PBE-Based Selective Abstraction and Refinement for Efficient Property Falsification of Embedded Software

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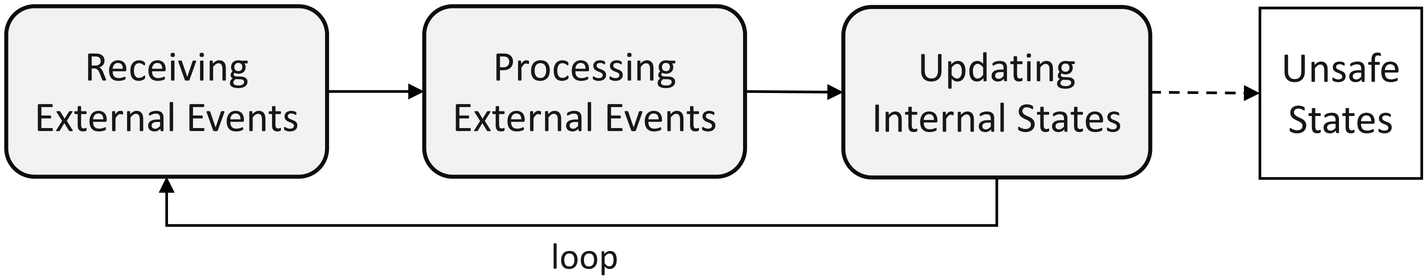
AGILE & AUTOMATED RESPONSE & REPAIR

Motivation

- Major characteristics of **embedded software**:
  - It constantly interacts with external events within an **infinite loop**
  - It maintains **internal states** whose updates must be traced
  - **Safety properties** may be violated only after many loop iterations



Motivation

- **Verification/Falsification** of embedded software:
  - e.g., (dis)proving "A car reduces its speed within a specified time"
  - We have seen decades of effort for this:
    - Most of them were **model-based** approaches applied to cyber-physical systems, automobiles, or medical devices, etc.
    - **Code-based** property verification/falsification is very **expensive**

Table 1: Code-based property falsification of an elevator controller (about 900 LoC)

Tools	# of refinements	Time usage	Memory usage
CBMC	N/A	8.3 hours	**> 80 GB (OOM)**
CPAchecker	**418**	**> 72 hours (T/O)**	7.1 GB

Motivating Example

Embedded Control Program

```c
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int xul = data[i * 5 + 2];
      int xlr = data[i * 5 + 3];
      int yul = data[i * 5 + 4];
      int ylr = data[i * 5 + 5];
      int width = abs(xul - xlr);
      int height = abs(yul - ylr);
      int area = width * height;
      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
    }
  }
  return max_index; }
```

```c
int timer = 0;
int speed = 0;
#define MAX_SPEED 100

int main() {
  int data[41];
  int i;
  while(1) {
    data = receive();
    i = process(data);
    if(i >= 0) {
      update(i, data);
    }
    assert(is_safe());
  }
}
```

```c
void update(int i, int *data) {
  speed = speed + data[i * 5 + 1];
  if(speed > MAX_SPEED) {
    speed = MAX_SPEED; }}
```

```c
int is_safe() {
  if(speed >= MAX_SPEED){
    timer = timer + 1;
  }
  else timer = 0;
  return timer < 1000;}
```

- Checking this **concrete** program suffers from state space explosion (OOM)
- Abstracting this program too **coarsely** produces many false alarms

Motivating Example

Embedded Control Program

```
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int
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      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
    }
  }
  return max_index; }
```

```
int timer = 0;
int speed = 0;
#define MAX_SPEED 100

int main() {
    if(i >= 0) {
      update(i, data);
    }
    assert(is_safe());
  }
}
```

```
) {
 + 1];
```

```
int is_safe() {
  if(speed >= MAX_SPEED){
    timer = timer + 1;
  }
  else timer = 0;
  return timer < 1000;}
```

We need to find a better abstraction approach for embedded software domain

- Checking this **concrete** program suffers from state space explosion (OOM)
- Abstracting this program too **coarsely** produces many false alarms

Main Idea 1: Selective Abstraction

Auxiliary Function

```c
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int xul = data[i * 5 + 2];
      int xlr = data[i * 5 + 3];
      int yul = data[i * 5 + 4];
      int ylr = data[i * 5 + 5];
      int width = abs(xul - xlr);
      int height = abs(yul - ylr);
      int area = width * height;
      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
    }
  }
  return max_index; }
```

Main Control Logic

```c
int timer = 0;
int speed = 0;
#define MAX_SPEED 100

int main() {
  int data[41];
  int i;
  while(1) {
    data = receive();
    i = process(data);
    if(i >= 0) {
      update(i, data);
    }
    assert(is_safe());
  }
}
```

```c
void update(int i, int *data) {
  speed = speed + data[i * 5 + 1];
  if(speed > MAX_SPEED) {
    speed = MAX_SPEED; }}
```

```c
int is_safe() {
  if(speed >= MAX_SPEED){
    timer = timer + 1;
  }
  else timer = 0;
  return timer < 1000;}
```

- **Auxiliary functions:** functions that do *not* update any internal states (e.g., global variables)

Main Idea 1: Selective Abstraction

Auxiliary Function

```
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int xul = data[i * 5 + 2];
```

Abstraction!

```
      int height = abs(yul - ylr);
      int area = width * height;
      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
    }
  }
  return max_index; }
```

Main Control Logic

```
int timer = 0;
int speed = 0;
#define MAX_SPEED 100

int main() {
  int data[41];
  int i;
  while(1) {
    data = receive();
    i = process(data);
    if(i >= 0) {
      update(i, data);
    }
    assert(is_safe());
  }
}
```

No Abstraction

```
i, int *data) {
+ data[i * 5 + 1];
X_SPEED) {
_SPEED; }}
```

```
int is_safe() {
  if(speed >= MAX_SPEED){
    timer = timer + 1;
  }
  else timer = 0;
  return timer < 1000;}
```

- **Main control logic** has a significant impact on the program & property
- Abstracting the **main control logic** is likely to produce many false alarms

Main Idea 2: PBE-Based Abstraction

(1) Initial Abstraction

```
int process(int *data) {
  return nondet();
}
```

240 seconds, but false alarm

(2) **Refined Abstraction**

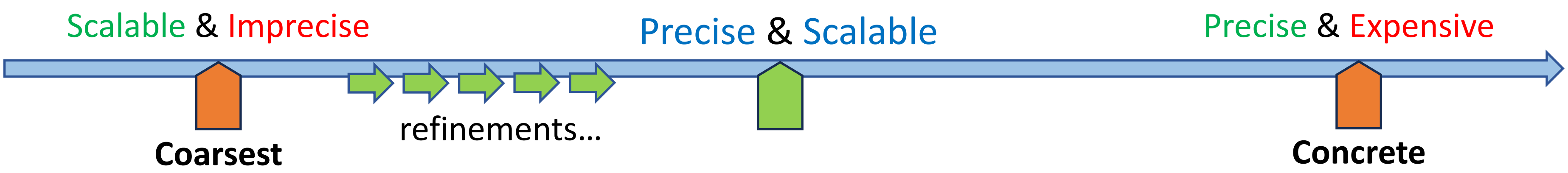
```
int process(int *data) {
  if(0 != data[36])
    if(data[0] >= data[15]) return 6;
    else return 7;
  else if(0 != data[1])
    if(data[12] < data[40]) return 5;
    else if(data[18] >= data[20]) return 1;
    else return 0;
  else if(0 != data[21]) return 4;
  else return -1; }
```

260 seconds, and **true alarm**!

(3) No Abstraction

```
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int xul = data[i * 5 + 2];
      int xlr = data[i * 5 + 3];
      int yul = data[i * 5 + 4];
      int ylr = data[i * 5 + 5];
      int width = abs(xul - xlr);
      int height = abs(yul - ylr);
      int area = width * height;
      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
    }
  }
  return max_index; }
```

Out-Of-Memory



Main Idea 2: PBE-Based Abstraction

(3) No Abstraction

```c
int process(int *data) {
  int max_area = -1;
  int max_index = -1;
  for(int i = 0; i < data[0]; i++) {
    if(data[5 * i + 1] != 0) {
      int xul = data[i * 5 + 2];
      int xlr = data[i * 5 + 3];
      int yul = data[i * 5 + 4];
      int ylr = data[i * 5 + 5];
      int width = abs(xul - xlr);
      int height = abs(yul - ylr);
      int area = width * height;
      if(area >= max_area) {
        max_area = area;
        max_index = i;
      }
urn max_index; }
```

Out-Of-Memory

(2) **Programming-By-Example (PBE) Based Abstraction**

```c
int process(int *data) {
  if(0 != data[36])
    if(data[0] >= data[15]) return 6;
    else return 7;
  else if(0 != data[1])
    if(data[12] < data[40]) return 5;
    else if(data[18] >= data[20]) return 1;
    else return 0;
  else if(0 != data[21]) return 4;
  else return -1; }
```

260 seconds, and **true alarm**!

(1) Initial Abstraction

```c
int process(int *data) {
  return nondet();
}
```

240 seconds, but false alarm

We could synthesize this abstraction using only 33 input-output examples!

Scalable & Imprecise

Precise & Scalable

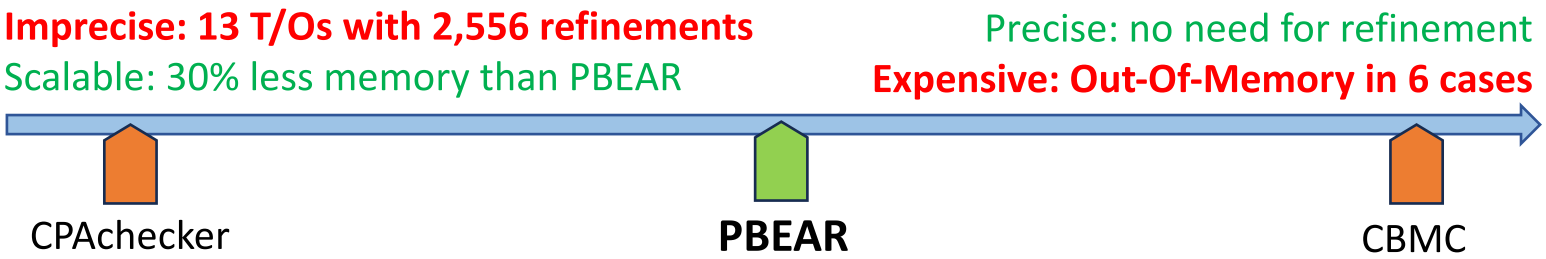
Precise & Expensive

Coarsest

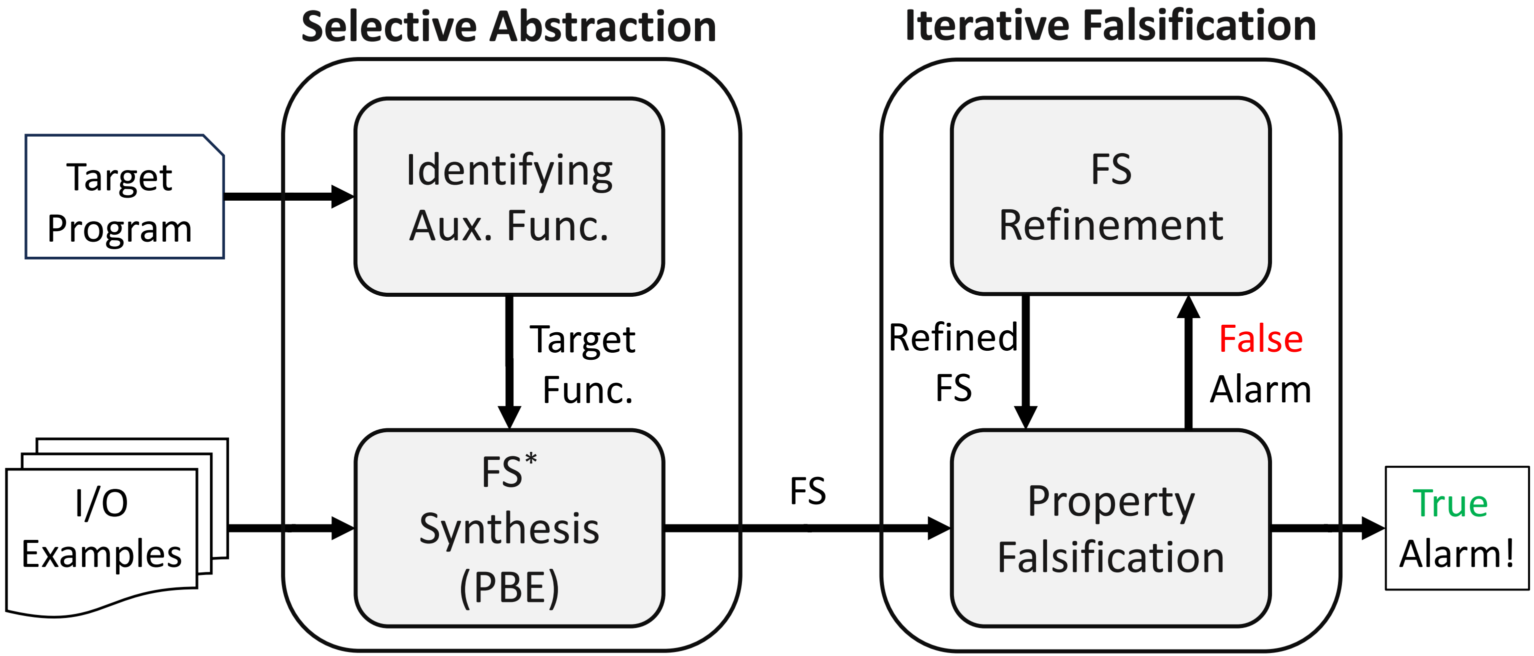
Concrete

PBEAR: **PBE**-Based Selective **A**bstraction and **R**efinement

- ✓ **PBEAR** suggests **selective abstraction** for efficient property falsification of embedded software
- ✓ **PBEAR** is **the first approach** utilizing **PBE** for more precise & scalable abstraction
- ✓ Out of 15 safety properties from three embedded software, **PBEAR** finds **5 to 12 more true alarms** than CBMC and CPAchecker



Overall Process of **PBEAR**



*FS: Function Summary

Problems & Solutions for Utilizing PBE

- **PBE** takes input/output (I/O) examples and produces a program that satisfies the given examples

Auxiliary Function

```
int gcd(int a,int b){
  if (a < 0) a = -a;
  if (b < 0) b = -b;
  while (b != 0) {
    int t = b;
    b = a % b;
    a = t;
  }
  return a;}
```

I/O Examples

```
gcd(1,-1)==1
gcd(4, 2)==2
gcd(9,-3)==3
```

PBE

Function Summary (FS)

```
int fs_gcd(int a,int b){
  if (b < 0) return -b;
  else return b;
}
```

1. Overfitting problems in PBE:

✓ **Iterative function summary synthesis**

2. PBE-based refinement may reproduce infeasible paths:

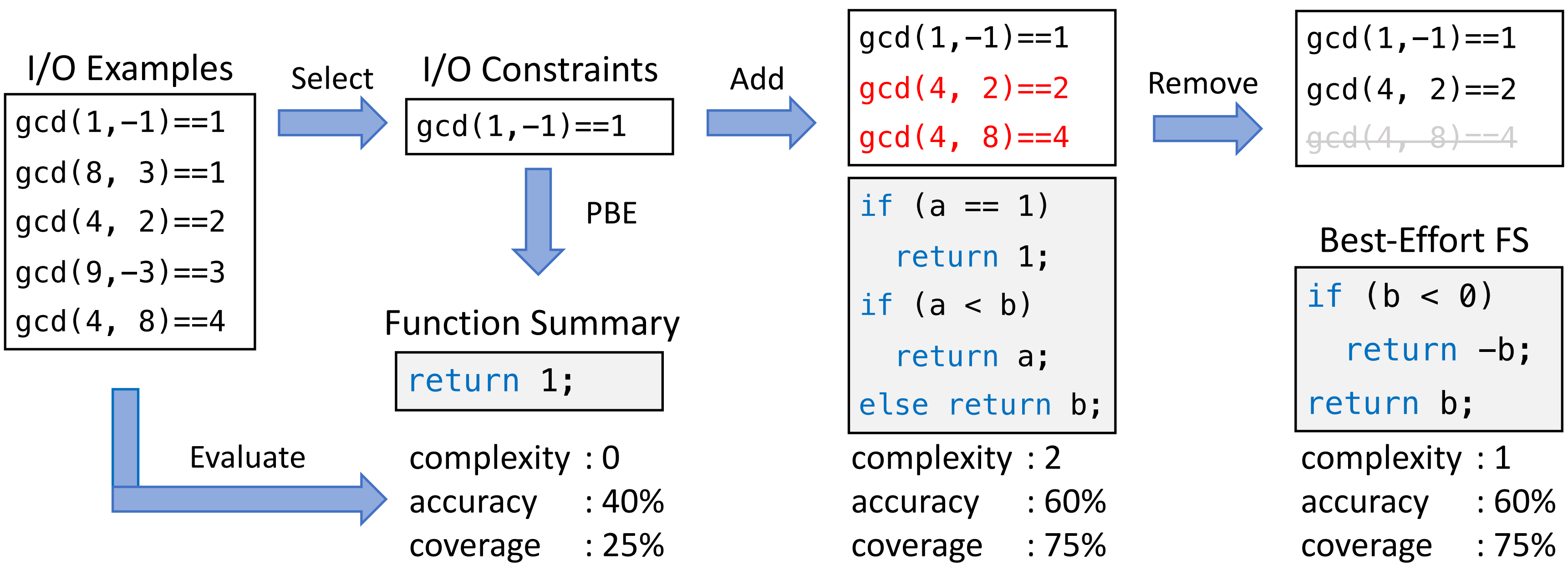
✓ **A novel PBE-based refinement with symbolic alarm filtering**

1. Overfitting ➔ Iterative FS Synthesis

Measurement:

- **Complexity**: # of branch statements
- **Similarity**: accuracy and output coverage

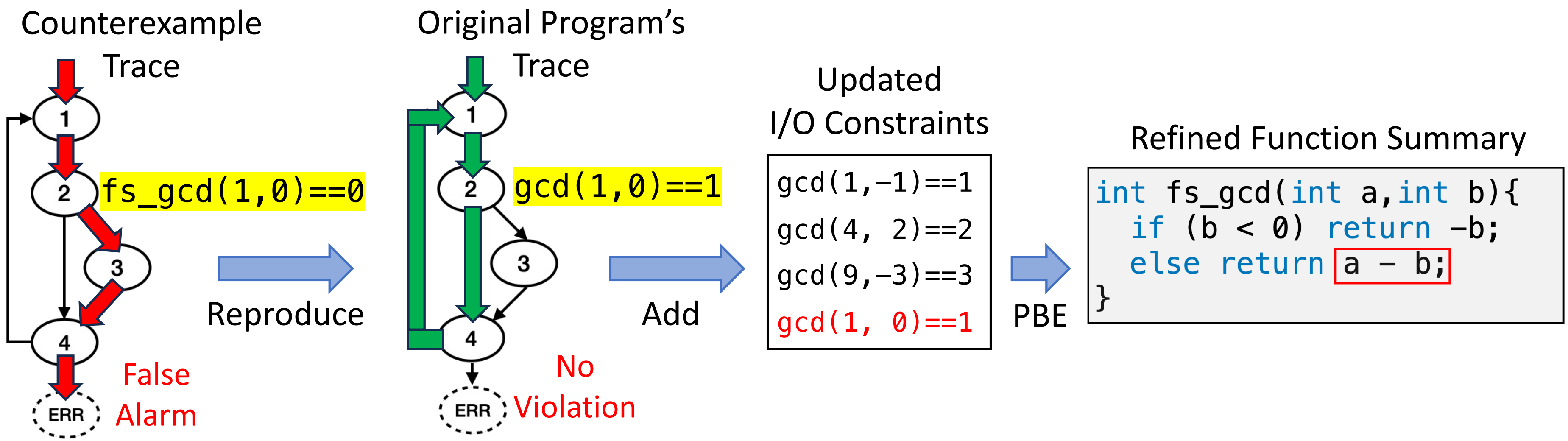
Synthesize until a given time budget (1 hour)



2. PBE Produces Infeasible Paths

Baseline of refinement approach:

1. Add new I/O constraints from the false alarm
2. Re-synthesize FS using the updated I/O constraints



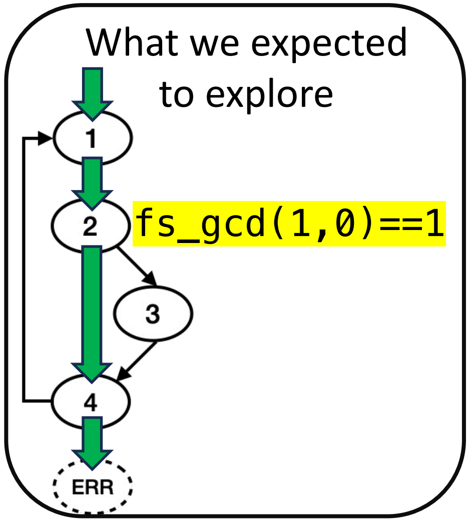
2. PBE **Re**produces Infeasible Paths

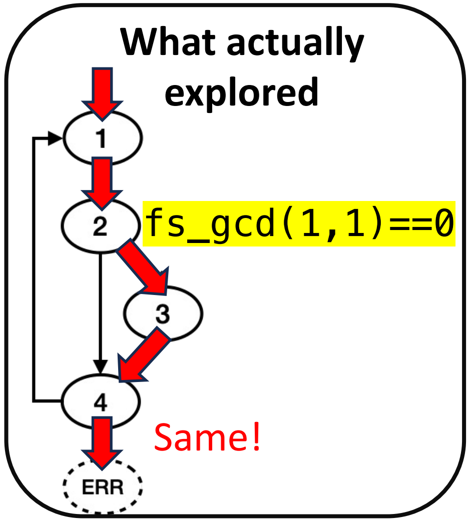
Problem: No guarantee for avoiding re-exploration of **previously identified infeasible paths**

Refined Function Summary

```
int fs_gcd(int a,int b){
  if (b < 0) return -b;
  else return a - b;
}
```

Falsify

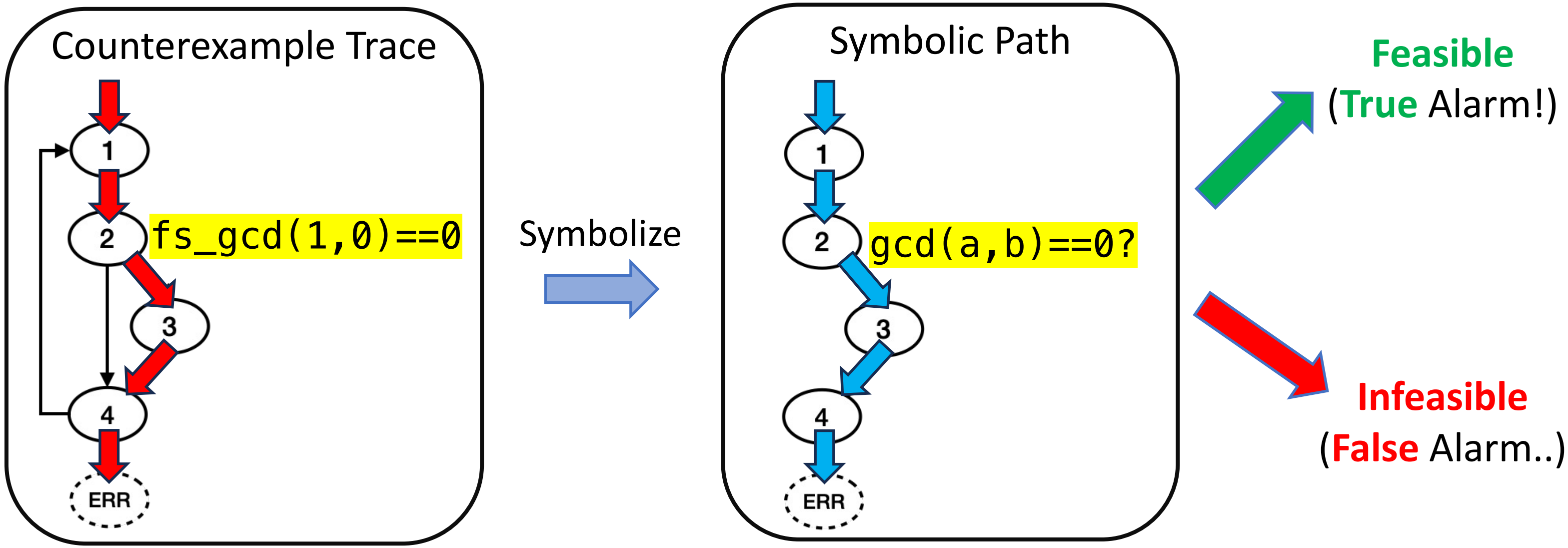




There is **another I/O example** leading to the same infeasible path

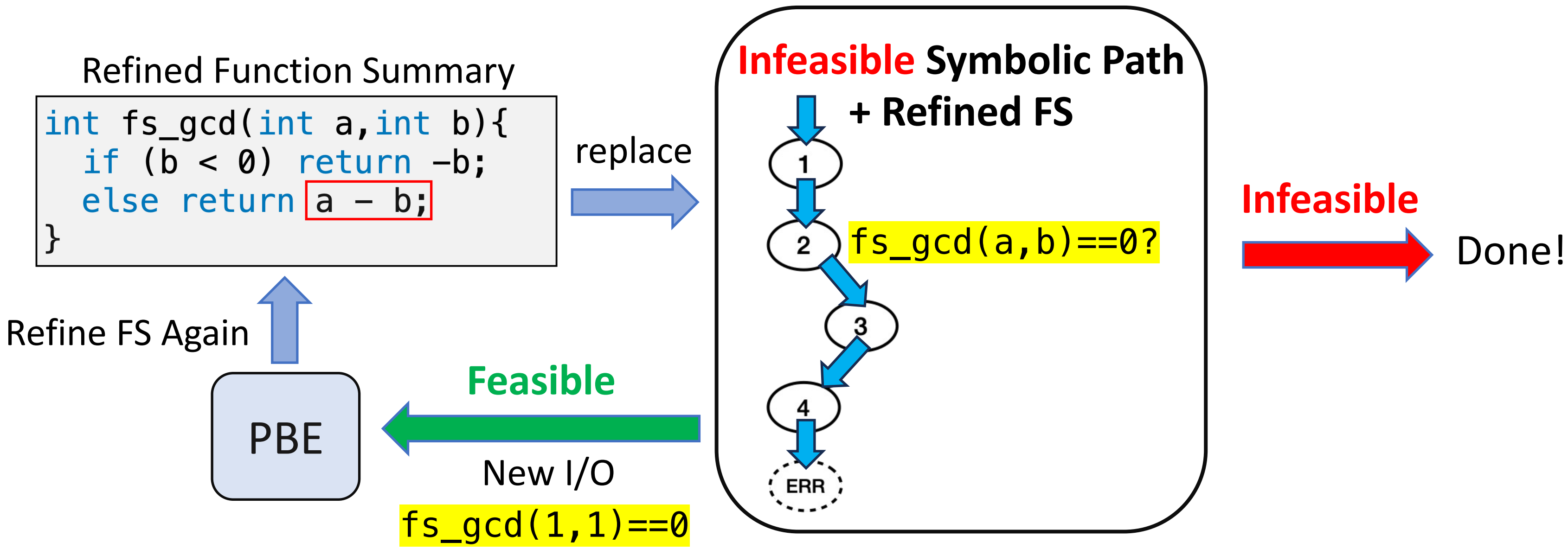
2. Solution: PBE-Based Refinement with Symbolic Alarm Filtering

1. Convert the counterexample trace into a **symbolic path**
2. Check the feasibility of the symbolic path using SAT solving

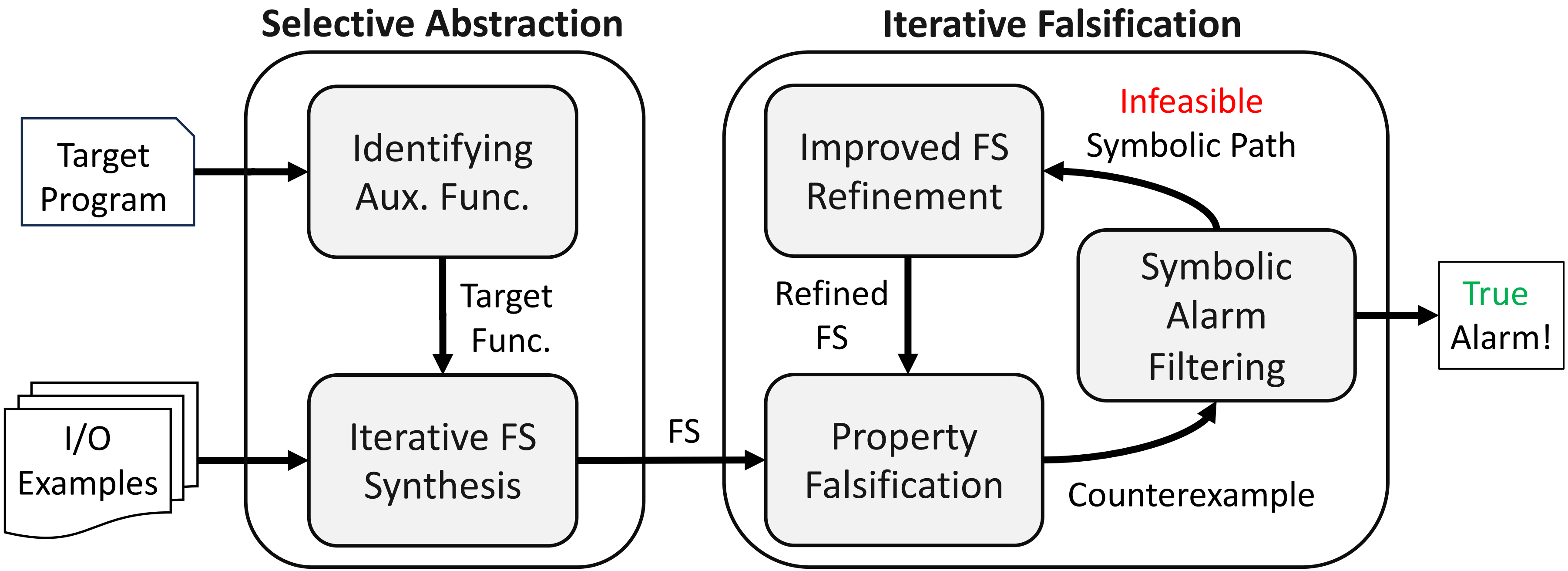


2. Solution: PBE-Based Refinement with Symbolic Alarm Filtering

3. **Iteratively refine FS using PBE until it does not make infeasible symbolic path feasible**



(Refined) Overall Process of **PBEAR**



Experiments

- Target
  - Checking assertion violations for 16 benchmark programs from SV-COMP
  - 15 safety properties from 3 embedded software (about 800~1,000 LoC)
    - Object following car, elevator controller, and clean-up robot

- RQ1: Performance of PBEAR vs. two state-of-the-art model checkers,
  - CBMC: bounded model checker
  - CPAchecker: predicate abstraction

- RQ2: Effectiveness of our improved FS refinement vs. PBEAR^{base}
  - PBEAR^{base}: baseline of refinement approach; no symbolic alarm filtering

* PBEAR uses DUET for function summary synthesis and CBMC for property falsification

RQ1: Performance of PBEAR (on SV-COMP)

Tools	# of refinements	Total time	Total memory	# of detected true alarms
PBEAR	**9**	**485 s**	**3.1 GB**	**15/16**
CBMC	N/A	177 s	3.9 GB	16/16
CPAchecker	57	4,334 s	10.3 GB	13/16

* T/O: 900 s

- CBMC was the best: the overhead of refinement did not pay off on these programs
- **PBEAR** showed competitive performance on **general-purpose programs**

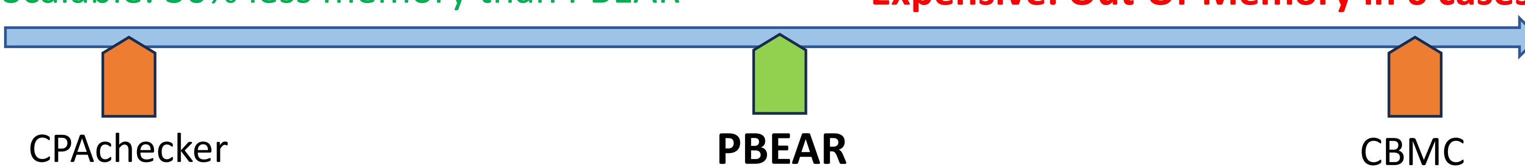
RQ1: Performance of PBEAR (on Embedded Software)

Tools	# of refinements	Total time	Total memory	# of detected true alarms
PBEAR	**77**	**135.4 h**	**423.5 GB**	**14/15**
CBMC	N/A	96.9 h	748.9 GB	9/15
CPAchecker	2,556	936.3 h	336.8 GB	2/15

* T/O: 72 hours; Out-Of-Memory: 80 GB

Imprecise: 13 T/Os with 2,556 refinements
Scalable: 30% less memory than PBEAR

Precise: no need for refinement
Expensive: Out-Of-Memory in 6 cases



RQ2: Effectiveness of Our Improved FS Refinement

Tools	# of refinements	Total time	# of detected true alarms
PBEAR	**86**	**133.6 h**	**13/15**
PBEAR^{base} (without symbolic alarm filtering)	210	217.4 h	12/15

* We omitted benchmarks where any refinements were not conducted by PBEAR^{base}

PBEAR^{base} took **additional 124 refinements** and **83.6 more hours**

Conclusion

- Contributions
  - **PBEAR** is **the first work** utilizing **PBE** for **selective abstraction**
  - We suggested **a novel PBE-based refinement approach** with **symbolic alarm filtering**
  - PBEAR showed **promising results** on three **embedded software** and competitive performance on general-purpose programs

- Future Work
  - PBEAR is highly dependent on the performance & limitation of PBE
    - We may need to combine PBEAR with other abstraction techniques
  - We plan to further investigate the applicability of PBEAR to:
    - Programs in other domains with control-oriented structures