Finding and Understanding Bugs in Software Model Checkers

Chengyu Zhang, Ting Su, Yichen Yan, Fuyuan Zhang,
Geguang Pu, Zhendong Su

Software Model Checking

Software Model Checking

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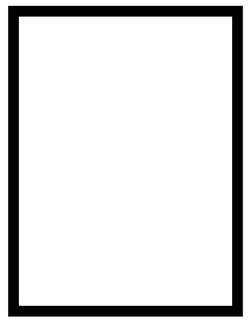
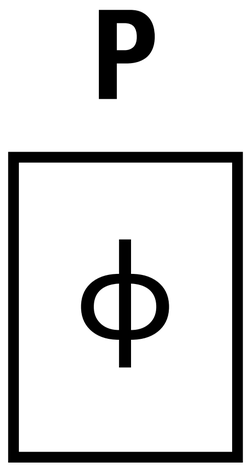
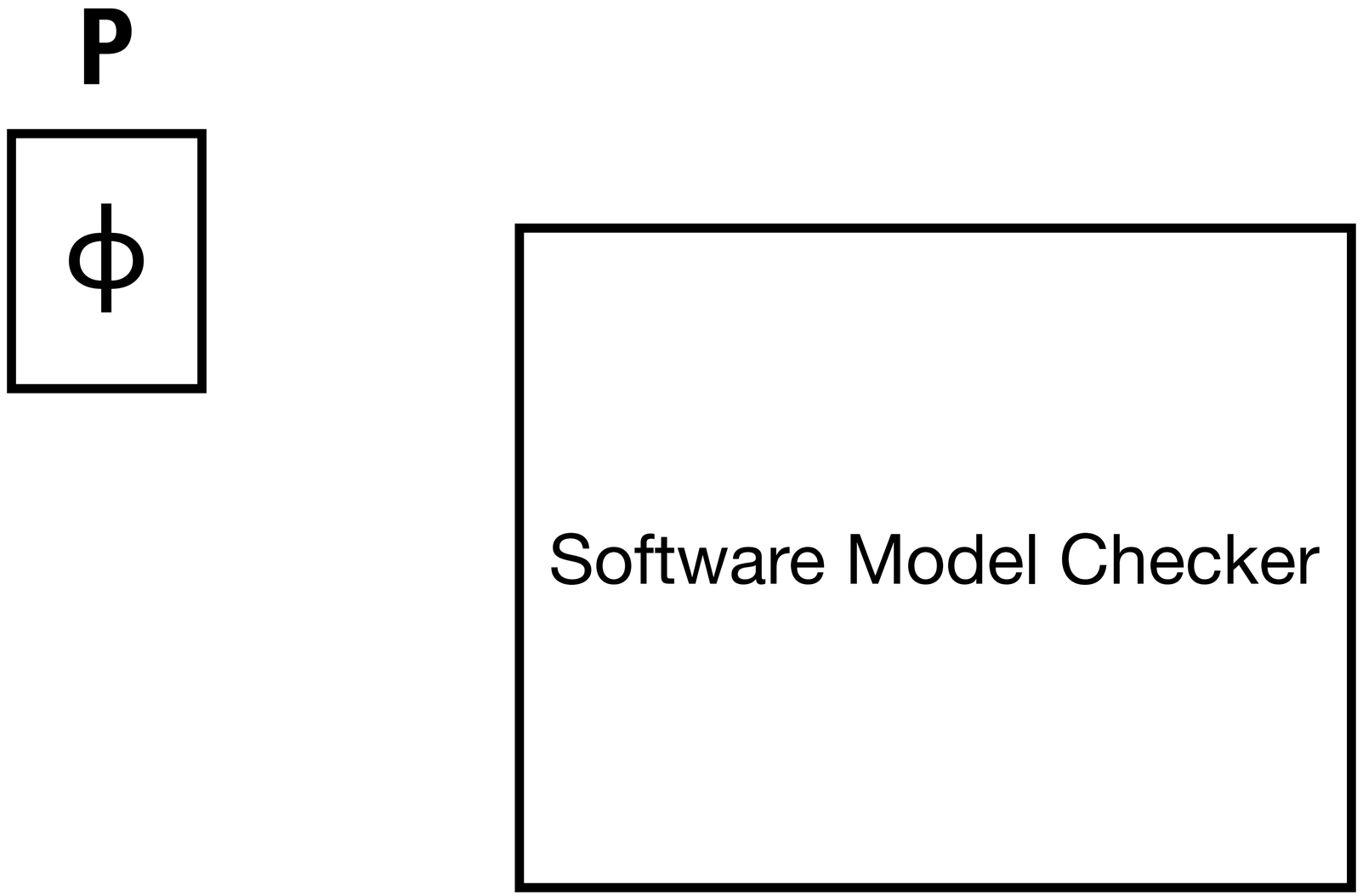


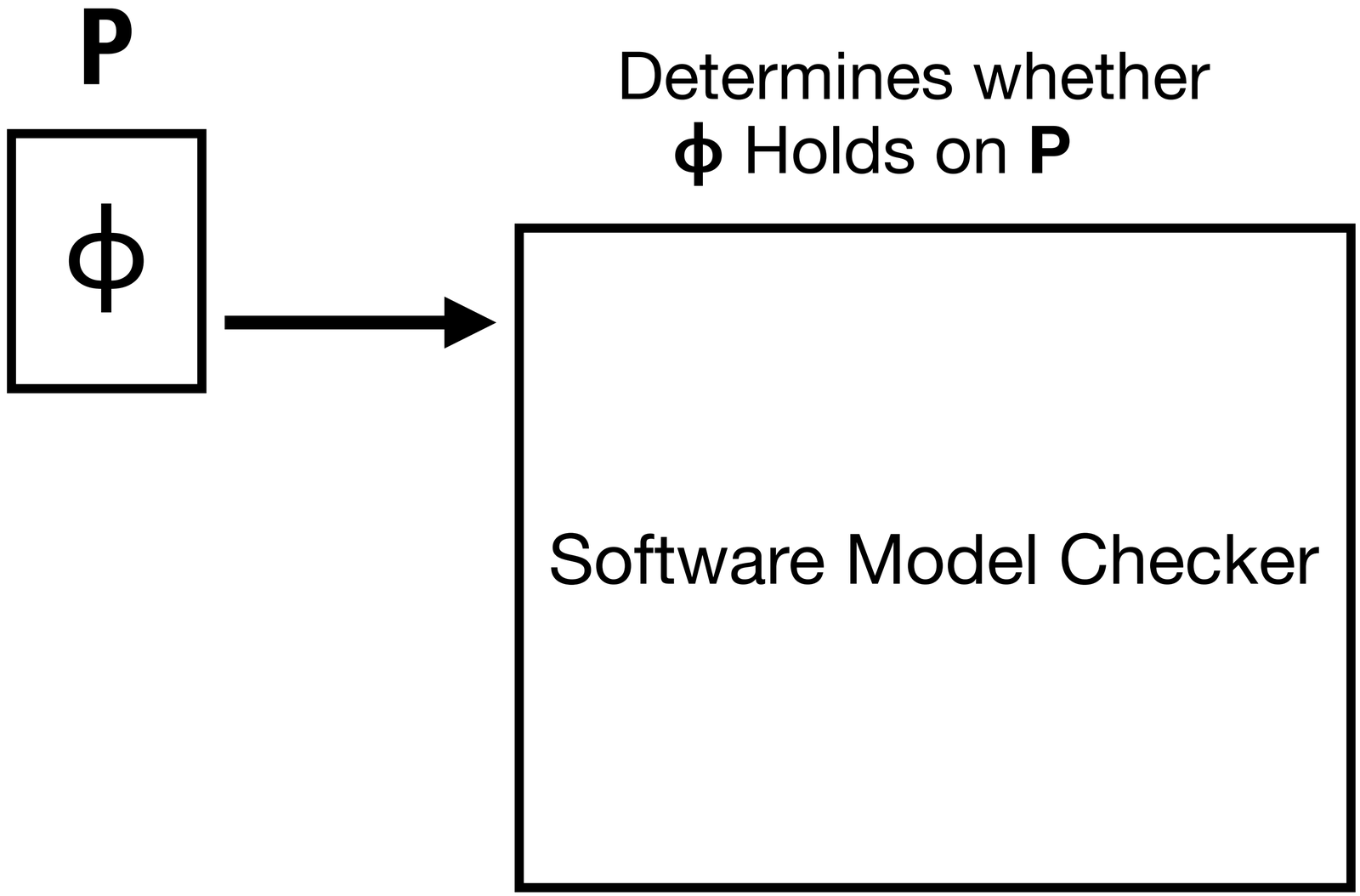
Software Model Checking



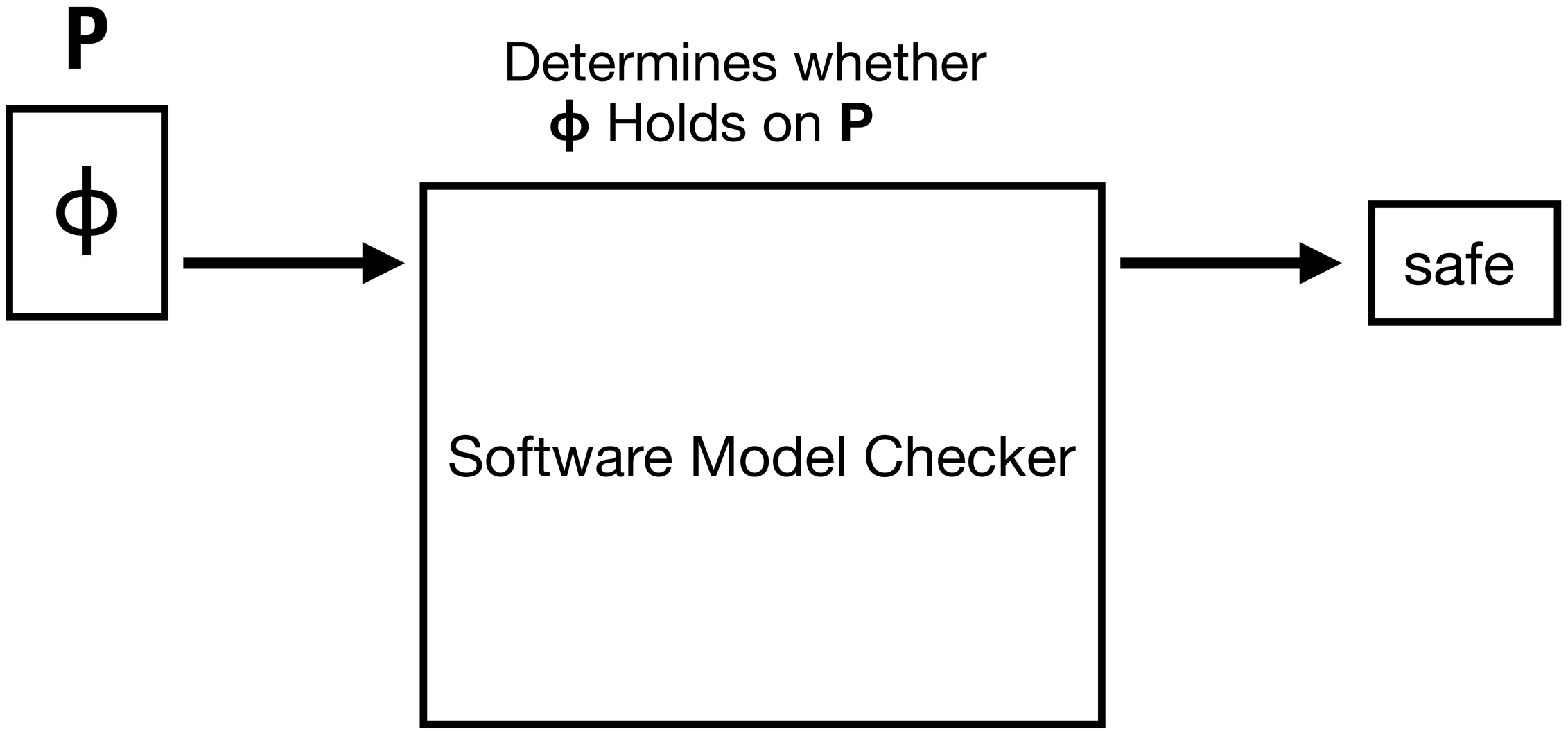
Software Model Checking



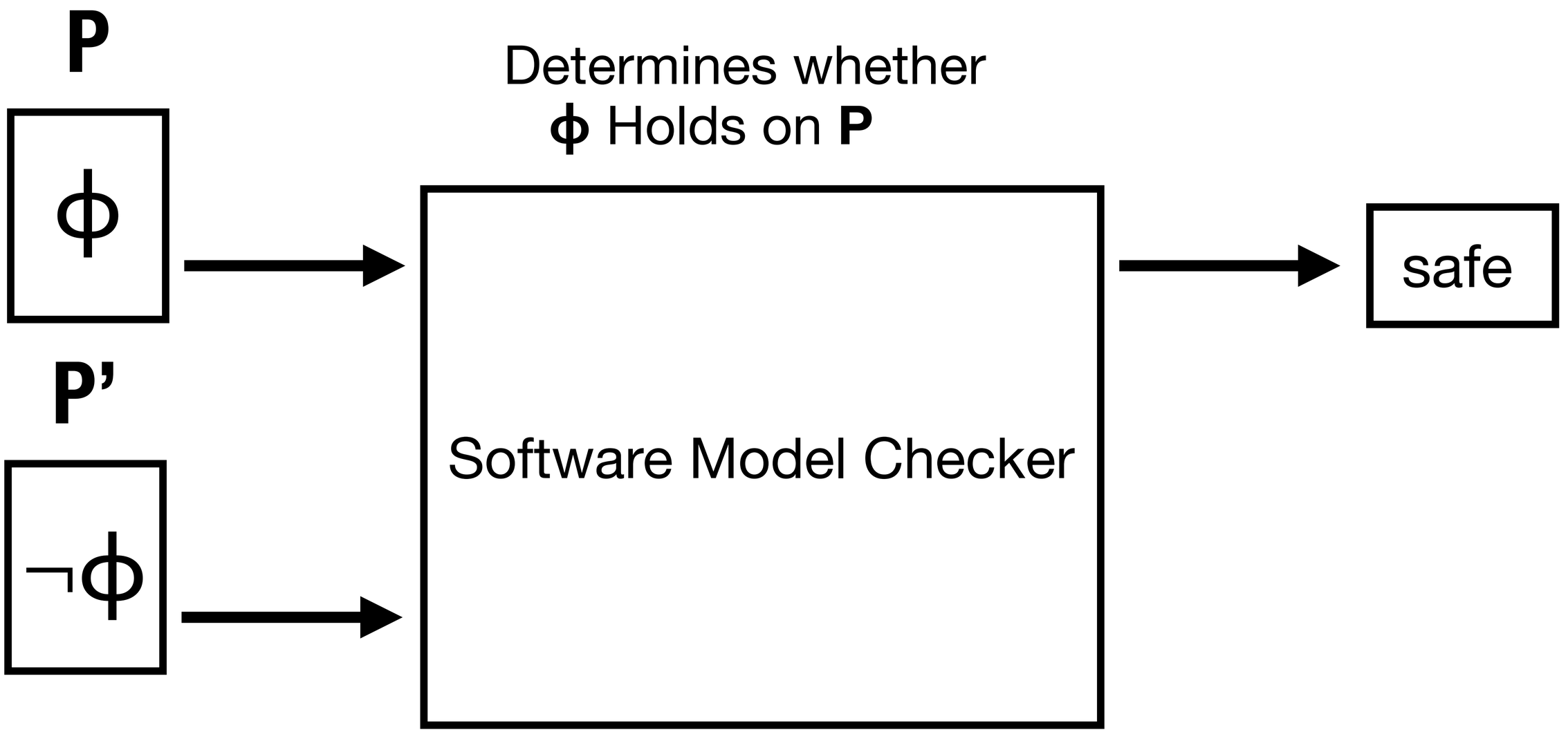
Software Model Checking



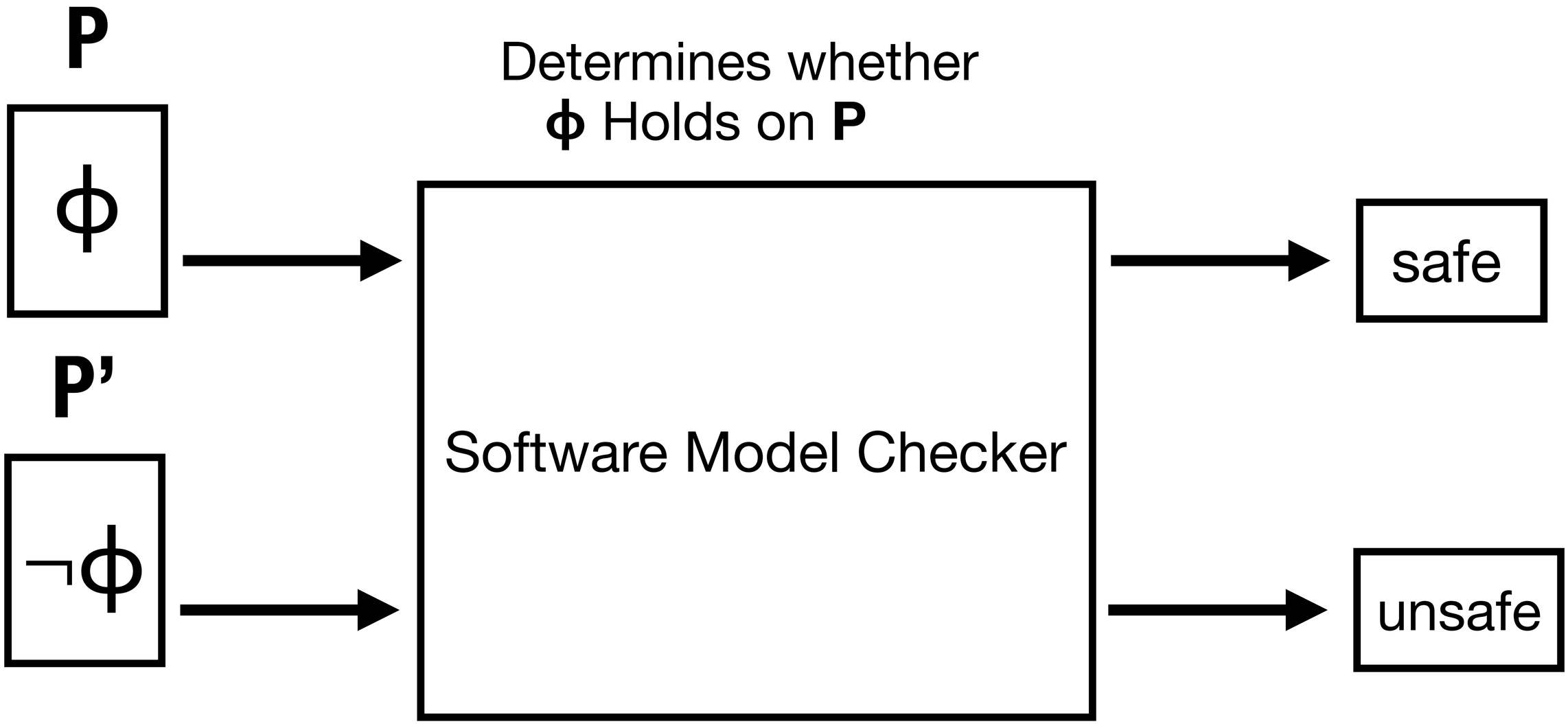
Software Model Checking



Software Model Checking



Software Model Checking

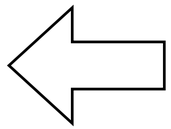


Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i > 0) {
       ……  //unreachable
      __VERIFIER_error();
  }
  return 0;
}
```

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i > 0) {
      ……  //unreachable
     __VERIFIER_error();
  }
  return 0;
}
```



Determines whether this function is reachable

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i > 0) {
       ……  //unreachable
      __VERIFIER_error();
  }
  return 0;
}
```

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i > 0) {
      ……  //unreachable
     __VERIFIER_error();
  }
  return 0;
}
```

SAFE!

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i == 0) {
       ……  //reachable
      __VERIFIER_error();
  }
  return 0;
}
```

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i == 0) {
       ……  //reachable
      __VERIFIER_error();
  }
  return 0;
}
```

UNSAFE!

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i == 0) {
       ……  //reachable
      __VERIFIER_error();
  }
  return 0;
}
```

software model checker:

SAFE!

Example: Reachability Safety Property

```
int main() {
  int i = 0;
  if (i == 0) {
       ……  //reachable
      __VERIFIER_error();
  }
  return 0;
}
```

software model checker:

SAFE!

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:0

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:0

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:1

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:1

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
      __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:1

UNSAFE

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
      __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

i:1

UNSAFE

Bug#529 in CPAchecker

```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
      __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

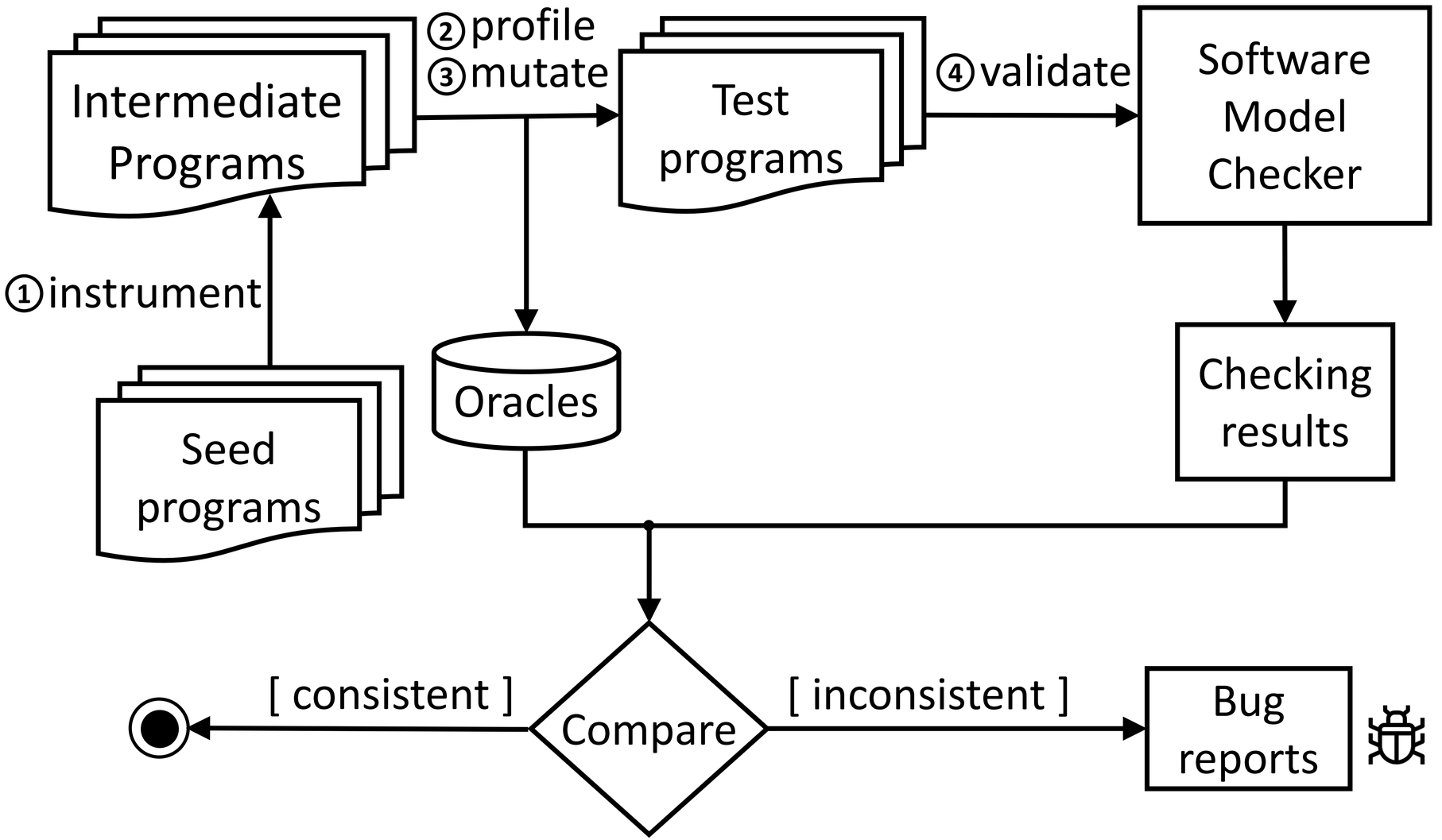
```
i:0
*(&i):1
```

Bug#529 in CPAchecker

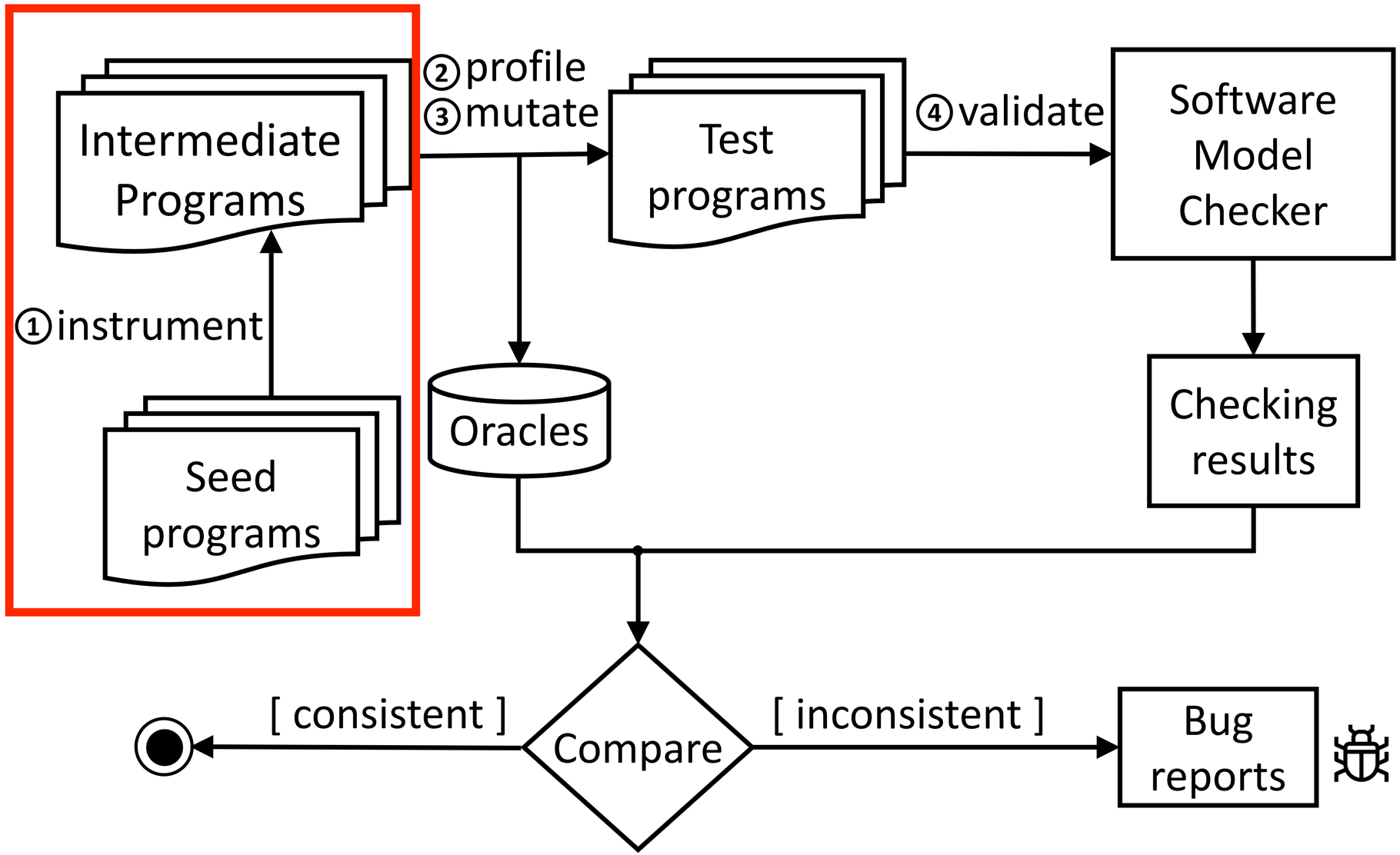
```
void main() {
  int i = 0;
  while (1) {
    if (i > 0) {
       __VERIFIER_error();
      break;
    }
    if (i == 0){
      *(&i) = *(&i) + 1;
    }
  }
}
```

```
i:0
*(&i):1
```

Workflow


Intermediate Programs
②profile
③mutate
Test programs
④validate
Software Model Checker
①instrument
Oracles
Checking results
Seed programs
[consistent]
Compare
[inconsistent]
Bug reports

Workflow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Approach I: Enumerative Reachability (ER)

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Approach I: Enumerative Reachability (ER)

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      __VERIFIER_error();
      if (i > 0) {
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
     }
   }
}
```

Intermediate Program 1

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
        __VERIFIER_error();
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
     }
   }
}
```

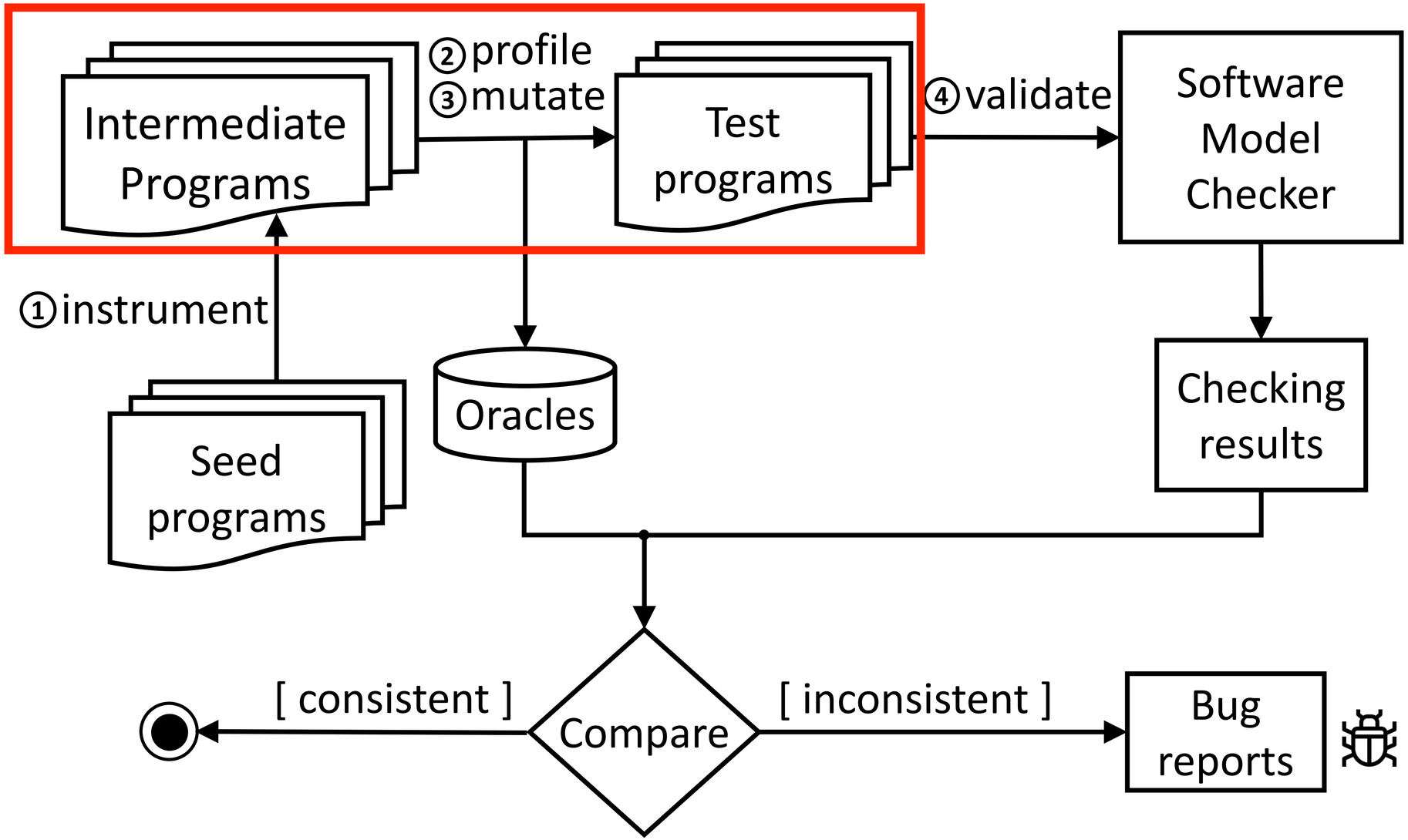
Intermediate Program 2

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
        __VERIFIER_error();
        *(&i) = *(&i) + 1;
     }
   }
}
```

Intermediate Program 3

Workflow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Approach I: Enumerative Reachability (ER)

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      __VERIFIER_error();
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Intermediate Program 1

Actual execution: unsafe

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         __VERIFIER_error();
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Intermediate Program 2

Actual execution: unsafe

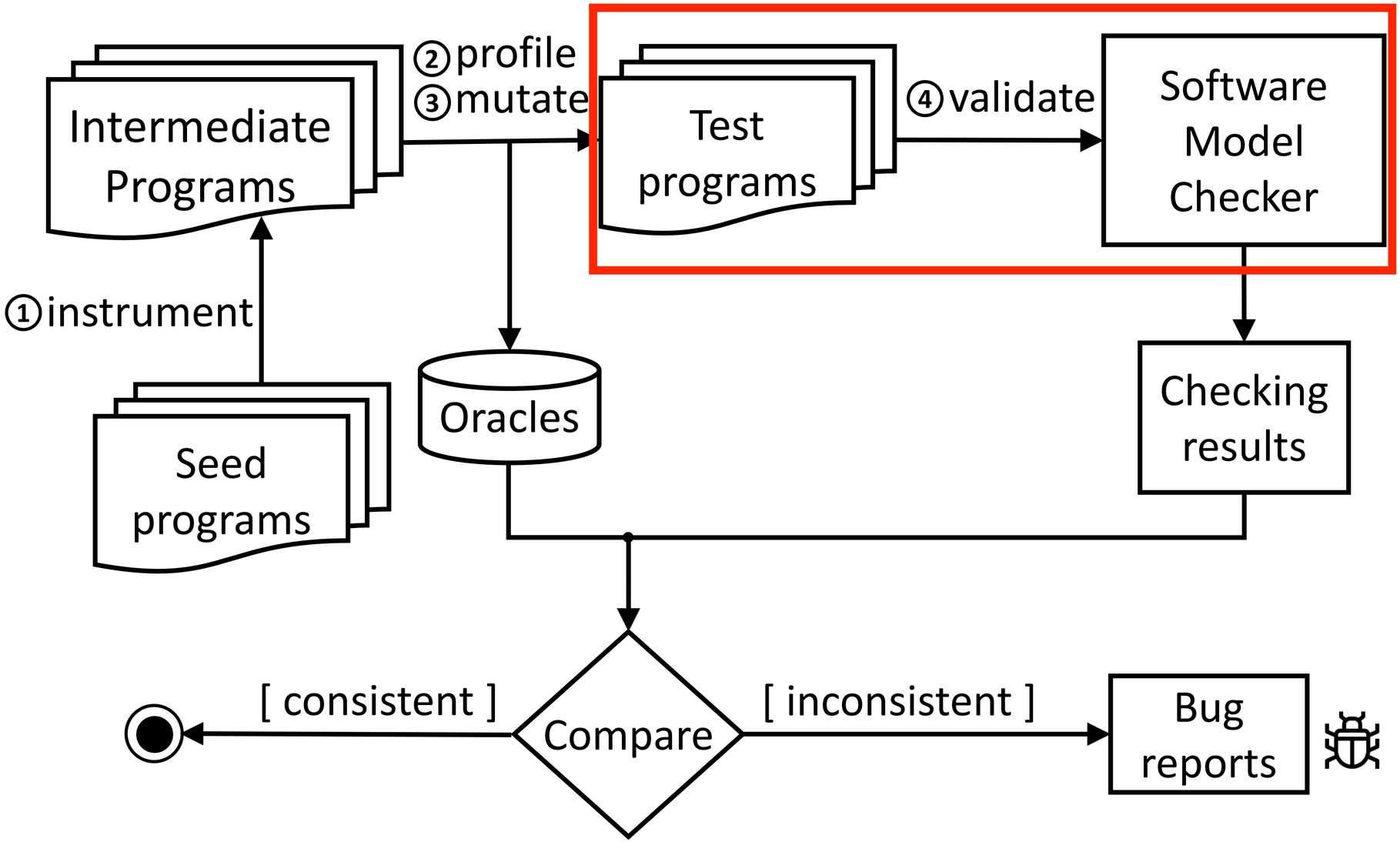
Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
         __VERIFIER_error();
    }
   }
}
```

Intermediate Program 3

Actual execution: unsafe

Workflow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Approach I: Enumerative Reachability (ER)

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```
void main() {
   int i = 0;
   while (1) {
      __VERIFIER_error();
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Test program 1

Actual execution: unsafe

Model checker: unsafe

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         __VERIFIER_error();
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Test program 2

Actual execution: unsafe

Model checker: safe

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
         __VERIFIER_error();
    }
   }
}
```

Test program 3

Actual execution: unsafe

Model checker: unsafe

Approach I: Enumerative Reachability (ER)

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      __VERIFIER_error();
         break;
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Test program 1

Actual execution: unsafe

Model checker: unsafe

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         __VERIFIER_error();
      }
      if (i == 0){
        *(&i) = *(&i) + 1;
    }
   }
}
```

Test program 2

Actual execution: unsafe

Model checker: safe

Bug#529 in CPAchecker

```
void main() {
   int i = 0;
   while (1) {
      if (i > 0) {
         break;
      }
      if (i == 0){
         __VERIFIER_error();
    }
   }
}
```

Test program 3

Actual execution: unsafe

Model checker: unsafe

Approach

- Approach I: Enumerative Reachability (ER)

Bug#534 in CPAchecker

```
int main(void){
  int a[3] = {1};
  int i = 0;
  while(i < 3){
    if(a[i] == 1) {
      ……
    }
    i++;
  }
  return 0;
}
```

a[3]:{1,0,0}

Bug#534 in CPAchecker

```
int main(void){
  int a[3] = {1};
  int i = 0;
  while(i < 3){
    if(a[i] == 1) {
      ……
    }
    i++;
  }
  return 0;
}
```

a[3]:{1,1,1}

Bug#534 in CPAchecker

```
int main(void){
  int a[3] = {1};
  int i = 0;
  while(i < 3){
    if(a[i] == 1) {
      ......
    }
    i++;
  }
  return 0;
}
```

a[3]:{1,1,1}: unsafe 

a[3]:{1,0,0}: unsafe

Bug#534 in CPAchecker

```
int main(void){
  int a[3] = {1};
  int i = 0;
  while(i < 3){
    if(a[i] == 1) {
      __VERIFIER_error();
    }
    i++;
  }
  return 0;
}
```

a[3]:{1,1,1}: unsafe 

a[3]:{1,0,0}: unsafe

Approach II: Enumerative **Counting** Reachability (ECR)

```c
int main(void){
   int a[3] = {1};
   int i = 0;

   while(i < 3){
     if(a[i] == 1) {

       ……
     }
     i++;
   }


   return 0;
}
```

```c
int main(void){
   int a[3] = {1};
   int i = 0;

   while(i < 3){

     if(a[i] == 1) {
       ……
     }
     i++;
   }


   return 0;
}
```

Approach II: Enumerative **Counting** Reachability (ECR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      if(a[i] == 1) {
         br++;
         ……
      }
      i++;
   }
   GetValue(br)

   return 0;
}
```

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      br++;
      if(a[i] == 1) {
         ……
      }
      i++;
   }
   GetValue(br)

   return 0;
}
```

Approach II: Enumerative **Counting** Reachability (ECR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      if(a[i] == 1) {
         br++;
         ……
      }
      i++;
   }
   GetValue(br)

   return 0;
}
```

Actual execution: br=1

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      br++;
      if(a[i] == 1) {
         ……
      }
      i++;
   }
   GetValue(br)

   return 0;
}
```

Actual execution: br=3

Approach II: Enumerative **Counting** Reachability (ECR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      if(a[i] == 1) {
         br++;
         ……
      }
      i++;
   }
   if(br != 1)
      __VERIFIER_error();
   return 0;
}
```

Actual execution: br=1

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      br++;
      if(a[i] == 1) {
         ……
      }
      i++;
   }
   if(br != 3)
      __VERIFIER_error();
   return 0;
}
```

Actual execution: br=3

Approach II: Enumerative **Counting** Reachability (ECR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      if(a[i] == 1) {
         br++;
         ……
      }
      i++;
   }
   if(br != 1)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      br++;
      if(a[i] == 1) {
         ……
      }
      i++;
   }
   if(br != 3)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe

Approach II: Enumerative **Counting** Reachability (ECR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      if(a[i] == 1) {
         br++;
         ……
      }
      i++;
   }
   if(br != 1)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe
Model checker: unsafe

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;
   while(i < 3){
      br++;
      if(a[i] == 1) {
         ……
      }
      i++;
   }
   if(br != 3)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe
Model checker: safe

Approach

- Approach I: Enumerative Reachability (ER)
- Approach II: Enumerative **Counting** Reachability (ECR)

Approach III: **Fused** Counting Reachability (FCR)

```
int main(void){
   int a[3] = {1};
   int i = 0;

   while(i < 3){

     if(a[i] == 1) {

       ……
     }
     i++;
   }


   return 0;
}
```

Approach III: **Fused** Counting Reachability (FCR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;int br2 = 0;
   while(i < 3){
      br1++;
      if(a[i] == 1) {
         br2++;
         ……
      }
      i++;
   }
   GetValue(br1)
   GetValue(br2)
   return 0;
}
```

Actual execution: br1=1; br2=3

Approach III: **Fused** Counting Reachability (FCR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;int br2 = 0;
   while(i < 3){
      br1++;
      if(a[i] == 1) {
         br2++;
         ……
      }
      i++;
   }
   if(br1 != 3 || br2 != 1)
      __VERIFIER_error();
   return 0;
}
```

Approach III: **Fused** Counting Reachability (FCR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;int br2 = 0;
   while(i < 3){
      br1++;
      if(a[i] == 1) {
         br2++;
         ……
      }
      i++;
   }
   if(br1 != 3 || br2 != 1)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe

Approach III: **Fused** Counting Reachability (FCR)

```
int main(void){
   int a[3] = {1};
   int i = 0;
   int br = 0;int br2 = 0;
   while(i < 3){
      br1++;
      if(a[i] == 1) {
         br2++;
         ……
      }
      i++;
   }
   if(br1 != 3 || br2 != 1)
      __VERIFIER_error();
   return 0;
}
```

Test oracle: safe

Model checker: unsafe

Approach

- Approach I: Enumerative Reachability (ER)
- Approach II: Enumerative **Counting** Reachability (ECR)
- Approach III: **Fused** Counting Reachability (FCR)

Approach

find more kinds of bugs

- Approach I: Enumerative Reachability (ER)
- Approach II: Enumerative **Counting** Reachability (ECR)
- Approach III: **Fused** Counting Reachability (FCR)

Approach

- Approach I: Enumerative Reachability (ER)
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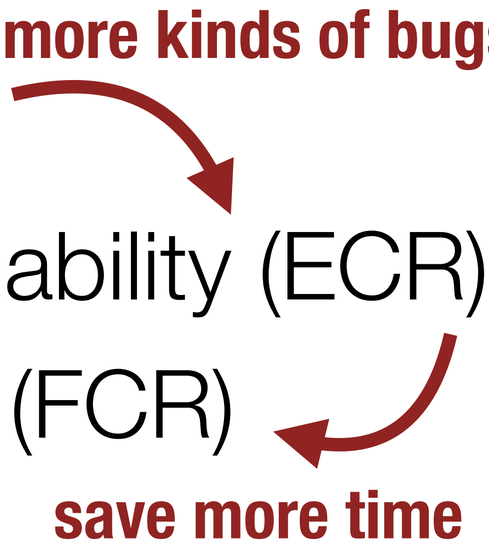

Evaluation Setup

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GCC test suite

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4,609 Files
219,636 Loc

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SeaHorn

IC3 based

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RQ1: Can our approaches find bugs?

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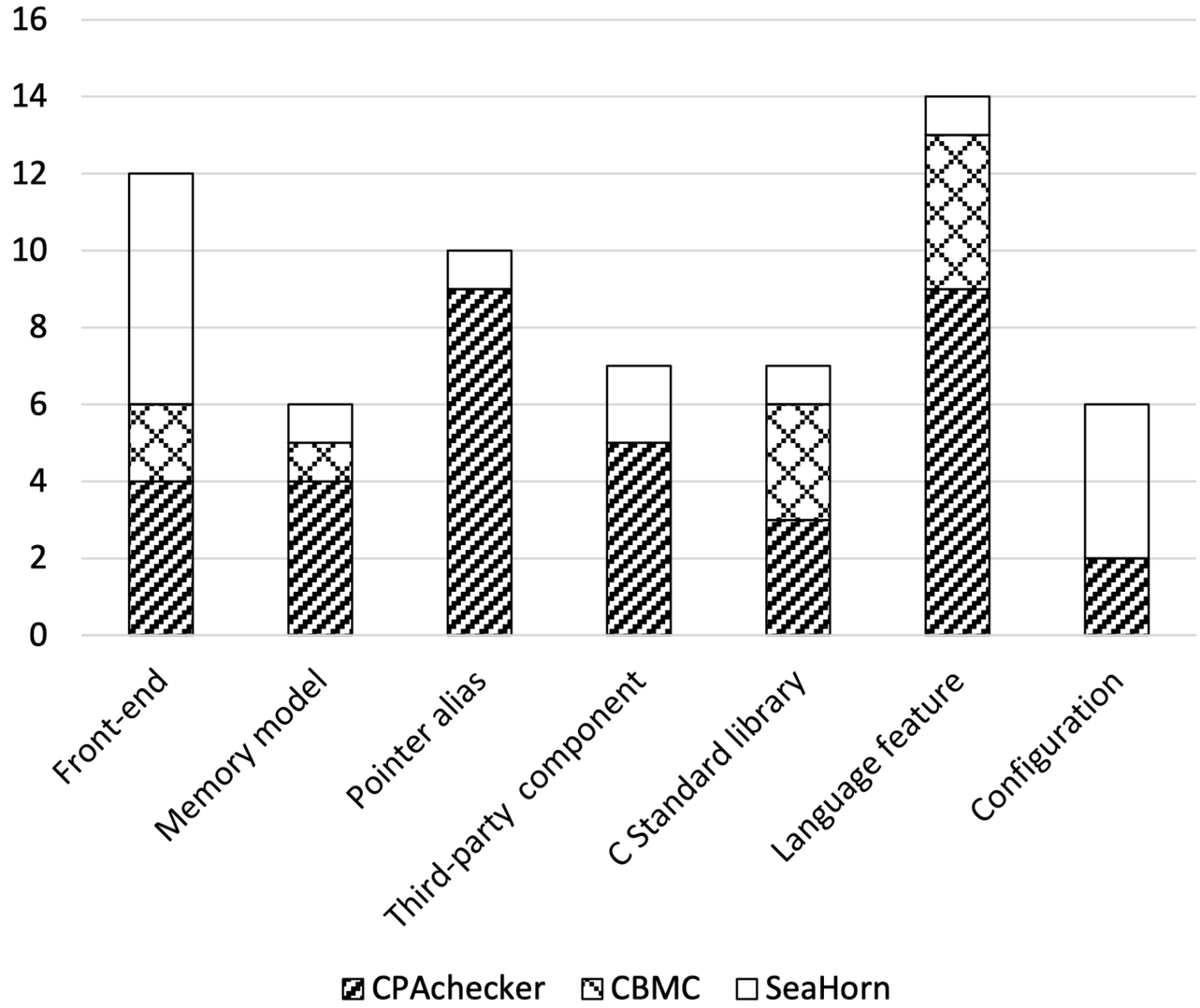

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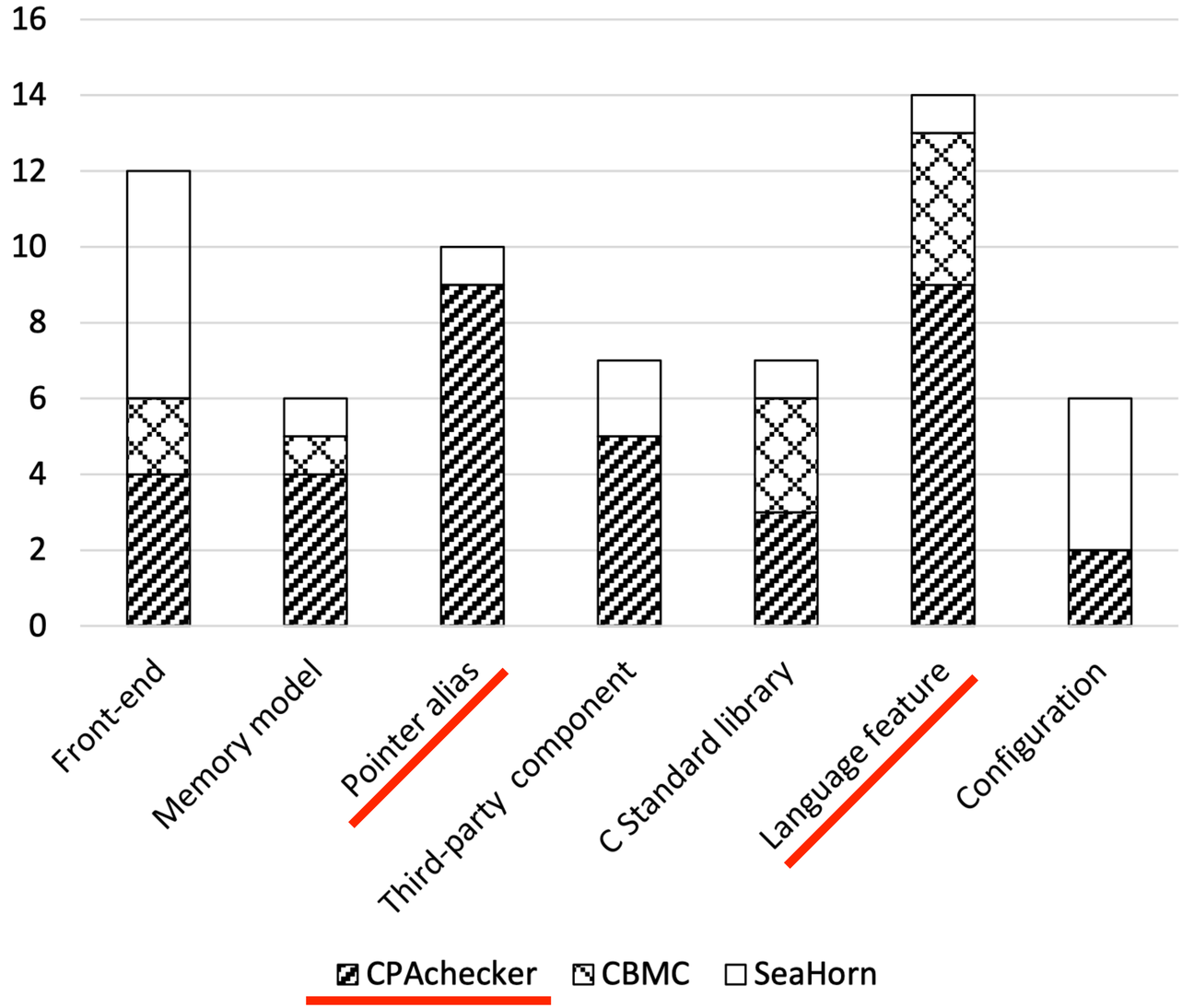

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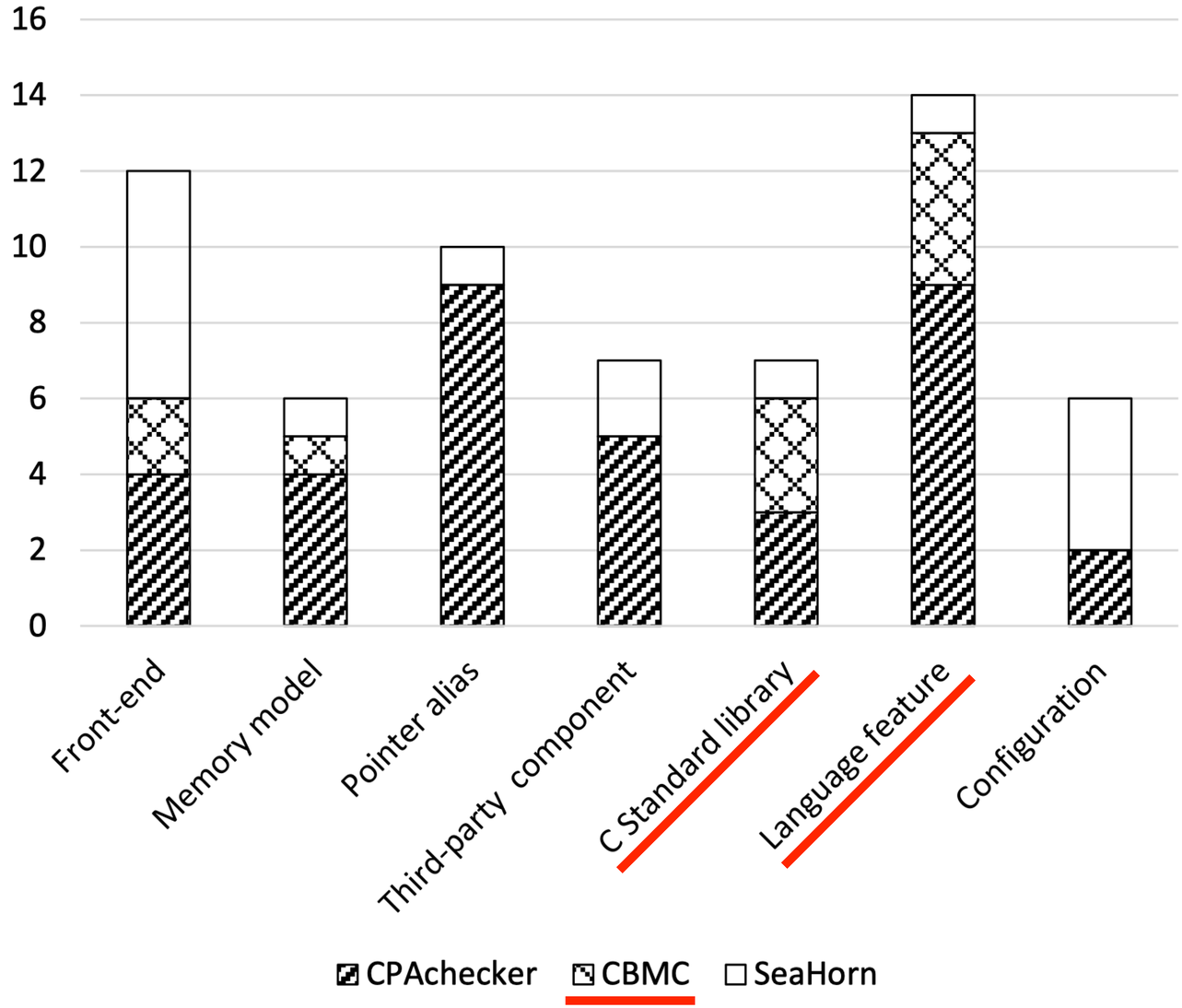

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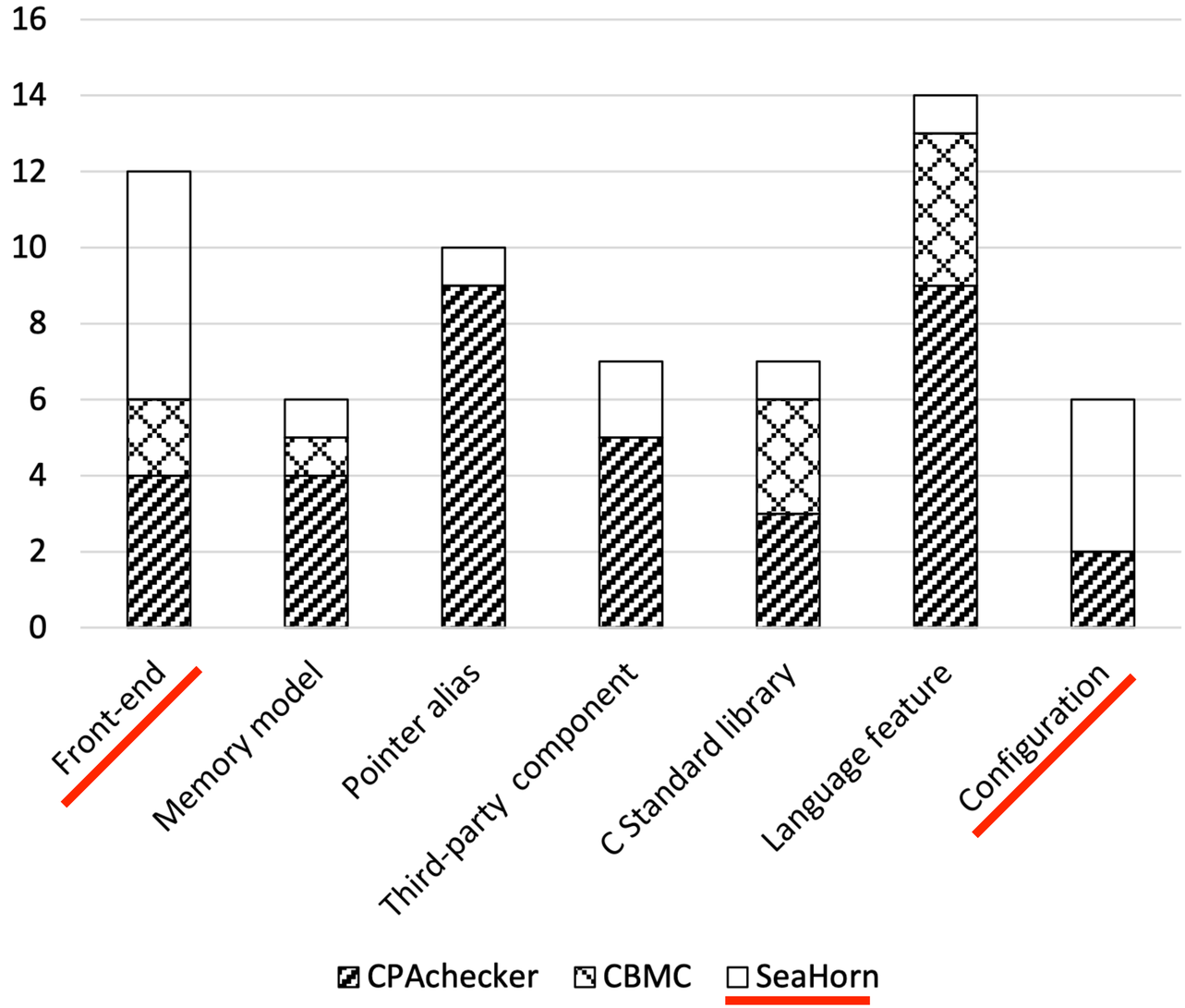

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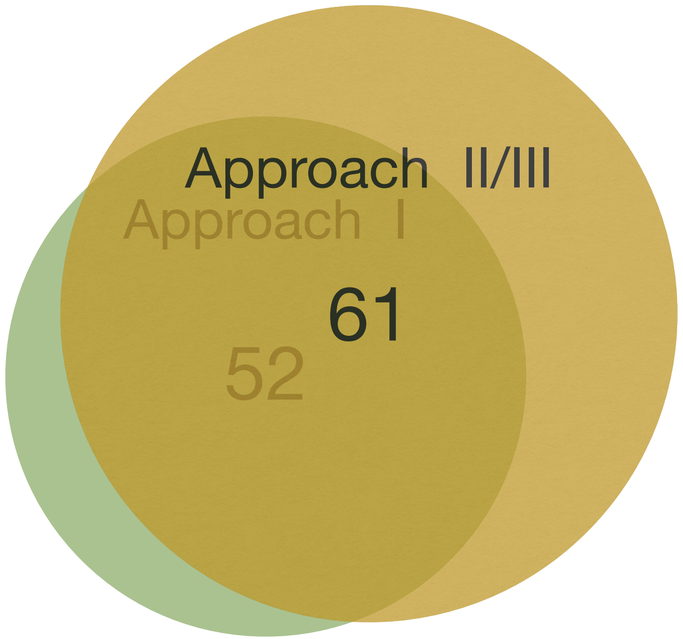

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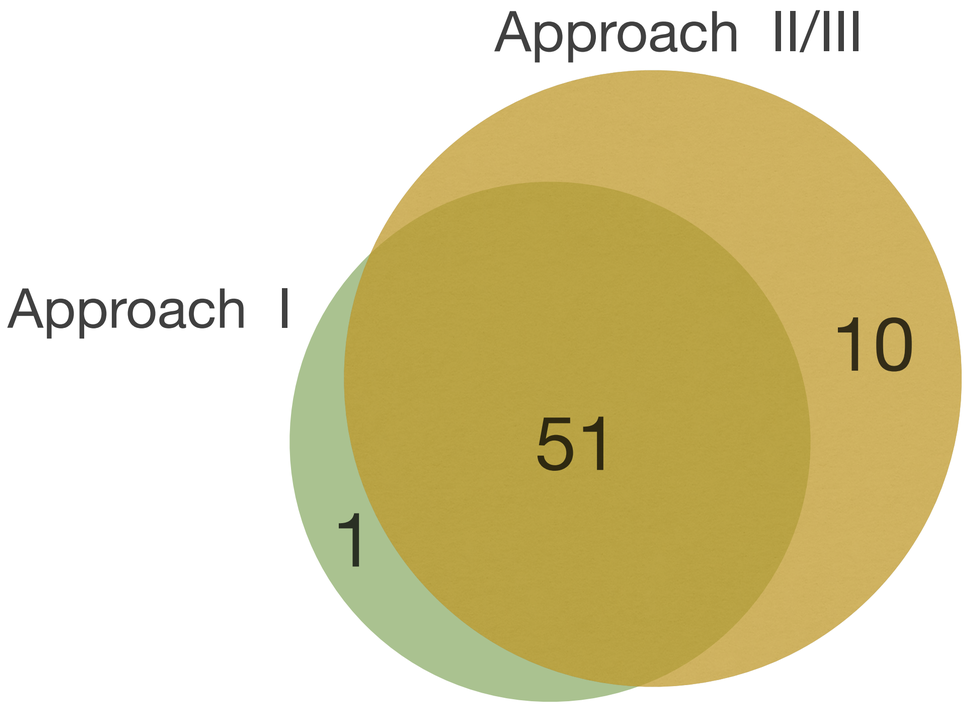

Bug#529 in CPAchecker (False negative in approach II/III)

```
void main() {
  int i = 0;

  while (1) {
     if (i > 0) {

        break;
     }
     if (i == 0){
       *(&i) = *(&i) + 1;
    }
  }


}
```

```
i:0
*(&i):1
```

Bug#529 in CPAchecker (False negative in approach II/III)

```
void main() {
  int i = 0;
  int br = 0;
  while (1) {
     if (i > 0) {
        br++;
        break;
     }
     if (i == 0){
       *(&i) = *(&i) + 1;
    }
  }
  if(br != 1)
     __VERIFIER_error();
}
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i:0
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Test oracle: safe

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Buggy model checker: safe

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RQ3: How much time does each approach consume?

Save 89% of time

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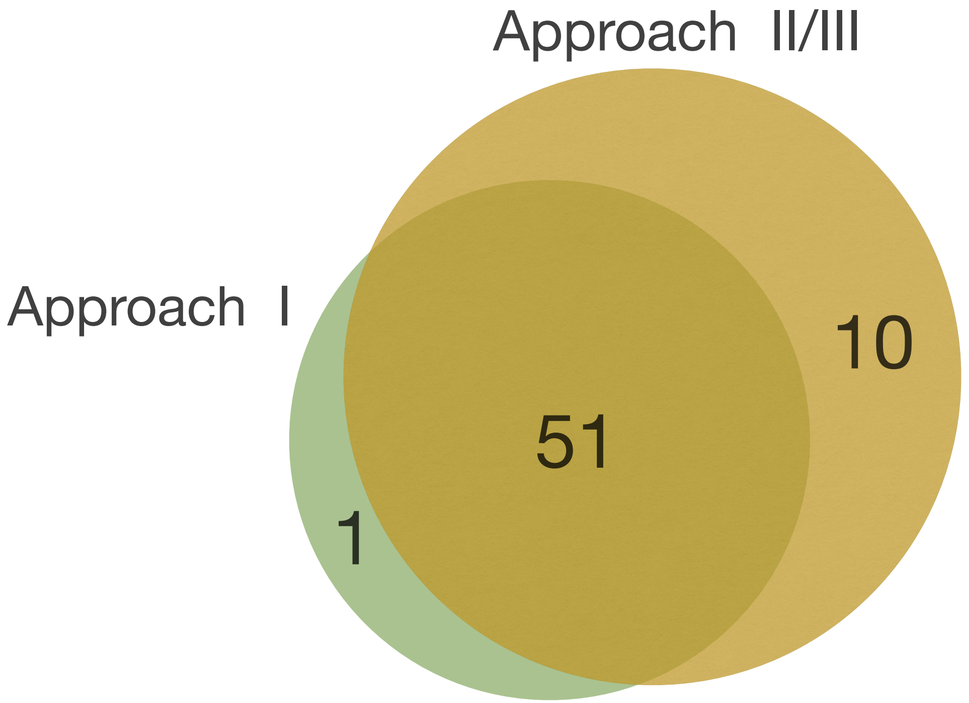

Assorted Bug Samples

- Front-end
- Memory model
- Pointer alias
- Third-party component
- C standard library
- Language feature
- Configuration

https://github.com/MCFuzzer/MCFuzz/issues

Example: Front-end related bug in CPAchecker

```
void f(int a, int b){
  if (a == b)
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}
int main(){
  int d = 0;
  int c = 4;
  int e = 2;
  f (d=c&&e, 1);
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d = c&&e = 1

Test oracle: unsafe

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Example: Language feature related bug in CBMC

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struct {
int a:4; int :4;
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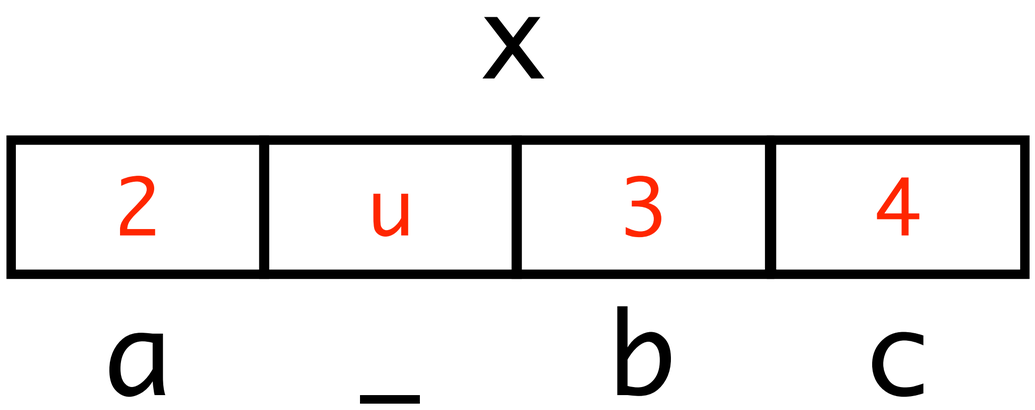
} x = { 2,3,4 };
int main (){
  if (x.b != 3)
    __VERIFIER_error();
  return 0;
}
```

Test oracle: safe



"Unnamed members of objects of structure type do not participate in initialization."

-- C standard

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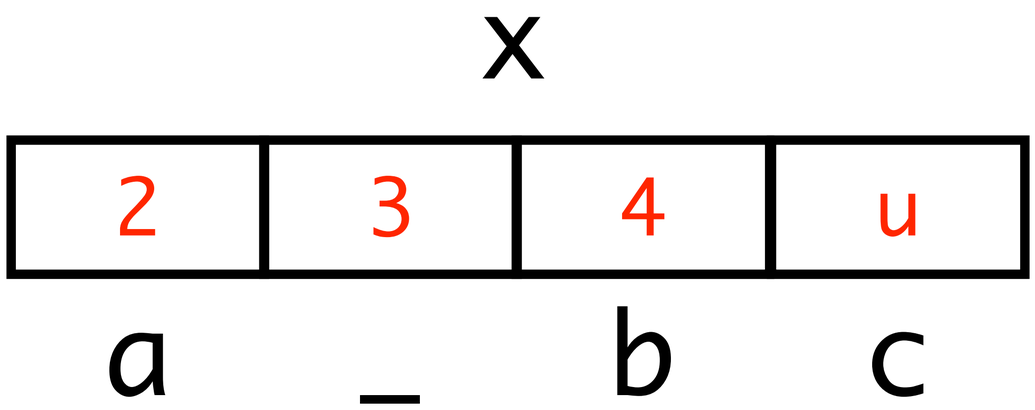

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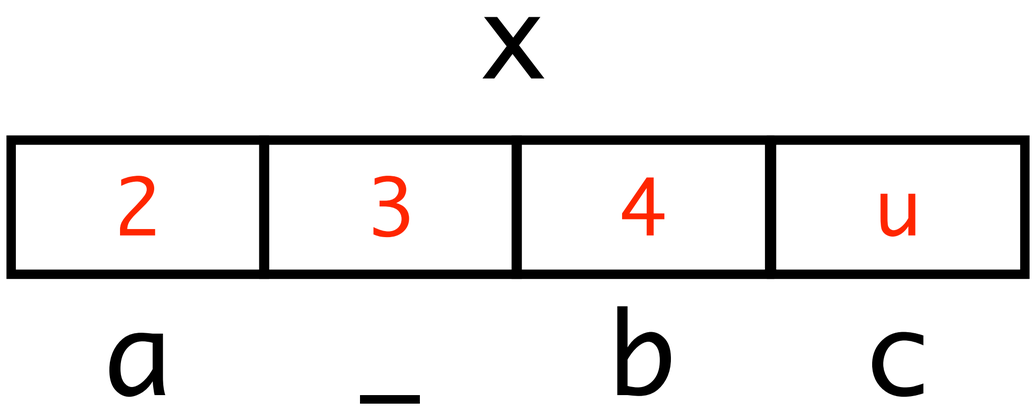
CBMC : unsafe



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Example: Configuration related bug in Seahorn

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void test(int x,int y,
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  if ((x / y) != q )
    __VERIFIER_error();
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int main (){
  test (7, 6, 1);
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7/6 == 1
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  - It is not the bug, but leads to false alarms.

Usability of software model checkers

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✓ Should not give wrong checking result.

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- ✓ Should not give wrong checking result.
- ✓ Should not let user to choose the right configuration.
- ✓ Better user manual.

Developers' Feedback

kuhar commented on Jul 26 • edited

Hello,

FYI, the MCFuzz issues filled against SeaHorn are now in its test suite and run in CI after every commit:
https://github.com/seahorn/seahorn/tree/master/test/mcfuzz

As of today, SeaHorn passes 9 out of the 16 test-cases provided.

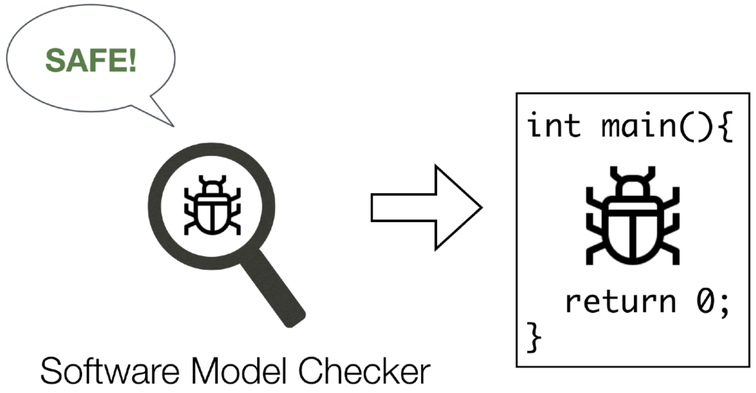
kroening commented on Jan 6 — Member

Many thanks; I've made a PR with a test for this as PR #3695.

Again, thank you very much for finding and reporting these cases!
This is very helpful for us.

Kind regards,
Philipp

Software model checker may have bugs



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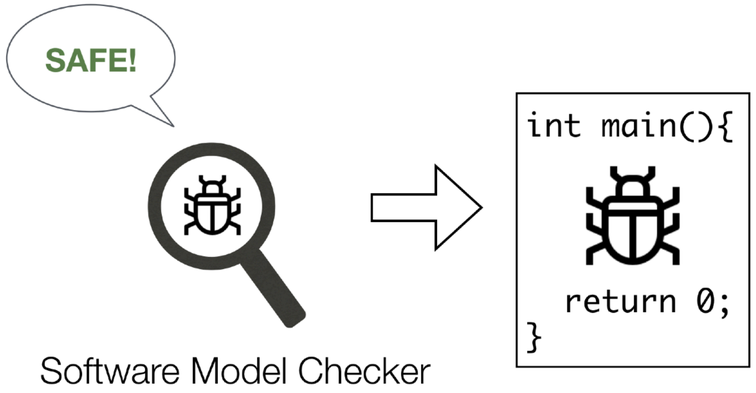

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find more kinds of bugs

save more time

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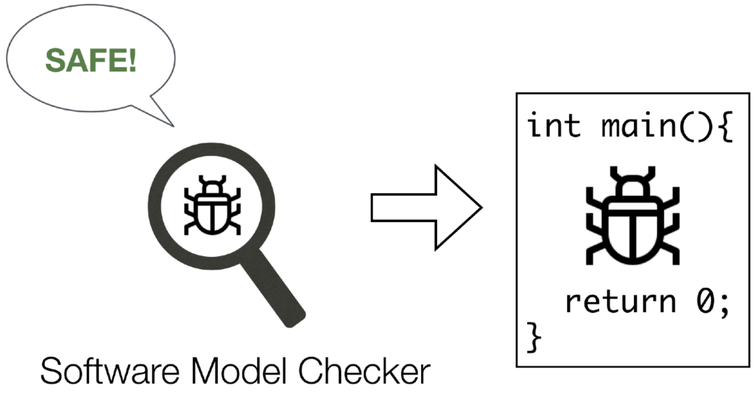

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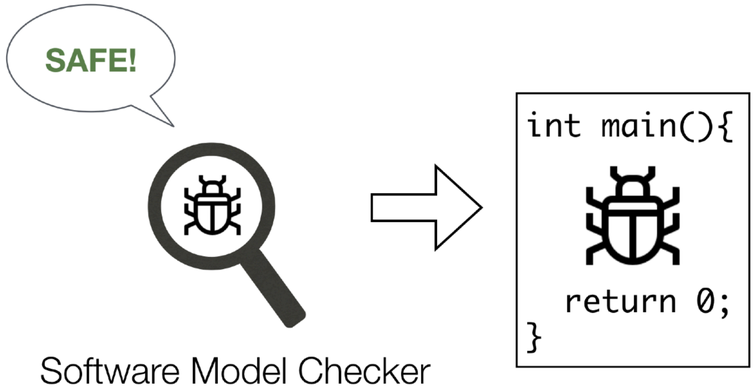

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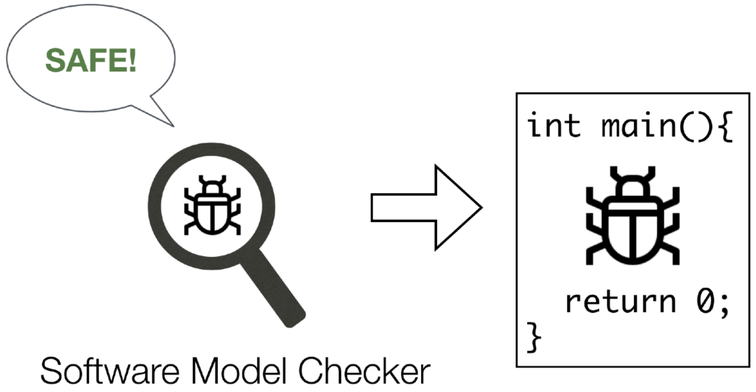

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