqq 1)\ \square\ (\textbf{assume}\ \neg B\ ;\ x\ \ \coloneqq -1)$$

Assume that Q is $x = 2$.

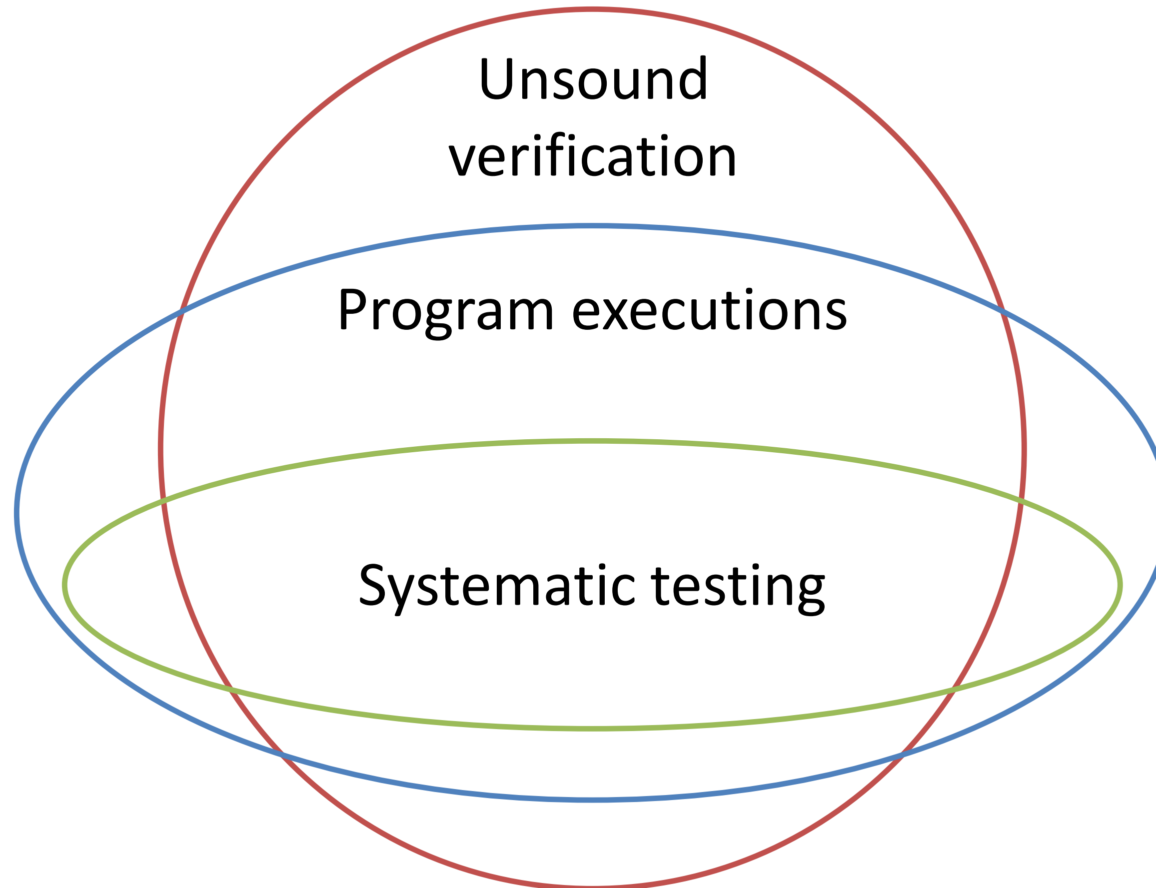
$$false$$

Fun:
Guiding Dynamic Symbolic Execution toward Unverified Program Executions

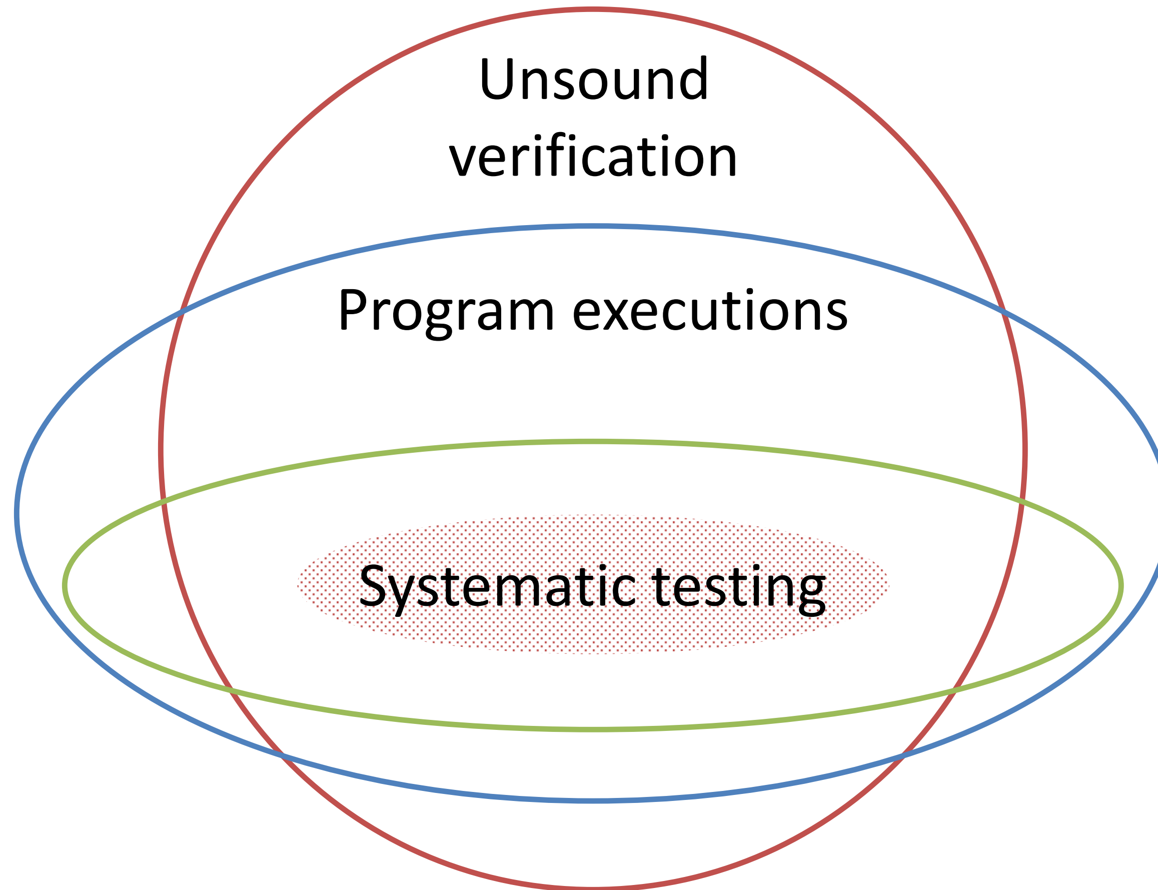
Verification and testing



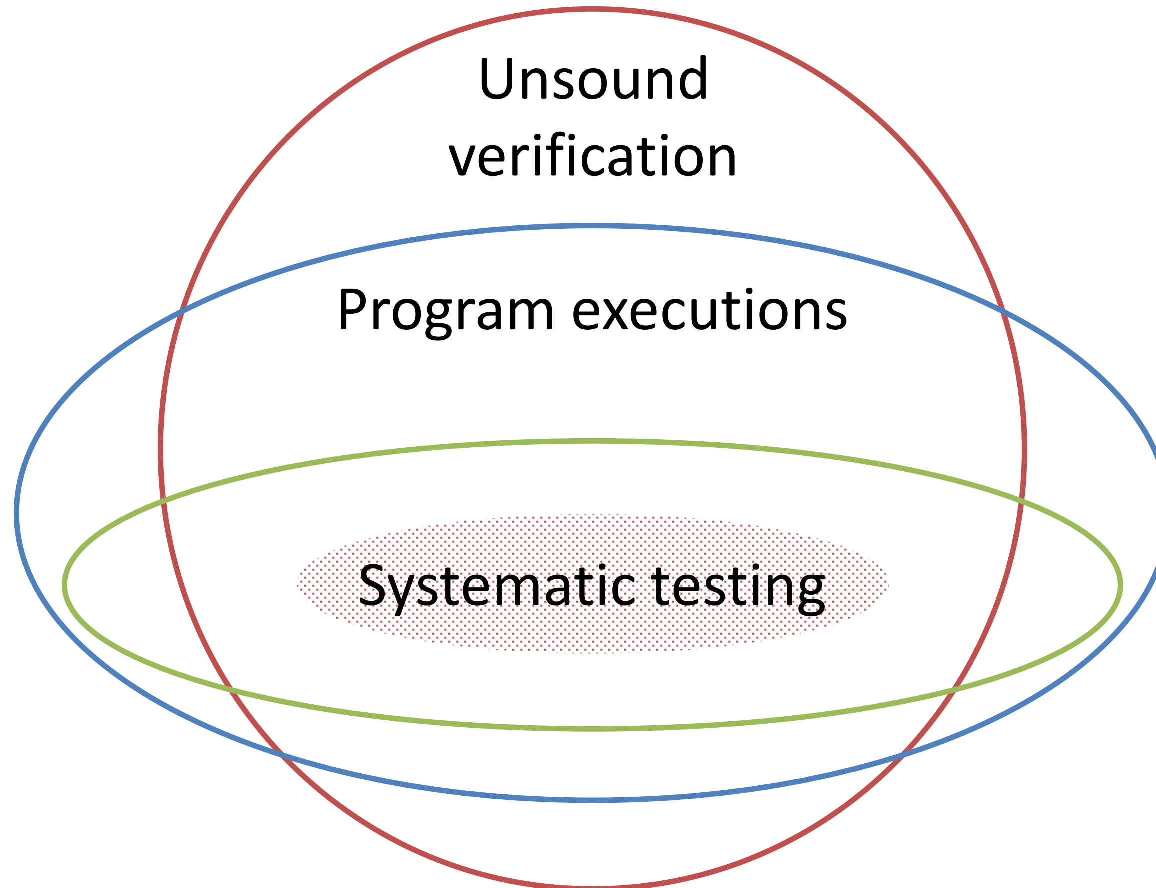
Verification and testing



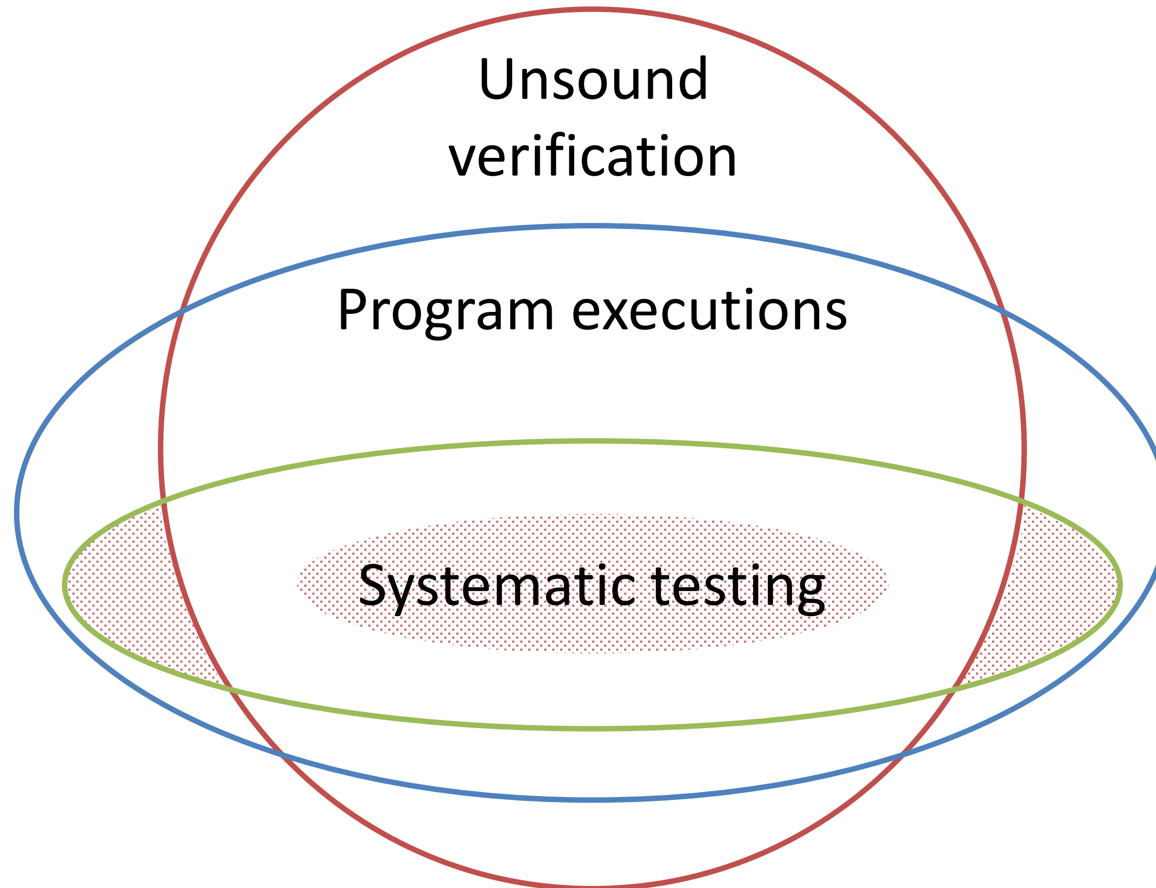
So far…



In our work…



In our work...



Static analysis

- Effective in detecting software errors
- Increasingly applied in industry
- Come in a wide range

Static analysis

- Effective in detecting software errors
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but…

Compromises

- Reduce the annotation overhead
- Reduce the number of false positives
- Increase performance
- Preserve modularity

Compromises

- Not checking program properties
- Making unjustified assumptions
- Being unsound

Example

C#

```
void Deposit(int amount) {
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assert balance >= old(balance);
}
```

Example

```
void Deposit(int amount) {
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
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  assert balance >= old(balance);
}
```

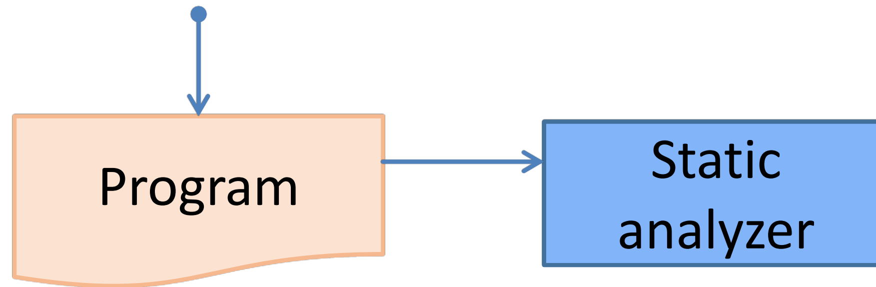
Example

```
void Deposit(int amount) {
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assert balance >= old(balance);
}
```

Consequences

- Absence of errors not guaranteed
- Test effort not reduced

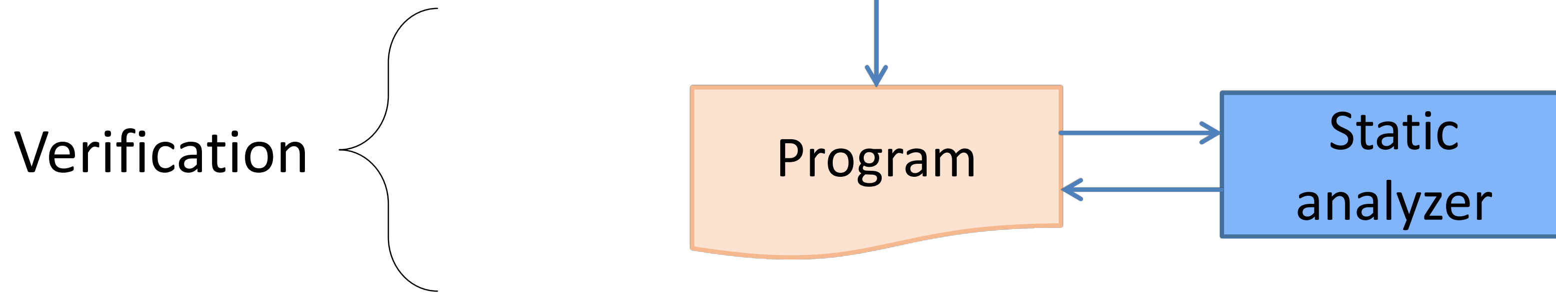
Architecture



Annotations

```
void Deposit(int amount) {
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    assumed noOverflowAdd(balance, amount) as a;
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assert balance >= old(balance) verified a;
}
```

Architecture

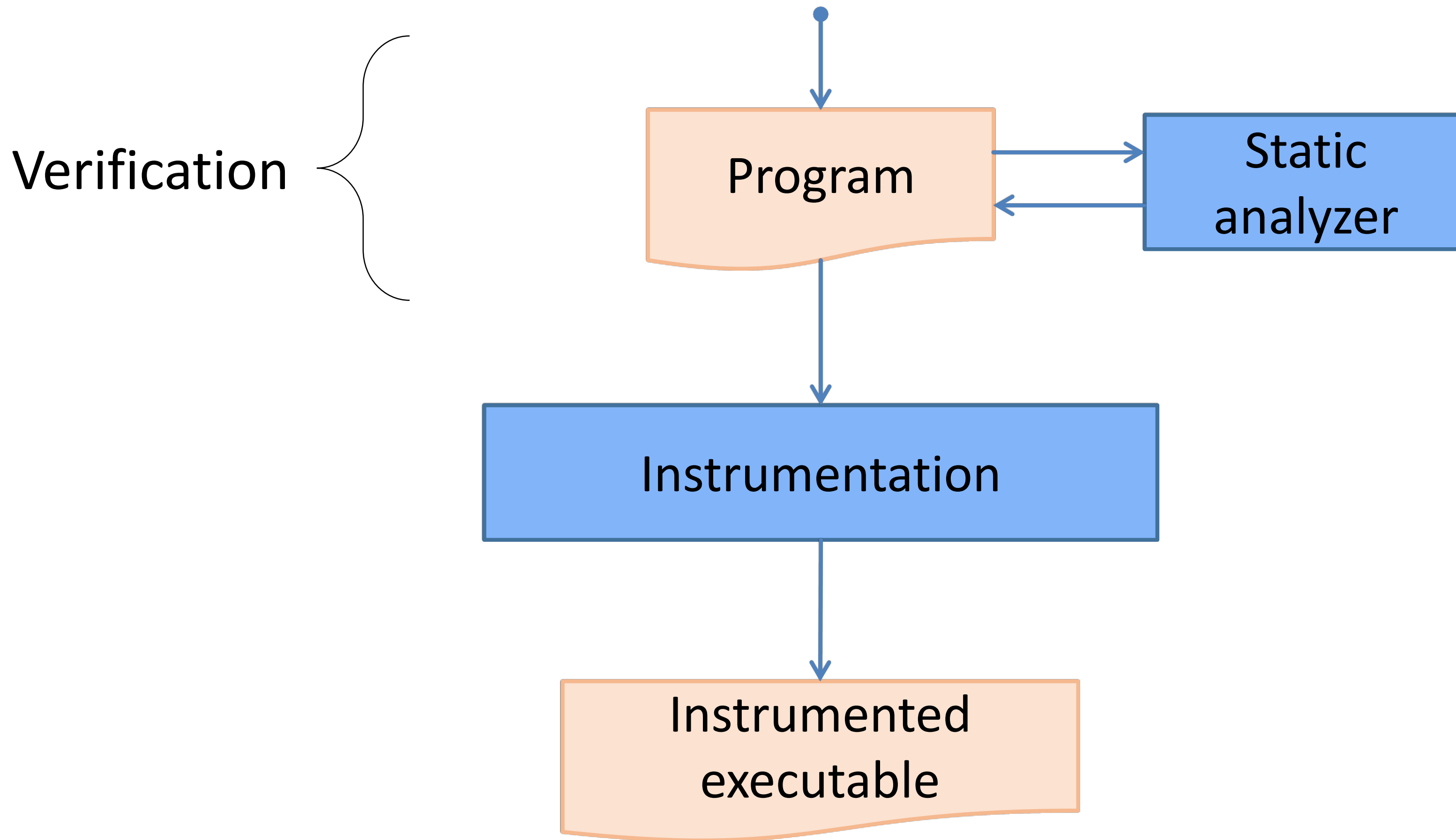


Instrumentation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

Architecture



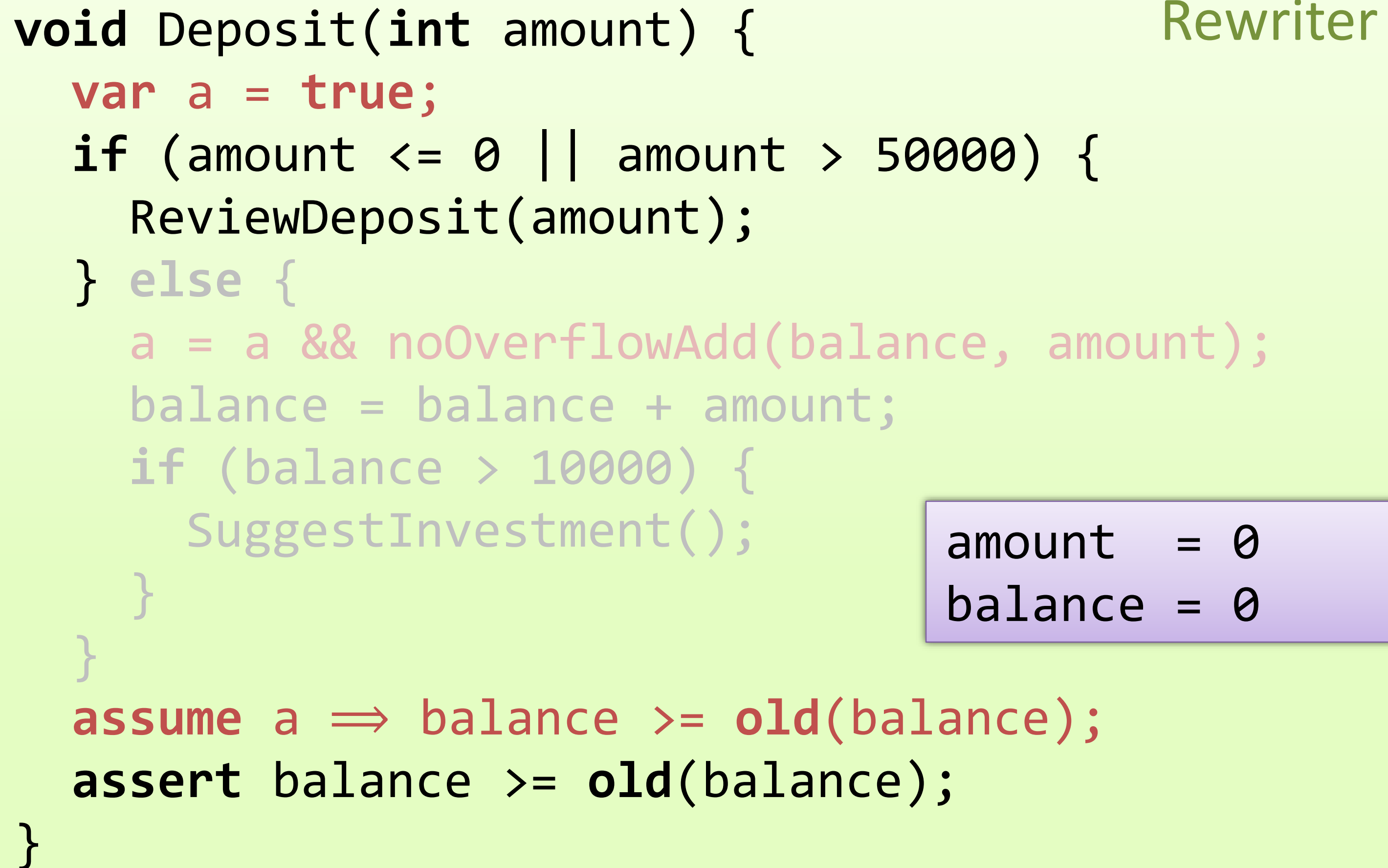
Dynamic test generation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = 0
balance = 0
```

Dynamic test generation



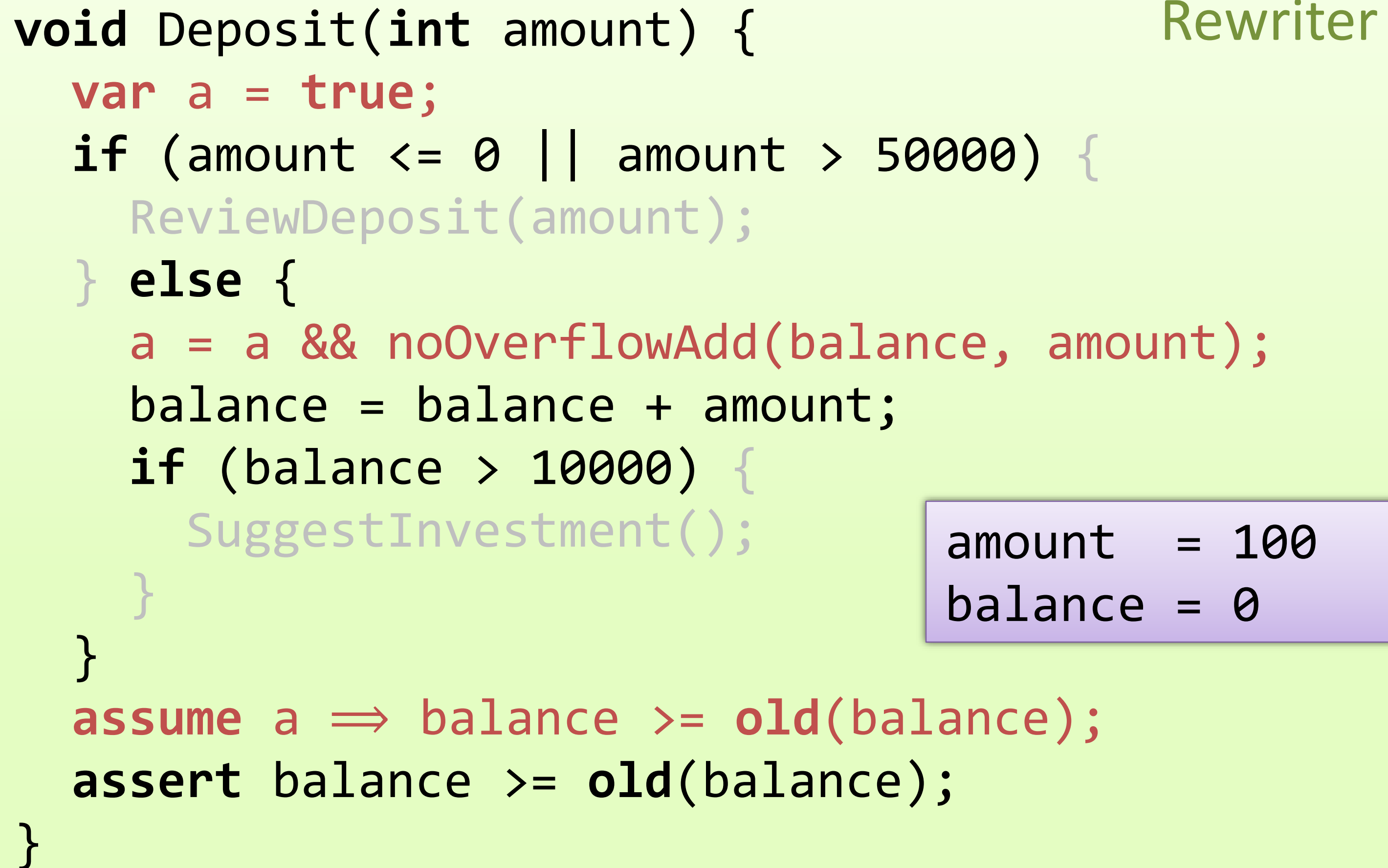
Dynamic test generation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = 100
balance = 0
```

Dynamic test generation



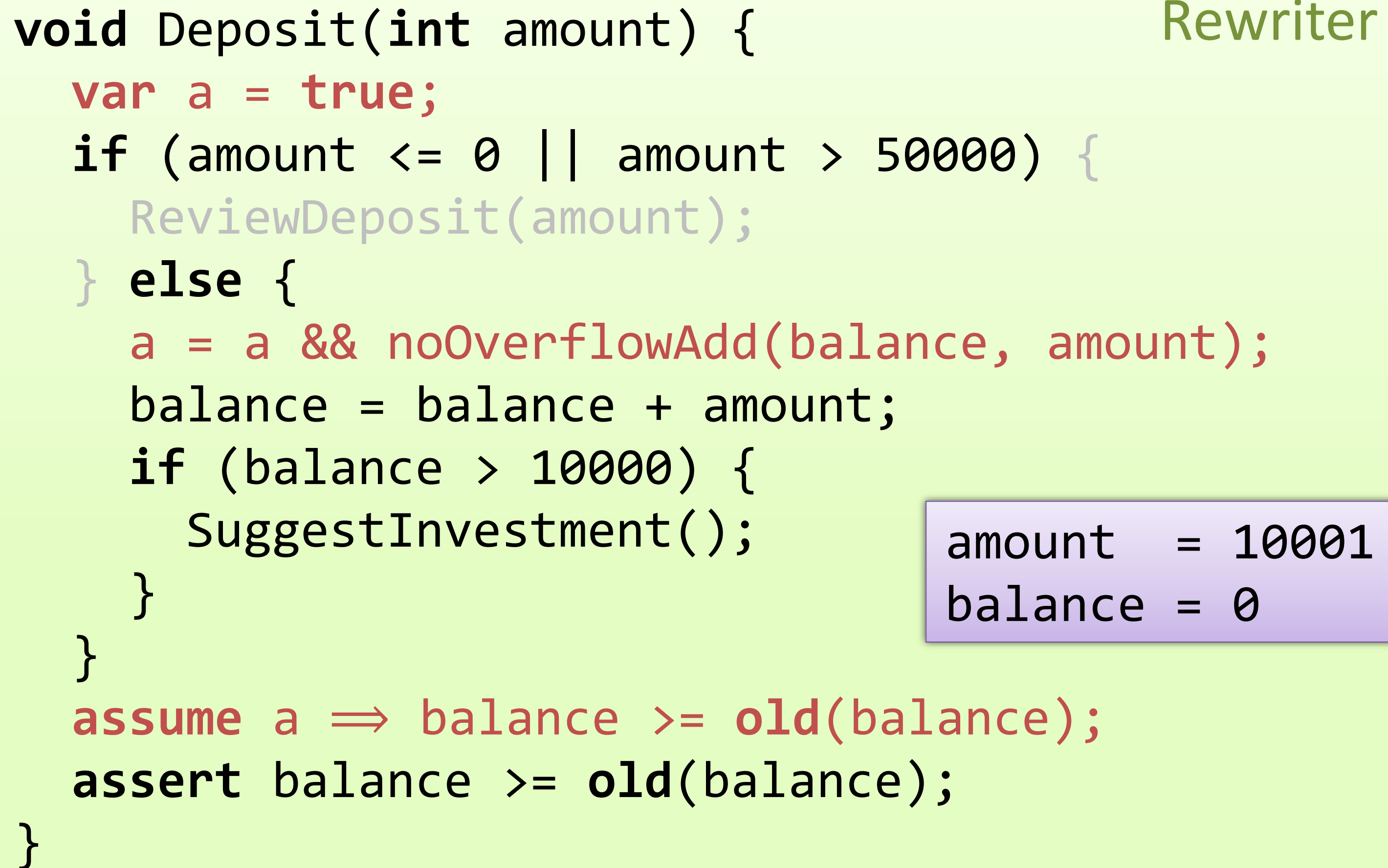
Dynamic test generation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = 10001
balance = 0
```

Dynamic test generation



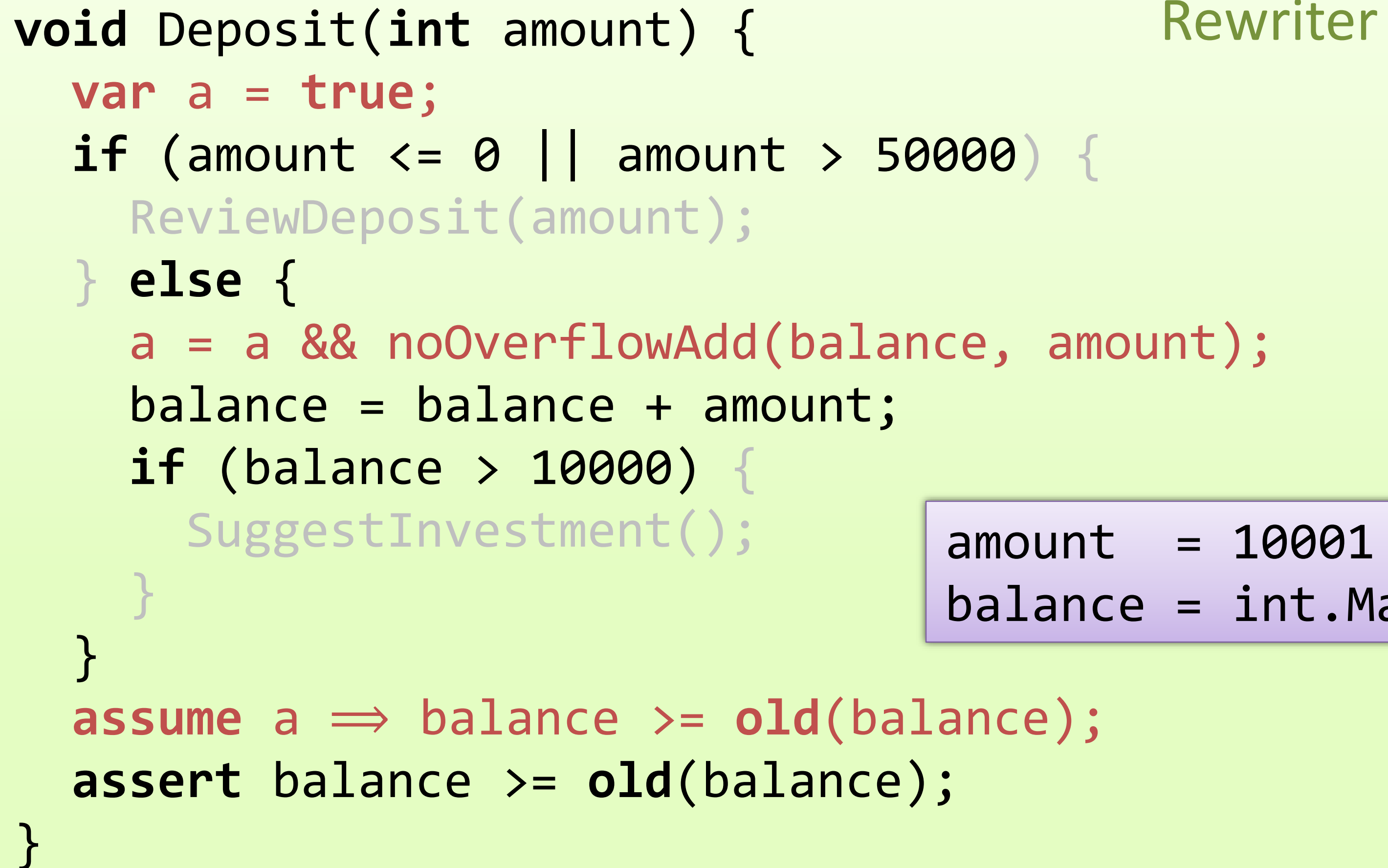
Dynamic test generation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = 10001
balance = int.MaxValue
```

Dynamic test generation



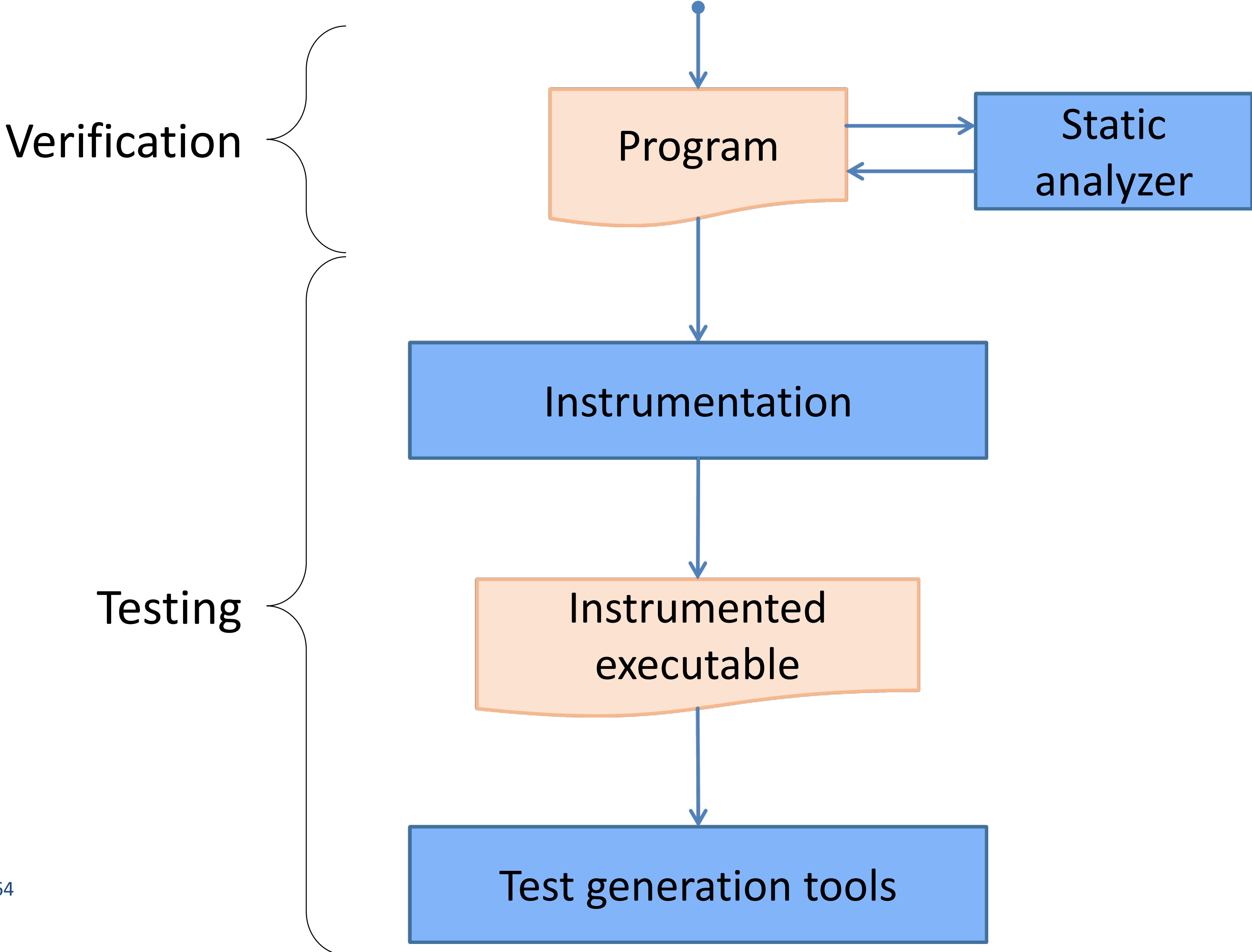
Dynamic test generation

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = ...
balance = ...
```

Architecture



Problem

Rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
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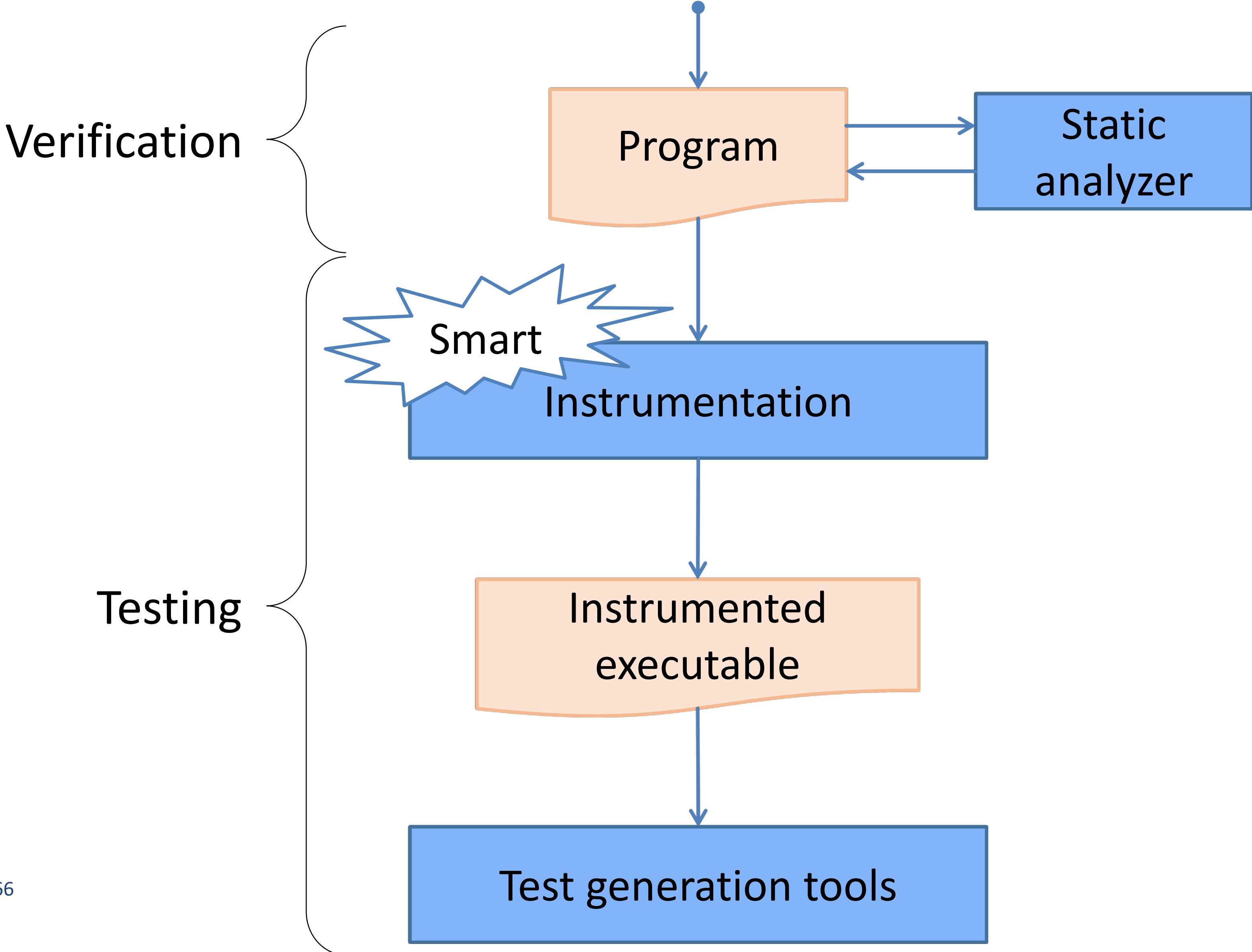
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

Architecture



Smart instrumentation

Idea:

- Propagate conditions about unverified executions higher up in the control flow

Under the hood:

- Compute an abstraction of the program
- Infer conditions about unverified executions
- Instrument the concrete program

Abstraction

```
void Deposit(int amount) {

  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    assumed noOverflowAdd(balance, amount) as a;
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assert balance >= old(balance) verified a;
}
```

Abstraction

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assert balance >= old(balance) verified a;
}
```

Smart rewriter

Abstraction

```
void Deposit {
  var a = true;
  if (⋆) {
    call Account.ReviewDeposit;
  } else {
    a = a && ⋆;

    if (⋆) {
      call Account.SuggestInvestment;
    }
  }
  assert ⋆ verified a;
}
```

Smart rewriter

Abstraction

```
void Deposit {
  var a = true;
  if (*) {
    call Account.ReviewDeposit;
  } else {
    a = a && *;

    if (*) {
      call Account.SuggestInvestment;
    }
  }
  assert * verified a;
}
```

Smart rewriter

syntactic
non-deterministic
sound

Inference

```
void Deposit {
  var a = true;
  if (★) {
    call Account.ReviewDeposit;
  } else {
    a = a && ★;

    if (★) {
      call Account.SuggestInvestment;
    }
  }
  assert ★ verified a;
}
```

Smart rewriter

Inference

Smart rewriter

```
void Deposit {
  var a = true;
  if (⋆) {

  } else {
    a = a && ⋆;

    if (⋆) {

    }
  }
  assert ⋆ verified a;
}
```

Inference

```
void Deposit {
  var a = true;
  if (*) {

  } else {
    a = a && *;

    if (*) {

    }
  }
  assert * verified a; {false}
}
```

Smart rewriter

unverified executions satisfy **`false`**

Inference

Smart rewriter

```
void Deposit {
  var a = true;
  if (*) {

  } else {
    a = a && *;

    if (*) {

    }
  } {!a}
  assert * verified a; {false}
}
```

unverified executions satisfy !a

Inference

Smart rewriter

```
void Deposit {
  var a = true;
  if (*) {

  } else { {true}
    a = a && *;
    {!a}
    if (*) {
      {!a}
    } {!a}
  } {!a}
  assert * verified a; {false}
}
```

Inference

```
void Deposit {
  var a = true;
  if (⋆) {
    {!a}
  } else { {true}
    a = a && ⋆;
    {!a}
    if (⋆) {
      {!a}
    } {!a}
  } {!a}
  assert ⋆ verified a; {false}
}
```

Smart rewriter

Inference

Smart rewriter

```
void Deposit {
  var a = true; {true}
  if (⋆) {
    {!a}
  } else { {true}
    a = a && ⋆;
    {!a}
    if (⋆) {
      {!a}
    } {!a}
  } {!a}
  assert ⋆ verified a; {false}
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Inference

Smart rewriter

```
void Deposit { {true}
  var a = true; {true}
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    a = a && ⋆;
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Inference

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void Deposit { {true}
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    {!a}
  } else { {true}
    a = a && ⋆;
    {!a}
    if (⋆) {
      {!a}
    } {!a}
  } {!a}
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```

Smart rewriter

$wp(\textbf{assert} * \textbf{verified}\ A, Q) \equiv A \wedge Q$

Inference

```
void Deposit { {true}
  var a = true; {true}
  if (*) {
    {!a}
  } else { {true}
    a = a && *;
    {!a}
    if (*) {
      {!a}
    } {!a}
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```

Smart rewriter

$$MAY(S) \equiv \neg wp(S, true)$$

Inference

Smart rewriter

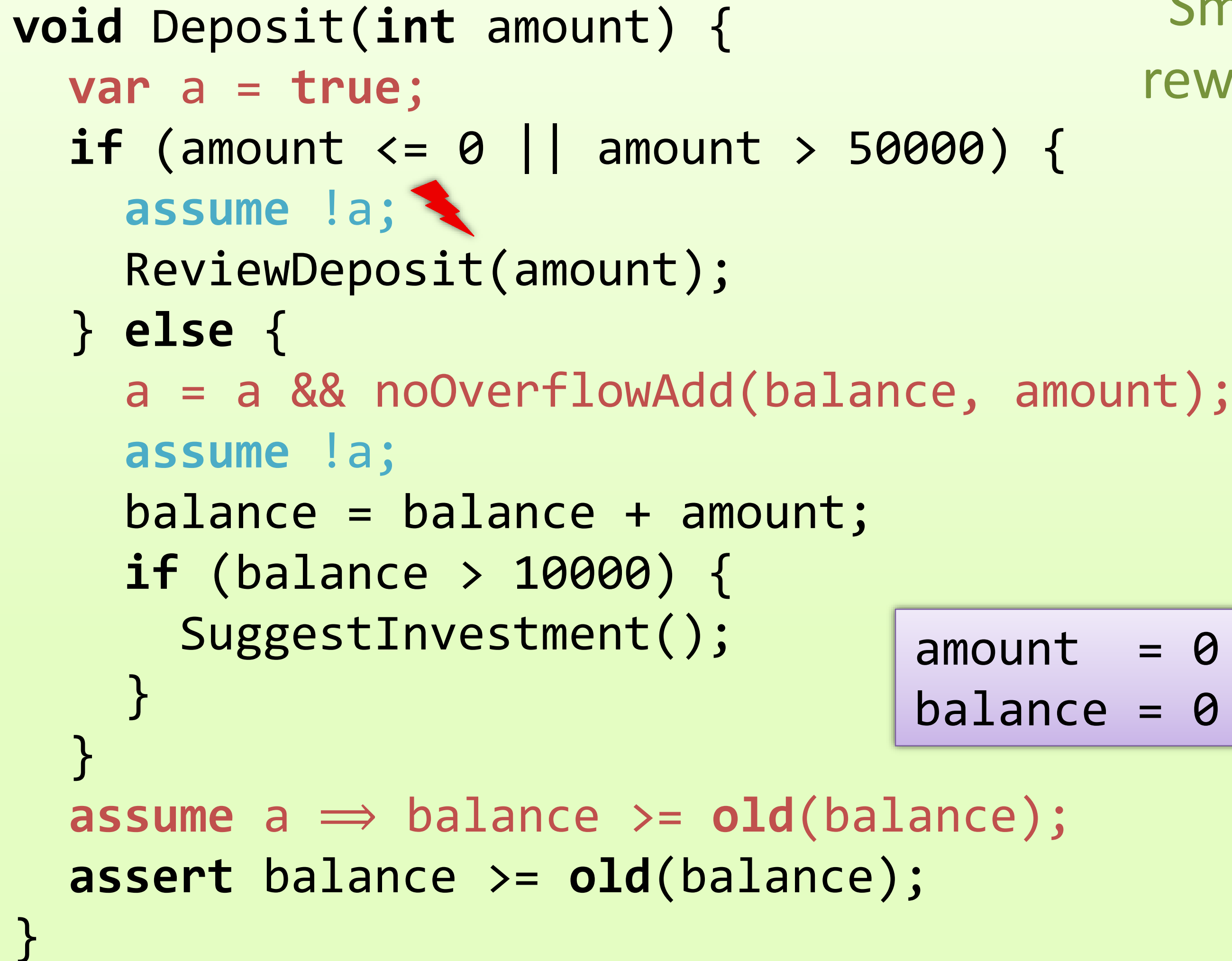
```
void Deposit { {true}
  var a = true; {true}
  if (⋆) {
    {!a}
  } else { {true}
    a = a && ⋆;
    {!a}
    if (⋆) {
      {!a}
    } {!a}
  } {!a}
  assert ⋆ verified a; {false}
}
```

Smart instrumentation

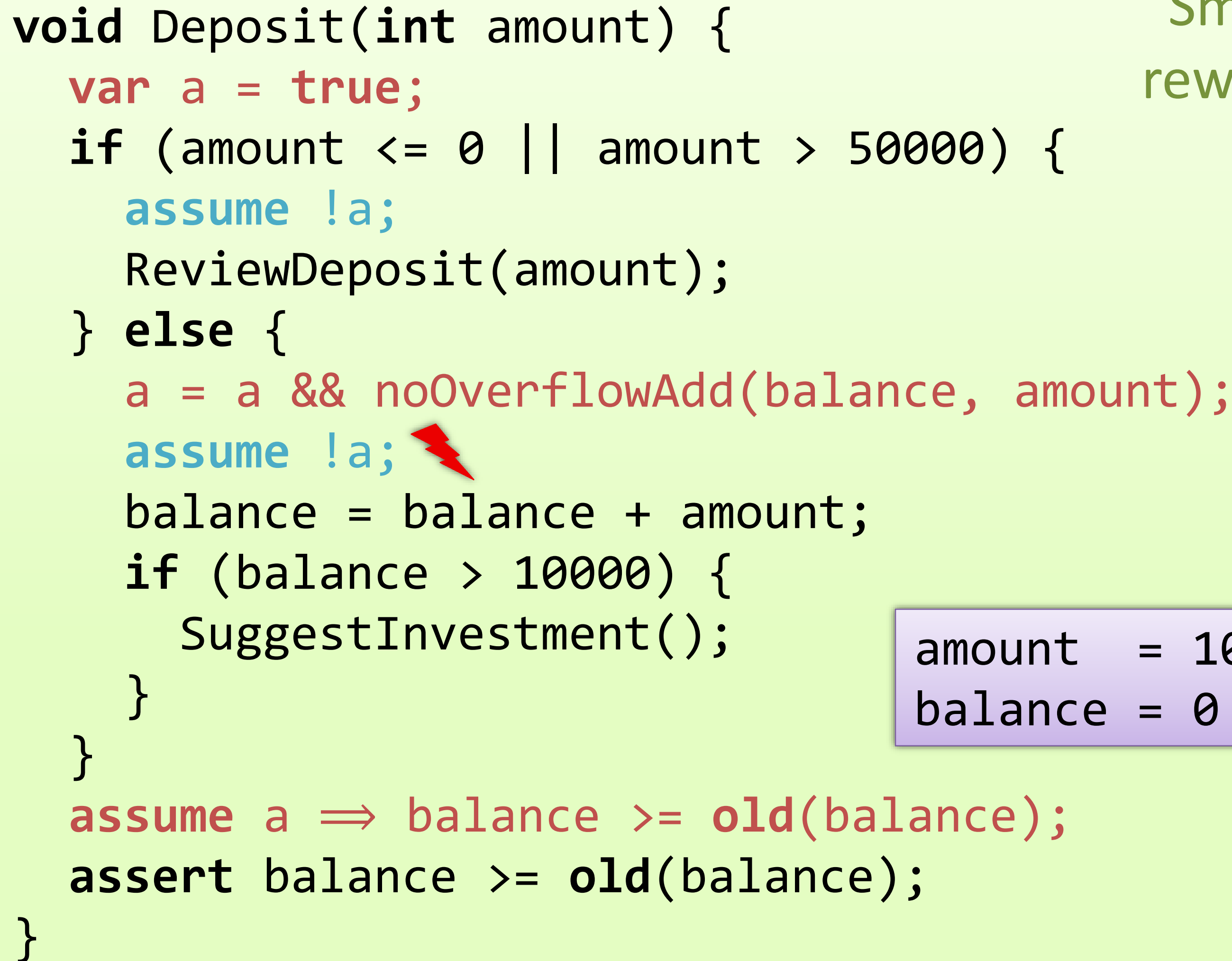
Smart rewriter

```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    assume !a;
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    assume !a;
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

Dynamic test generation



Dynamic test generation



Dynamic test generation

Smart rewriter

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```

```
amount  = 10001
balance = int.MaxValue
```

Dynamic test generation

Smart rewriter

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    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

```
amount  = 10001
balance = 0
```

Dynamic test generation

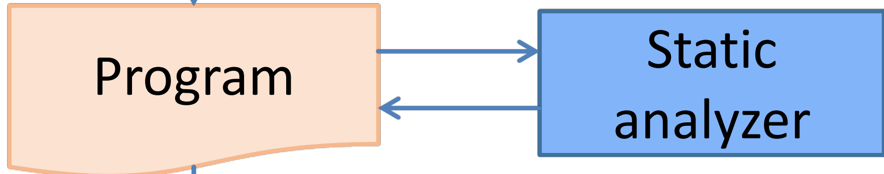
Smart rewriter

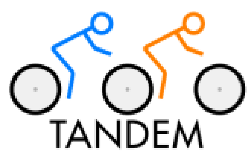
```
void Deposit(int amount) {
  var a = true;
  if (amount <= 0 || amount > 50000) {
    assume !a;
    ReviewDeposit(amount);
  } else {
    a = a && noOverflowAdd(balance, amount);
    assume !a;
    balance = balance + amount;
    if (balance > 10000) {
      SuggestInvestment();
    }
  }
  assume a ⟹ balance >= old(balance);
  assert balance >= old(balance);
}
```

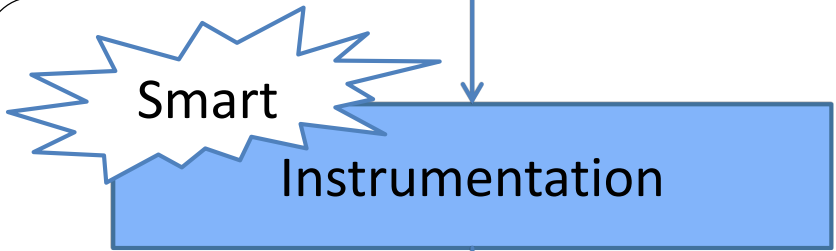
```
amount  = ...
balance = ...
```

Architecture

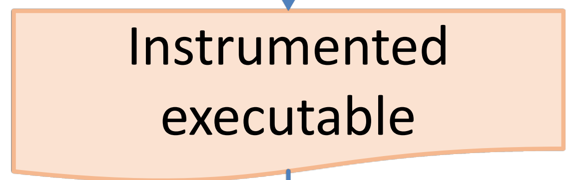
Verification

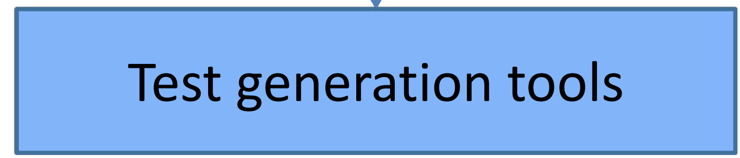






Testing





Evaluation highlights

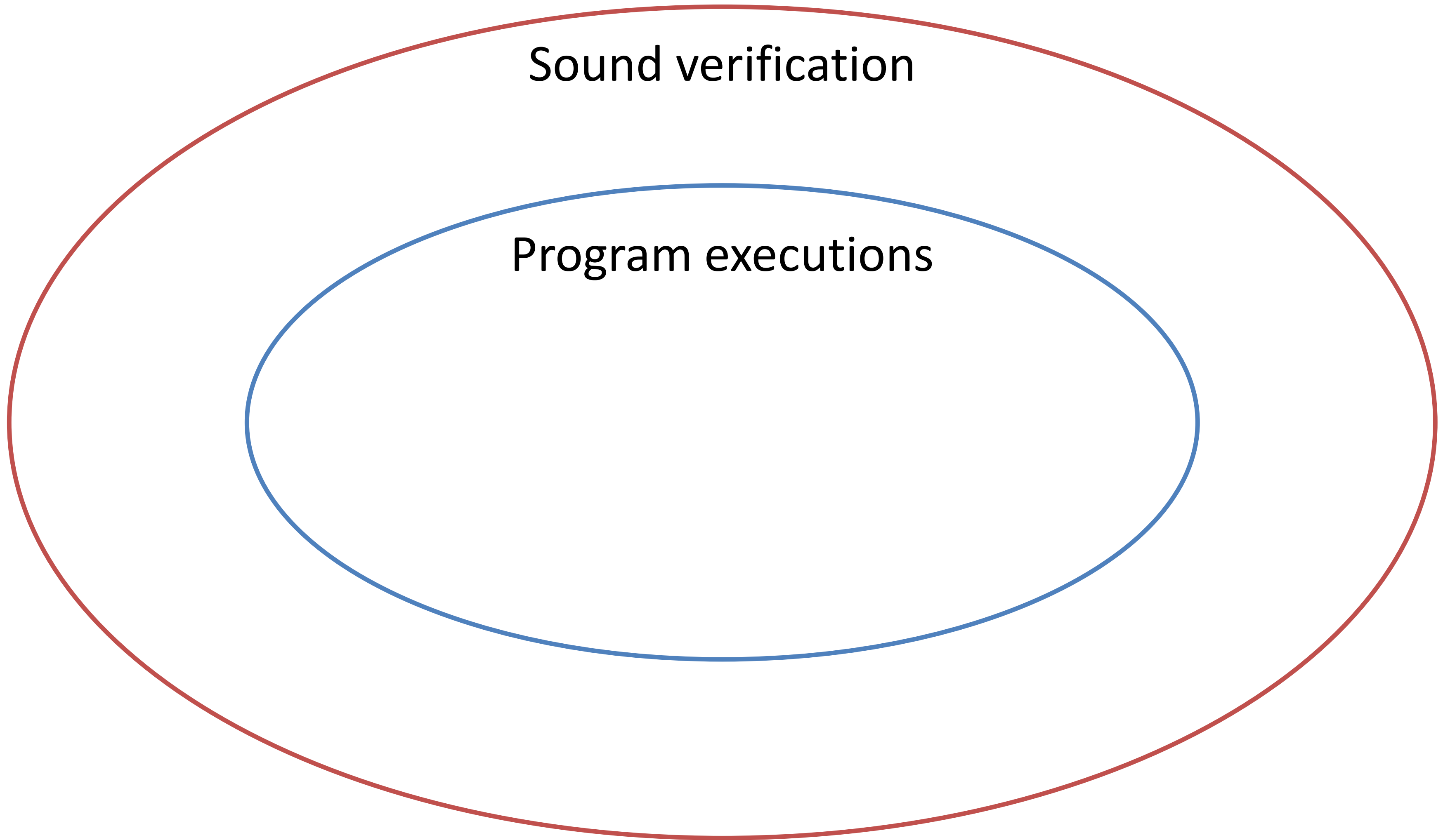
- 19.2% smaller test suites
- 7.1% more unverified executions
- 51.7% shorter testing time
- 29.3% fewer exploration bounds

Takeaways

- Verification and systematic testing
  - Tight and effective collaboration
  - Increased software quality
  - Reduced test effort

Fun:
Failure-Directed Program Trimming

Safe executions



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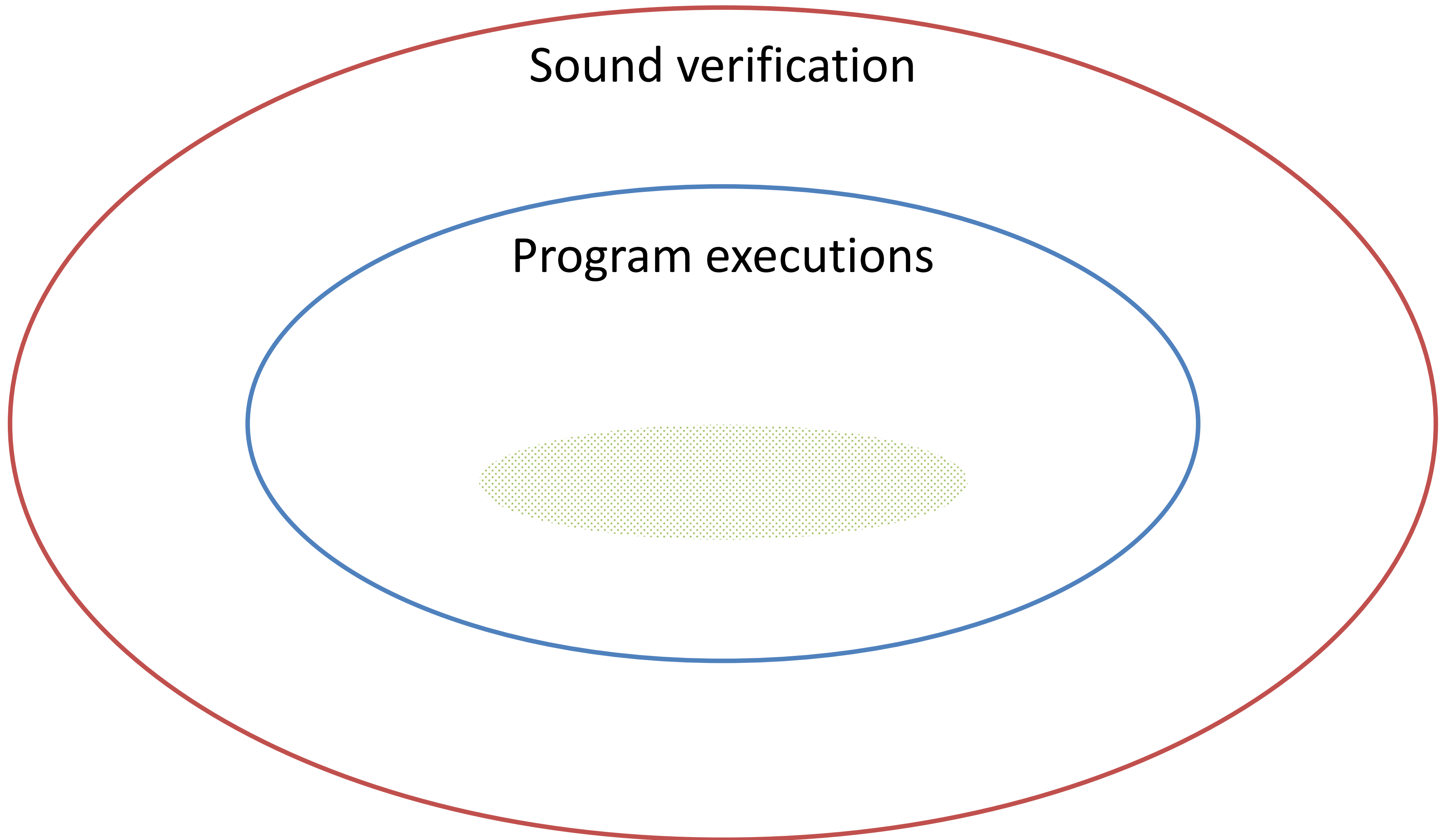

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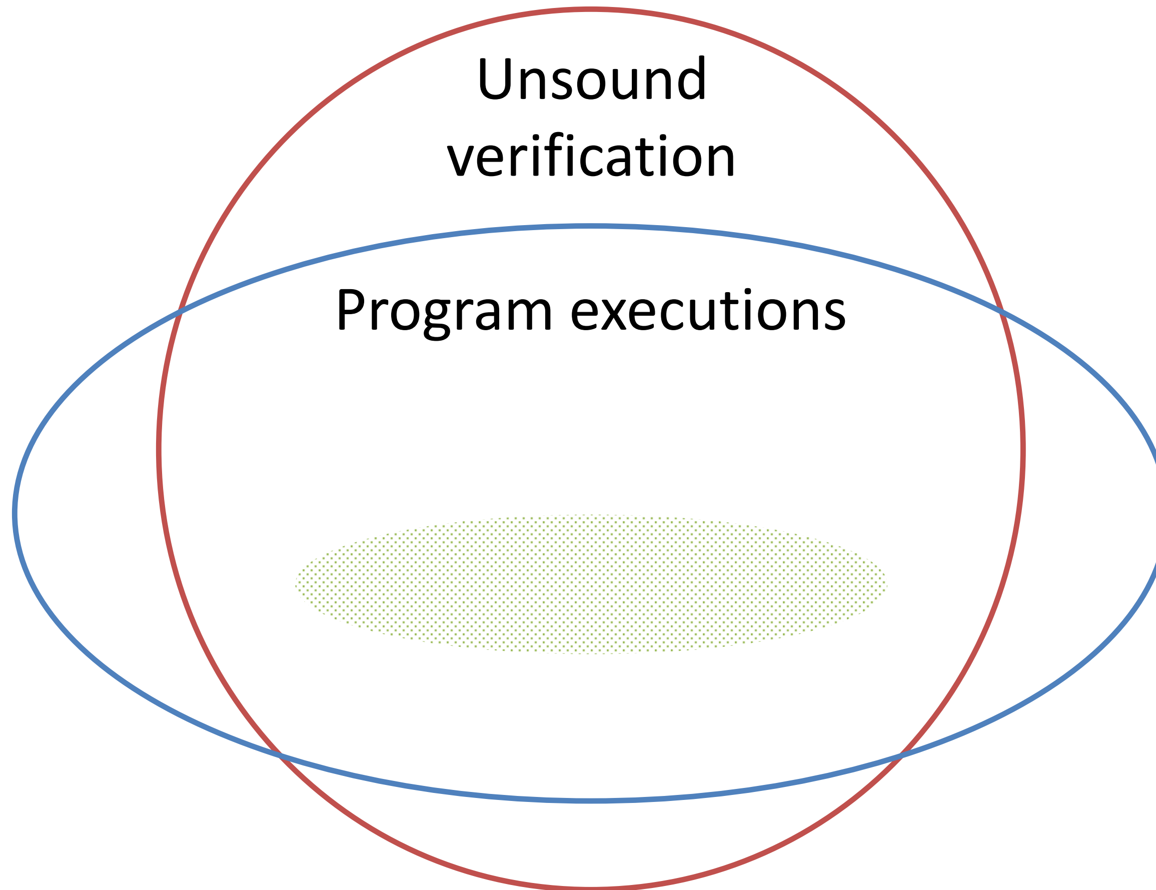

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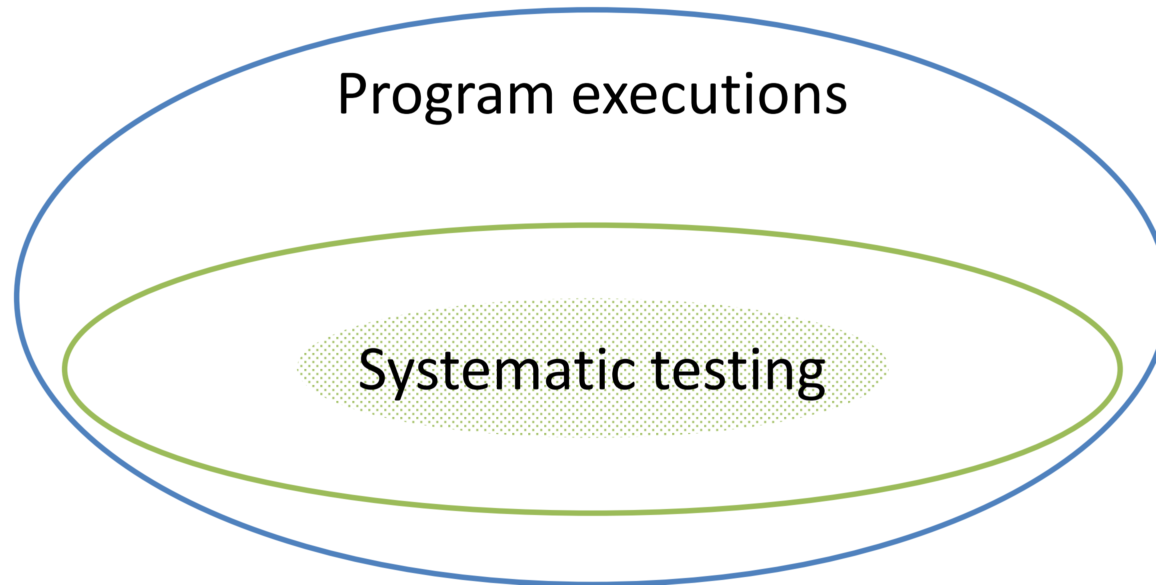
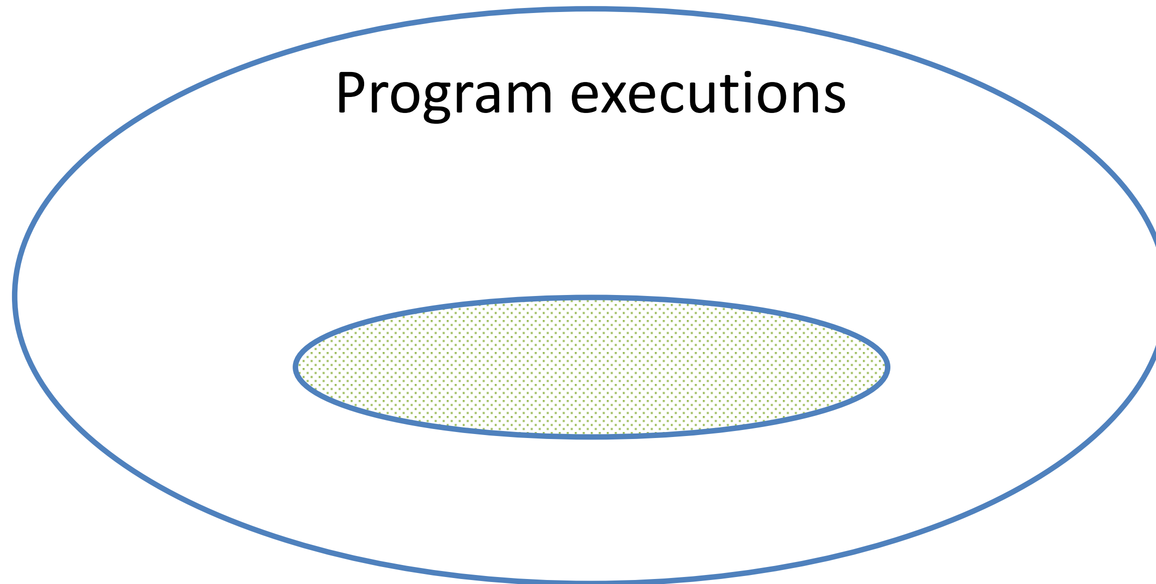
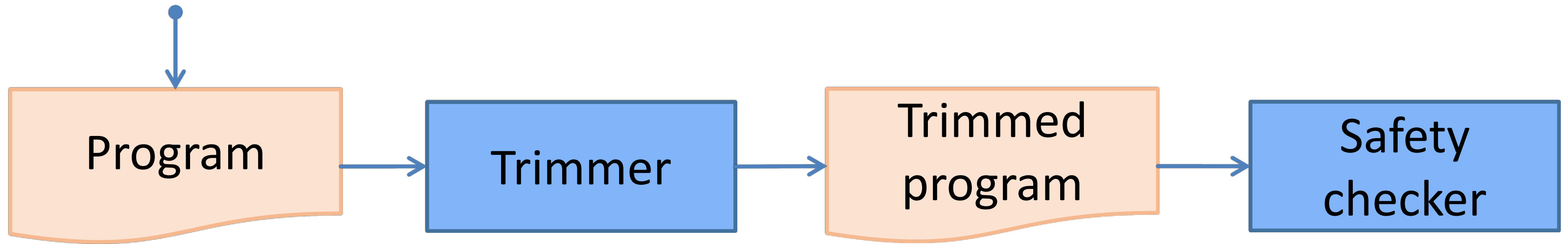


Trimming safe executions



Program trimming



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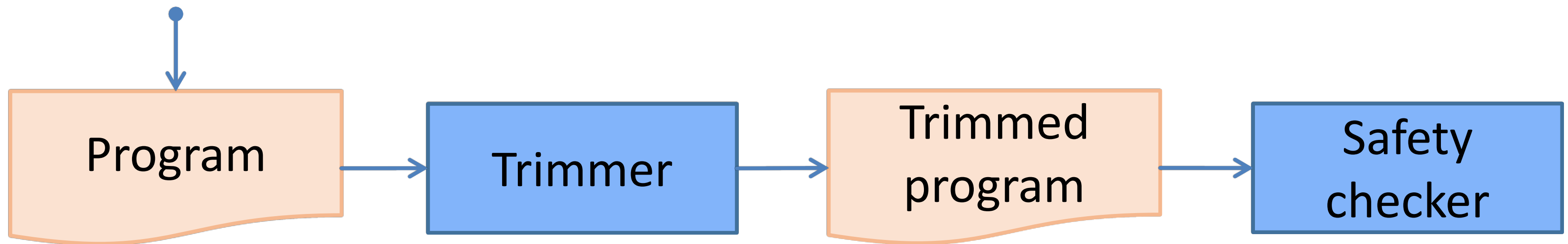

- Simplifies programs
- Makes safety checkers property directed
- Improves scalability and precision of safety checkers

Example

```c
x = *; y = *;                C

if (y > 0) {
  while (x < 10) {
    x = x + y;
  }
} else {
  x = x - 1;
}
assert x > 0;
```

Example

```
x = *; y = *;

if (y > 0) {
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```

```
x = *; y = *;
assume y <= 0;
x = x - 1;
assert x > 0;
```

Trimmed program

- Given P, program trimming generates P_{tr}
- P and P_{tr} are equi-safe
- P_{tr} contains fewer execution paths than P

Example

```
x = *; y = *;

if (y > 0) {
  while (x < 10) {
    x = x + y;
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} else {
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Example

```
x = *; y = *;                 P

if (y > 0) {
  while (x < 10) {
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  }
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}
assert x > 0;
```

```
x = *; y = *;                 P_tr
assume y <= 0;
x = x - 1;
assert x > 0;
```

How to trim a program

- Statically infer safety conditions
- Negate the safety conditions to obtain trimming conditions
- Instrument the program with assumptions of the trimming conditions

Example

```
x = ⋆; y = ⋆;        P

if (y > 0) {
  while (x < 10) {
    x = x + y;
  }
} else {
  x = x - 1;
}
assert x > 0;
```

```
x = ⋆; y = ⋆;        Ptr
assume y <= 0;
x = x - 1;
assert x > 0;
```

Example

P

```
x = *; y = *;

if (y > 0) {
  while (x < 10) {
    x = x + y;
  }
} else {
  x = x - 1;
}
assert x > 0;
```

P_{tr}

```
x = *; y = *;
assume y <= 0;
if (y > 0) {
  while (x < 10) {
    x = x + y;
  }
} else {
  x = x - 1;
}
assert x > 0;
```

Condition properties

- Safety conditions are sufficient for correctness
- To be lightweight, we infer stronger safety conditions
- Trimming conditions are necessary for failure
- By definition, assuming the trimming conditions preserves unsafe executions

Benefit 1: Scalability

```
int fact(int n) {
  assume 0 <= n;
  int r = 1;
  if (n != 0) {
    r = n * fact(n - 1);
  }
  return r;
}

void main() {
  int m = ⋆;

  int f = fact(m);
  assert m != 123 || f == 0;
}
```

Benefit 1: Scalability

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int fact(int n) {
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$m \neq 123 \vee f = 0$

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Benefit 2: Precision

```
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  return r;
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void main() {
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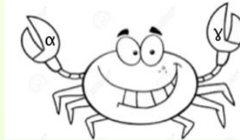
  int f = fact(m);
}
```

Benefit 2: Precision

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void main() {
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```

$n = 0$

Benefit 2: Precision

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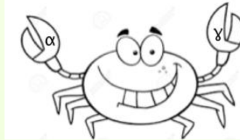


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Inference of safety conditions

- Lightweight, summary-based static analysis
- Similar to a weakest-precondition computation

Inference of safety conditions

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- Similar to a weakest-precondition computation

but…

Inference of safety conditions

- Lightweight, summary-based static analysis
- Similar to a weakest-precondition computation

but…

- Relies on several inference innovations
  - Heap writes
  - Procedure calls

Evaluation highlights

- 26-60% more safe programs
  with three abstract domains of Crab

- The cheapest trimming configuration
  proves 23% more programs safe than
  the most expensive Crab configuration
  in less than half of the time

Evaluation highlights

- 16-18% more safe programs
  with three search strategies of KLEE
- KLEE with trimming explores
  30-39% fewer paths
- The total running time of KLEE
  decreases by 23-36%

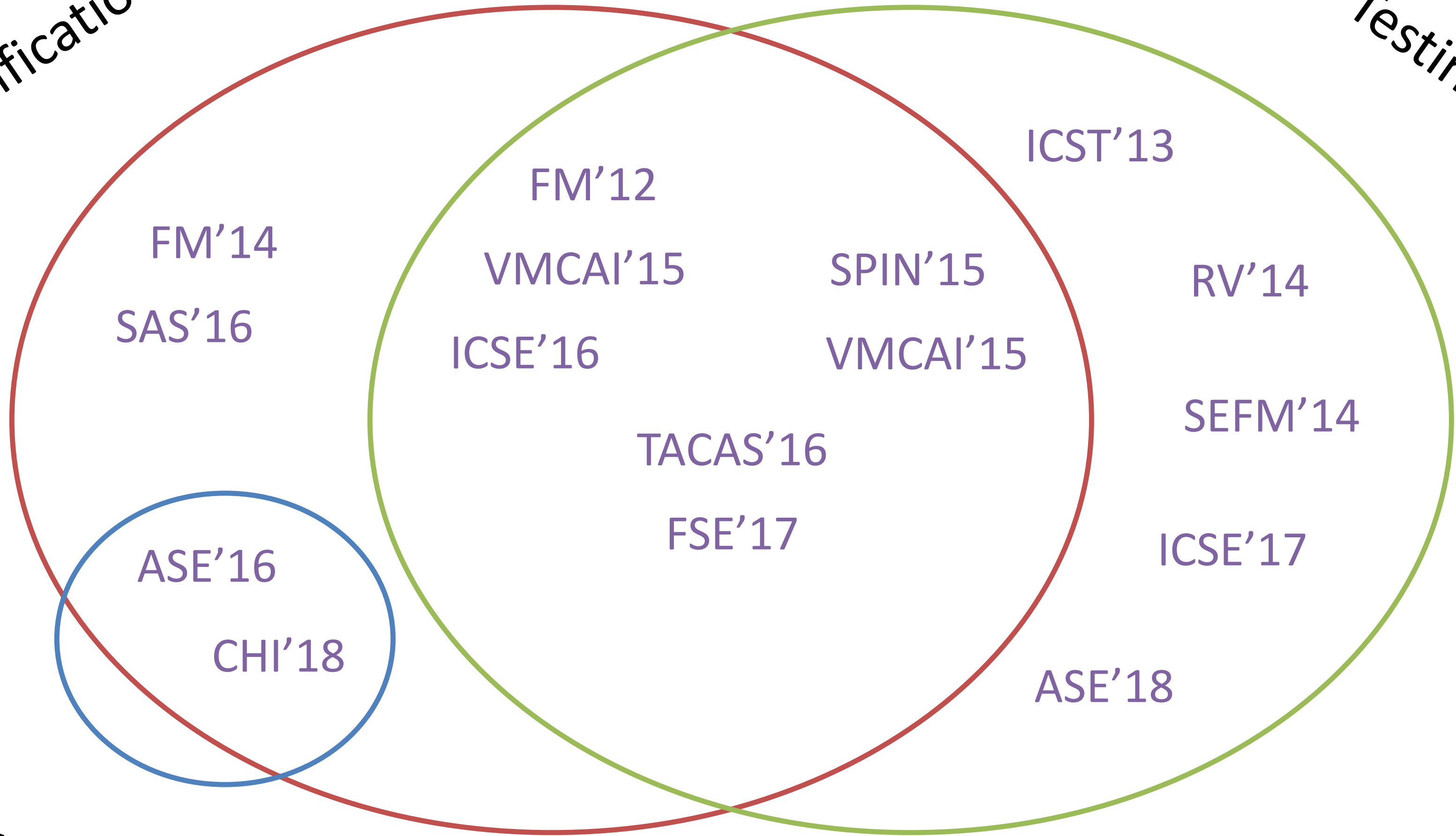
Evaluation highlights

- The total time for trimming all benchmarks

  ranges from 5-9 secs

Takeaways

- Program trimming, a program simplification technique
  - Reduce the number of execution paths
  - Preserve unsafe executions of the original program
  - Positively impact efficiency and precision of safety checkers


Verification
Testing
ESE & HCI
FM'14
SAS'16
FM'12
VMCAI'15
ICSE'16
SPIN'15
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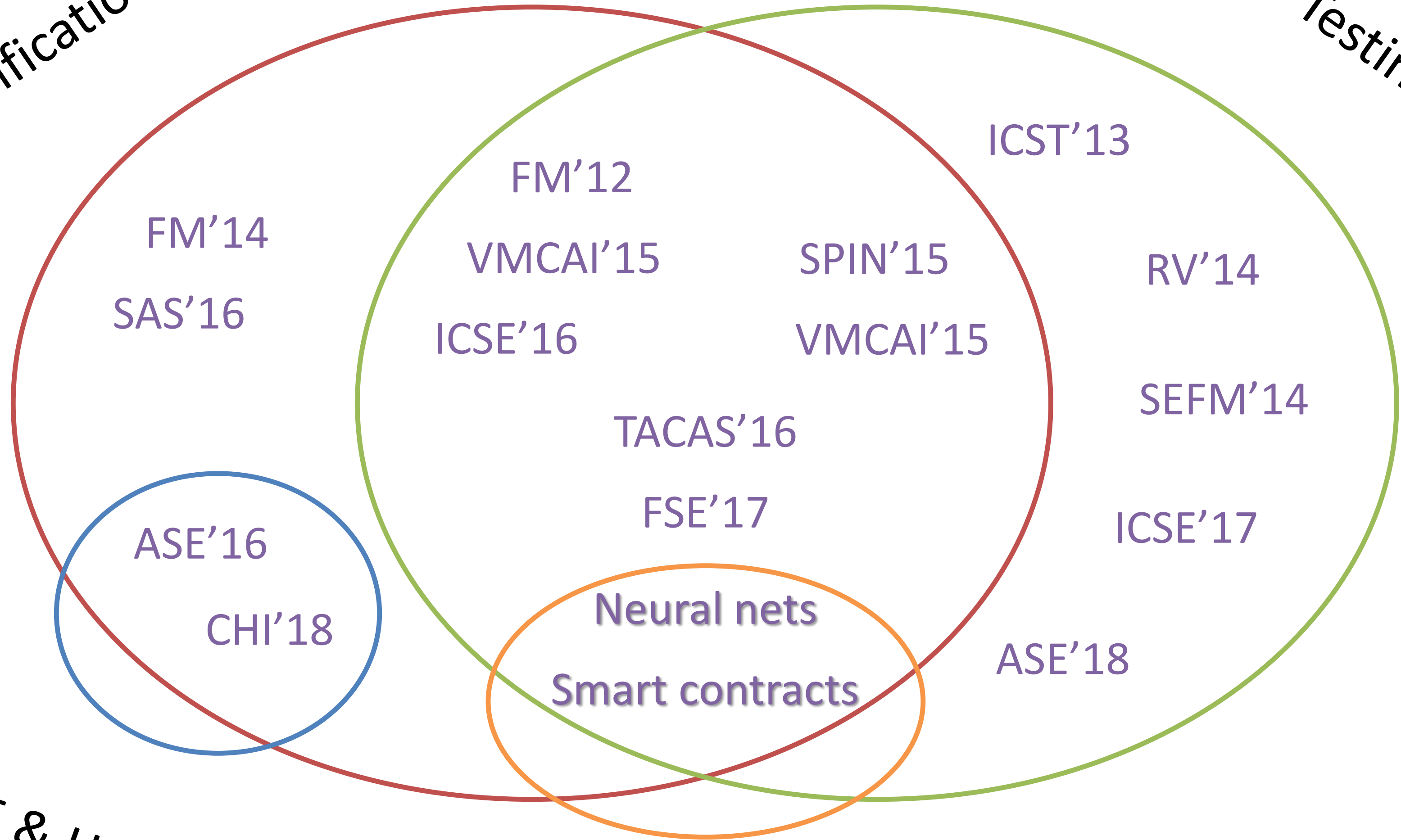
TACAS'16
FSE'17
ICST'13
RV'14
SEFM'14
ICSE'17
ASE'18
ASE'16
CHI'18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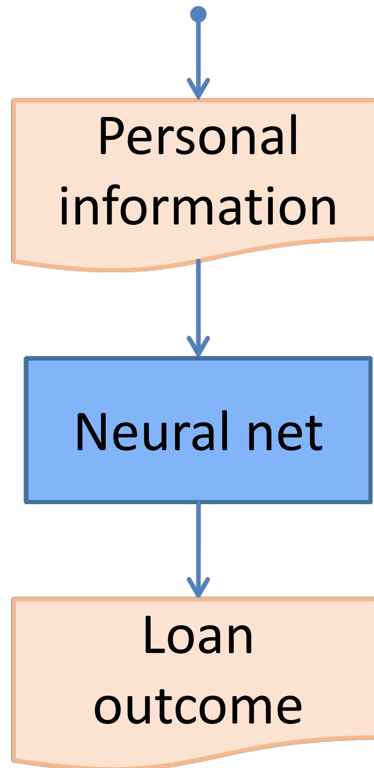
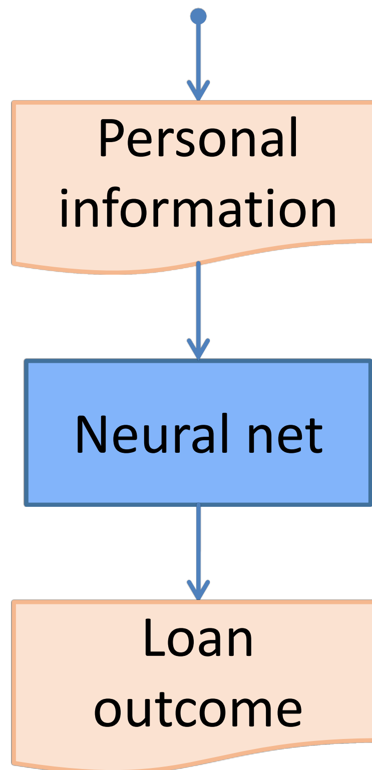
Neural nets
Smart contracts
ESE & HCI
Security & Privacy

Neural nets



Neural nets



Which parts of the input affect which output?

Are there privacy concerns?

Smart contracts

- Manage digital assets according to a protocol
- May jeopardize significant amounts of money
- Have subtle interactions at execution time
- Are written in expressive languages

Smart contracts

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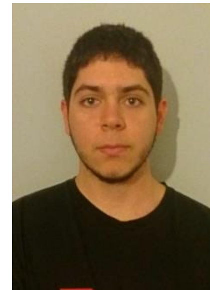
How to effectively detect security vulnerabilities?

How to help developers understand their possible behaviors?

Shameless plug

I am looking for motivated and talented students and interns!



Static Program Analysis Meets Test Case Generation

Maria Christakis
MPI-SWS, Germany