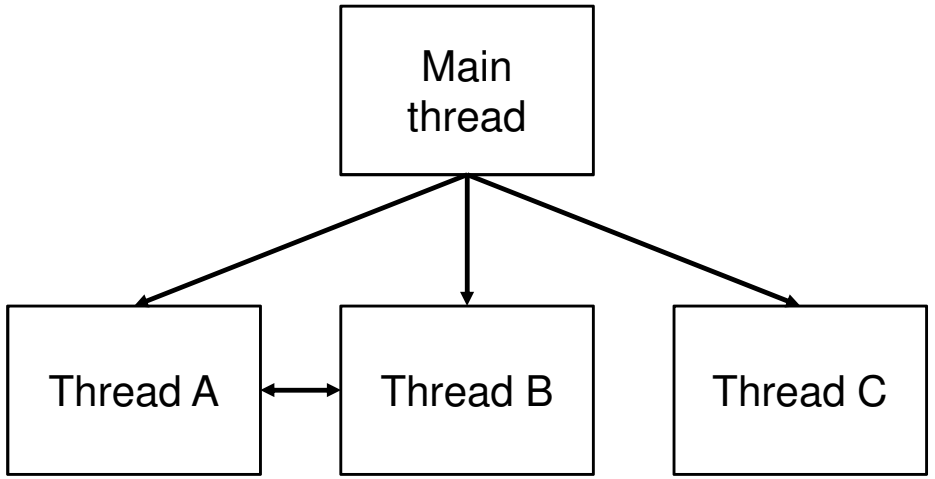
V Brazilian Symposium on Computing Systems Engineering

Fault Localization in Multi-threaded C Software using Bounded Model Checking

Erickson H. da S. Alves, Lucas C. Cordeiro,
and Eddie B. de Lima Filho

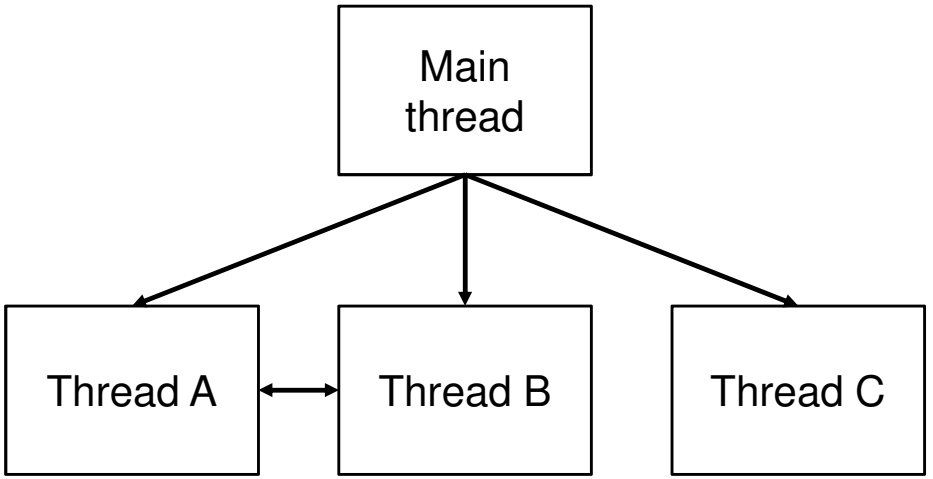
Multi-threaded Software and Difficulties

- Multi-threaded software are more common in embedded systems
- Despite several advantages, they present difficulties related to **asserting their correctness**



Multi-threaded Software and Difficulties

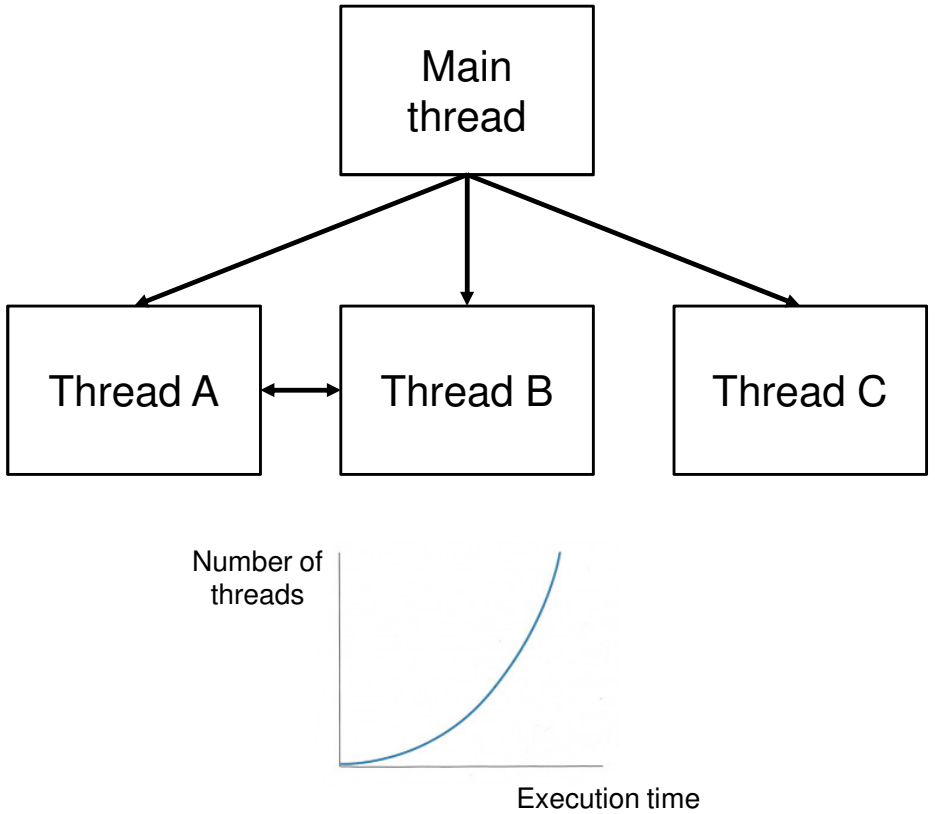
- Multi-threaded software are more common in embedded systems
- Despite several advantages, they present difficulties related to **asserting their correctness**
- Multi-threaded software difficulties are:
  - **Concurrent bugs usually occur under specific thread interleavings**
  - The number of interleavings grows exponentially with the number of threads and program statements
  - Context switches among threads increase the number of possible executions
  - However, concurrent bugs usually occur in few context switches [Qadeer&Rehof'05]



Possible Interleaving: $T_A \rightarrow T_B \rightarrow T_C \rightarrow T_B \rightarrow T_C \rightarrow T_A$

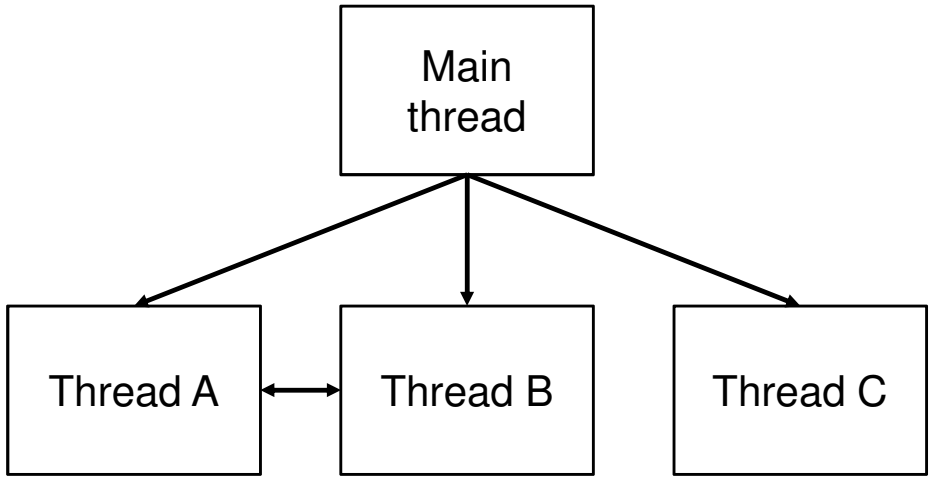
Multi-threaded Software and Difficulties

- Multi-threaded software are more common in embedded systems
- Despite several advantages, they present difficulties related to **asserting their correctness**
- Multi-threaded software difficulties are:
  - **Concurrent bugs usually occur under specific thread interleavings**
  - **The number of interleavings grows exponentially with the number of threads and program statements**
  - Context switches among threads increase the number of possible executions
  - However, concurrent bugs usually occur in few context switches [Qadeer&Rehof'05]



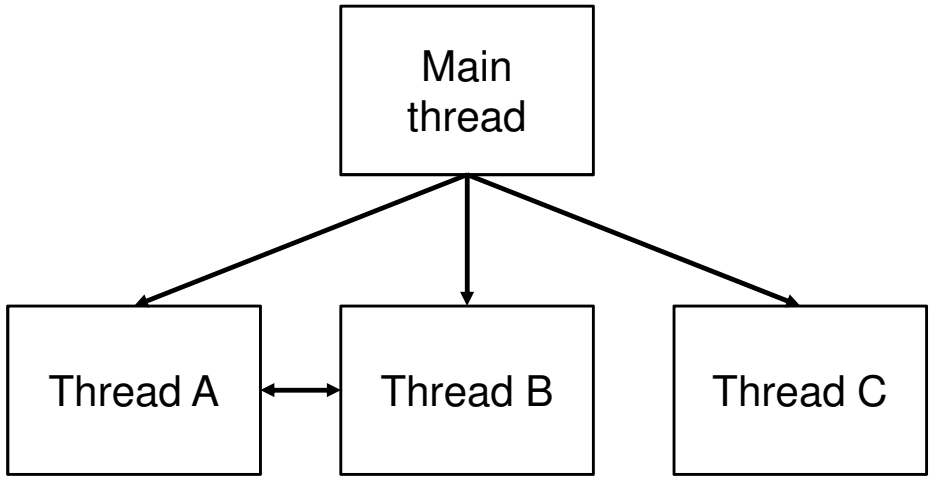
Multi-threaded Software and Difficulties

- Multi-threaded software are more common in embedded systems
- Despite several advantages, they present difficulties related to **asserting their correctness**
- Multi-threaded software difficulties are:
  - **Concurrent bugs usually occur under specific thread interleavings**
  - **The number of interleavings grows exponentially with the number of threads and program statements**
  - **Context switches among threads increase the number of possible executions**
  - **However, concurrent bugs usually occur in few context switches [Qadeer&Rehof'05]**



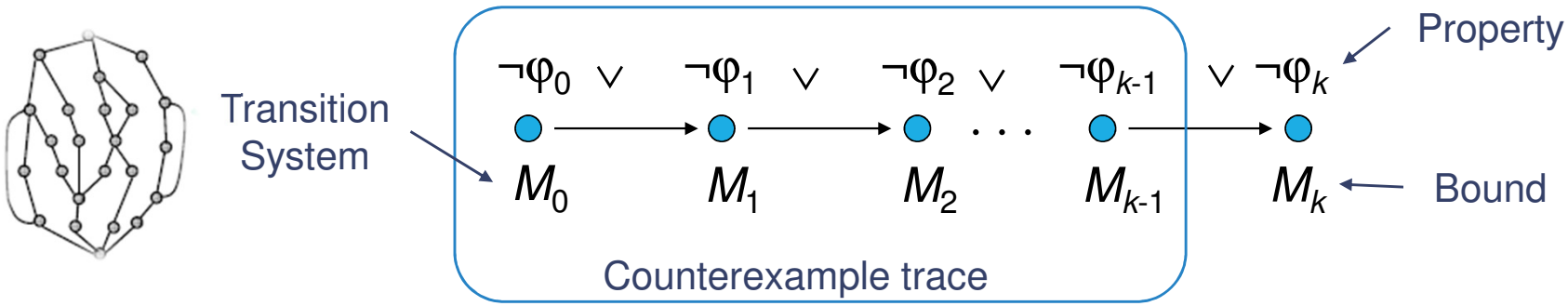
Multi-threaded Software and Difficulties

- Multi-threaded software are more common in embedded systems
- Despite several advantages, they present difficulties related to **asserting their correctness**
- Multi-threaded software difficulties are:
  - **Concurrent bugs usually occur under specific thread interleavings**
  - **The number of interleavings grows exponentially with the number of threads and program statements**
  - **Context switches among threads increase the number of possible executions**
  - **However, concurrent bugs usually occur in few context switches [Qadeer&Rehof'05]**



Bounded Model Checking (BMC)

- Basic Idea: given a transition system *M*, check negation of a given property φ up to given depth *k*



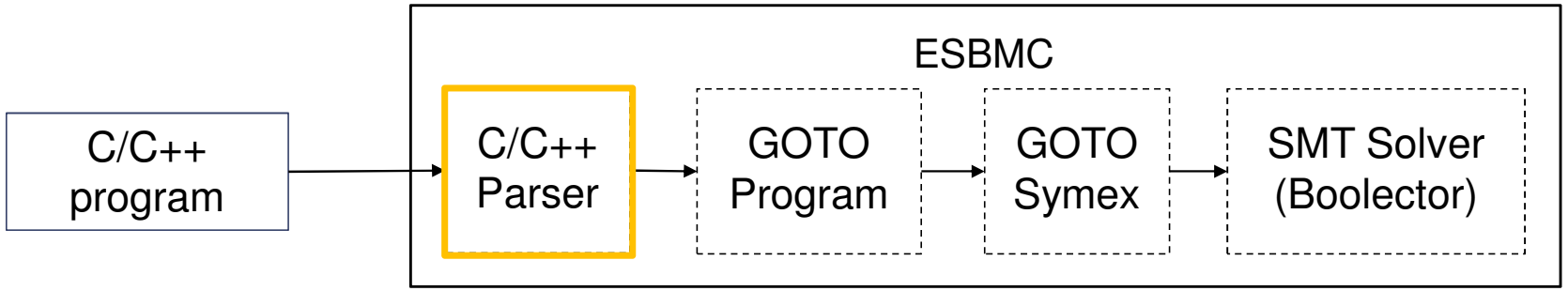
- Translated into a VC ψ such that: **ψ is satisfiable iff φ has counterexample of max. depth *k***
- BMC has been applied successfully to verify multi-threaded software since 2005, but there are some limitations

Objectives

Provide a methodology to localize faults in multi-threaded C software using BMC techniques

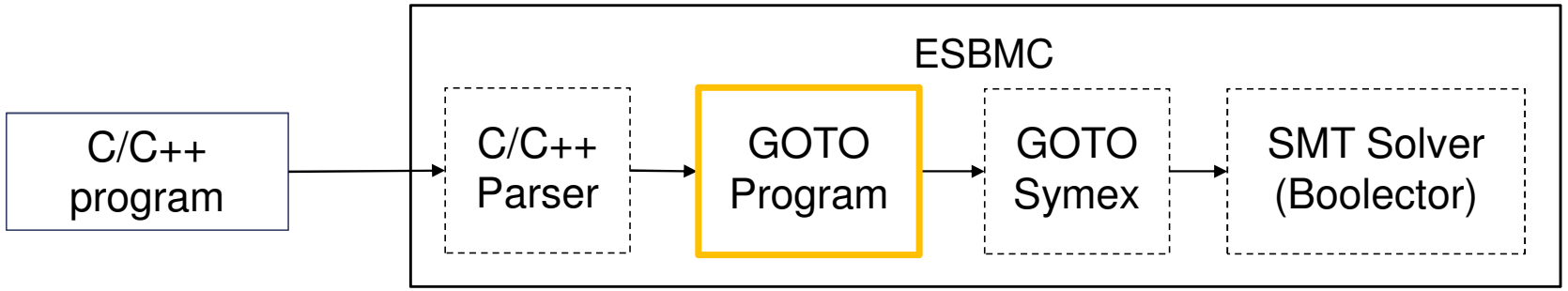
- Expand existing fault localization approaches to sequential programs to handle multi-threaded software and provide a sequentialization method to translate multi-threaded C software into sequential software
- Design a grammar to model functions and variables related to multi-threaded programming in C
- Evaluate our proposed method using benchmarks from the Software Verification Competition (SV-Comp)

The Efficient SMT-Based Context-Bounded Model Checker (ESBMC)



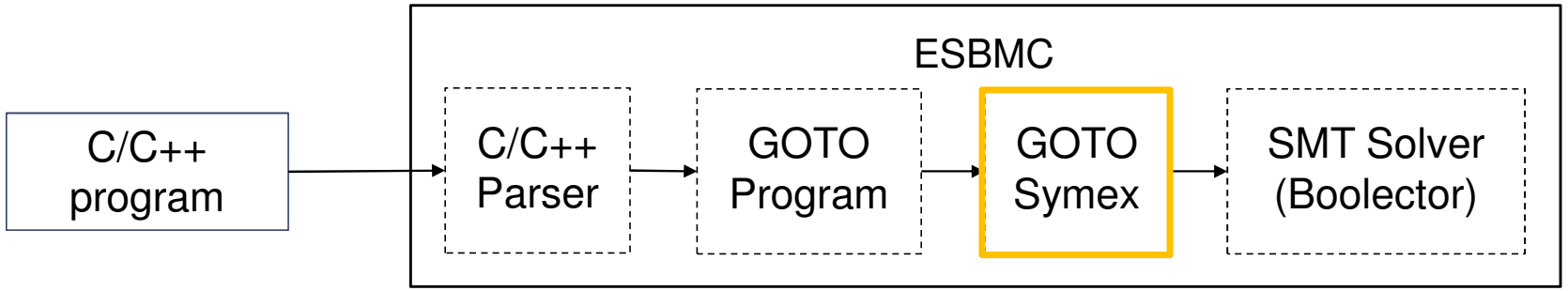
C parser: processes the ANSI-C file and builds an Abstract Syntax Tree (AST)

The Efficient SMT-Based Context-Bounded Model Checker (ESBMC)



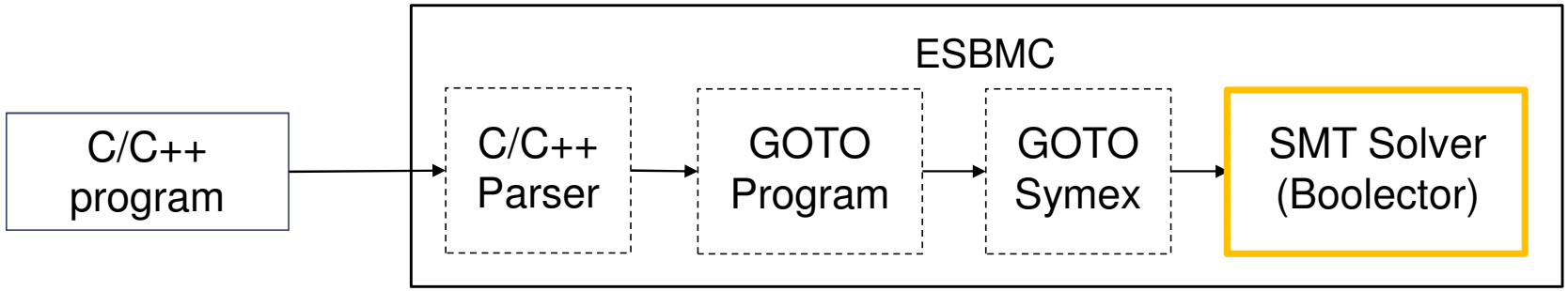
GOTO Program: converts an ANSI-C program into a GOTO-Program (replacement of *switch* and *while* by *if* and *goto* expressions)

The Efficient SMT-Based Context-Bounded Model Checker (ESBMC)



GOTO Symex: performs a symbolic execution of the program and generates SMT equations for constraints (*C*) and properties (*P*)

The Efficient SMT-Based Context-Bounded Model Checker (ESBMC)



SMT Solver: evaluates the expression $C \wedge \neg P$, using the specified solver

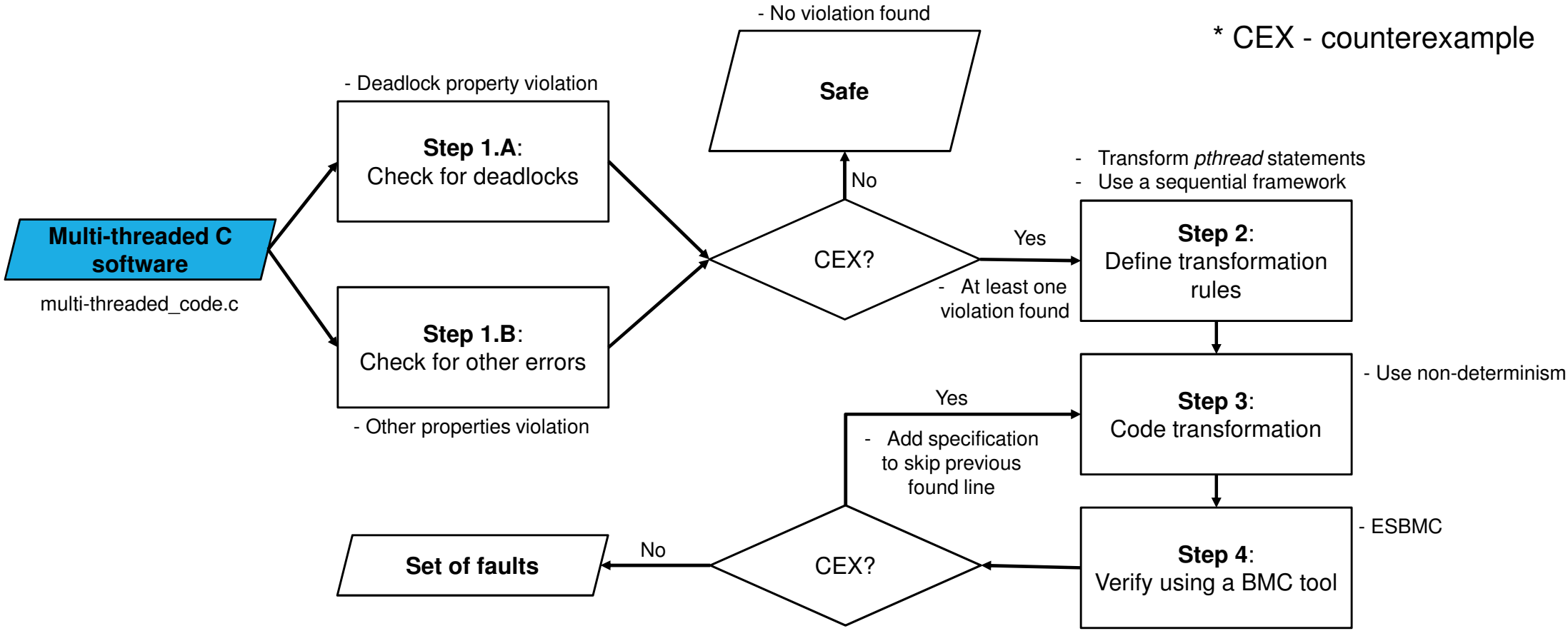
Fault Localization using Model Checking

- [Griesmeyer'07] proposed a method to localize faults in sequential C code
  - It uses non-determinism to obtain values for a variable (**diag**), which represent faulty lines
  - Assignments are replaced by a non-deterministic version of them. If a counterexample is obtained, it also contains a value for **diag**

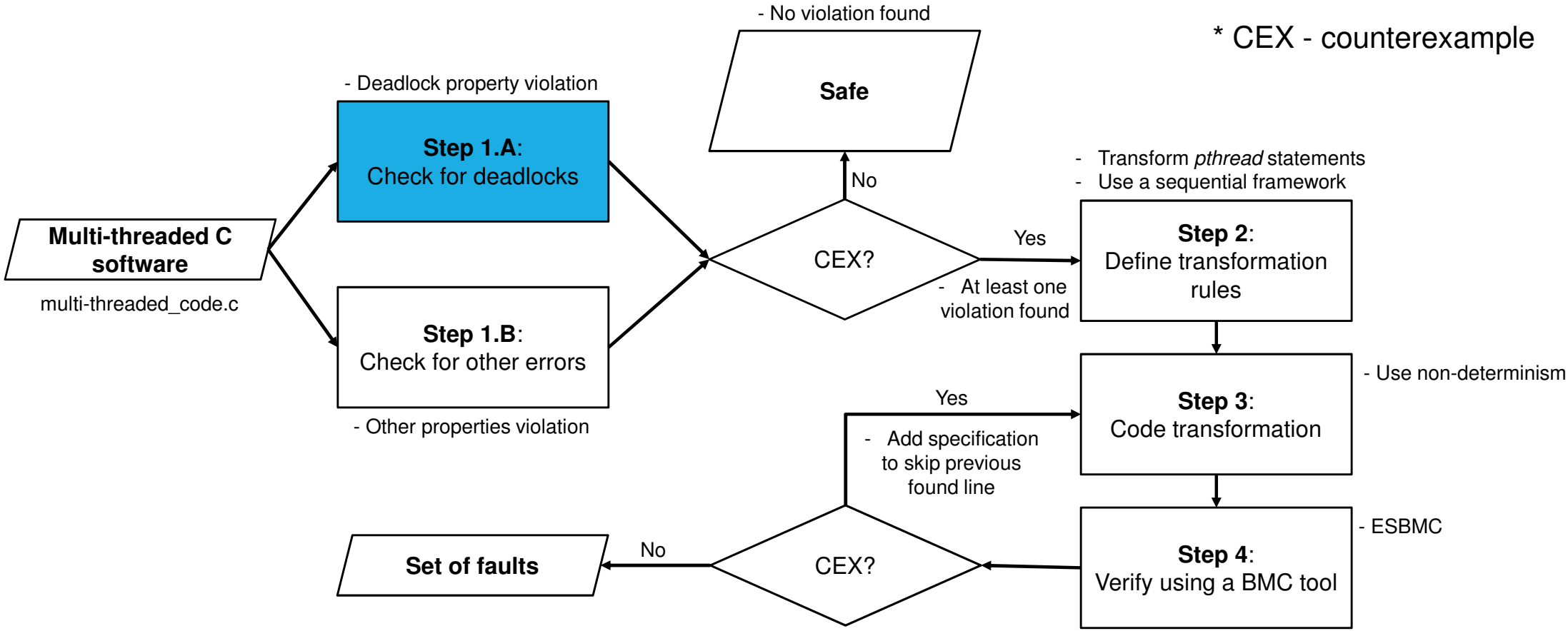
```
int non_det();
int diag;
...
int main(void *args) {
    diag = non_det();
    ...
    assert(0);
}
```

```
(17) i = 7;
...
i = (diag == 17 ? non_det() : 7);
```

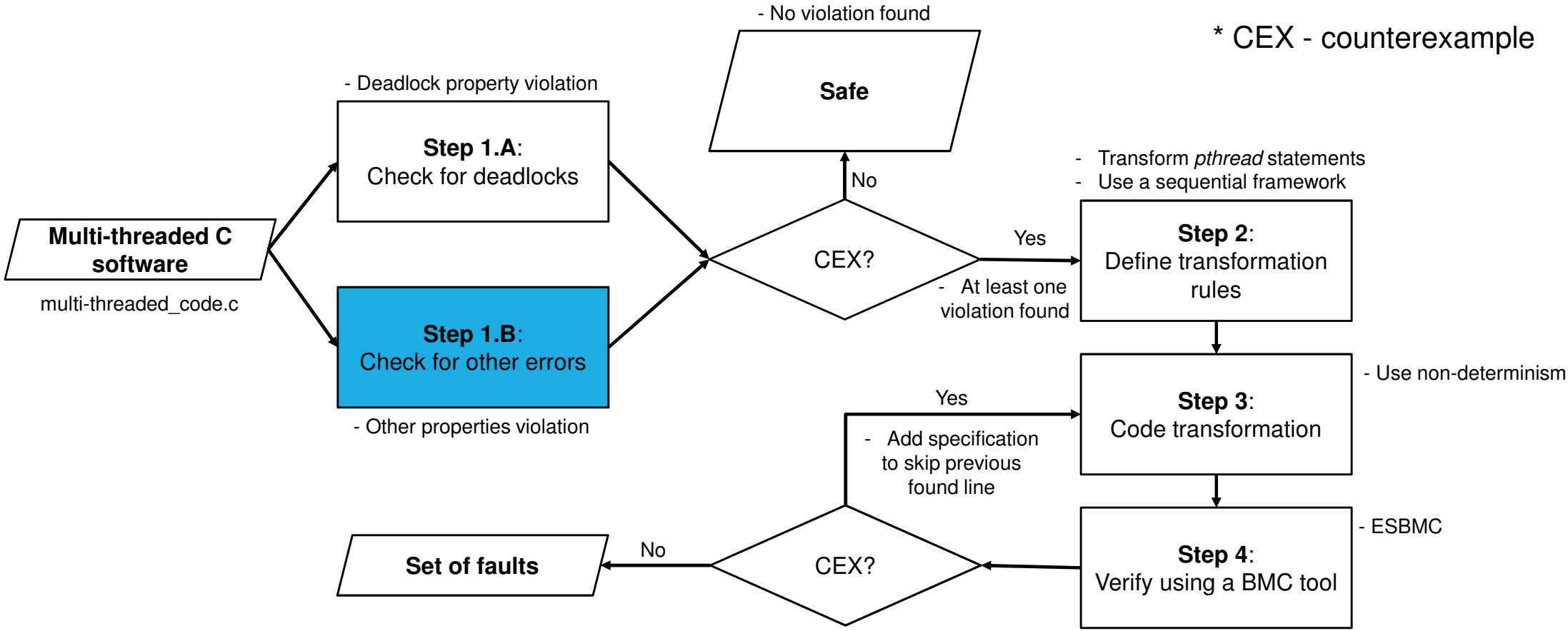
Our Proposed Methodology



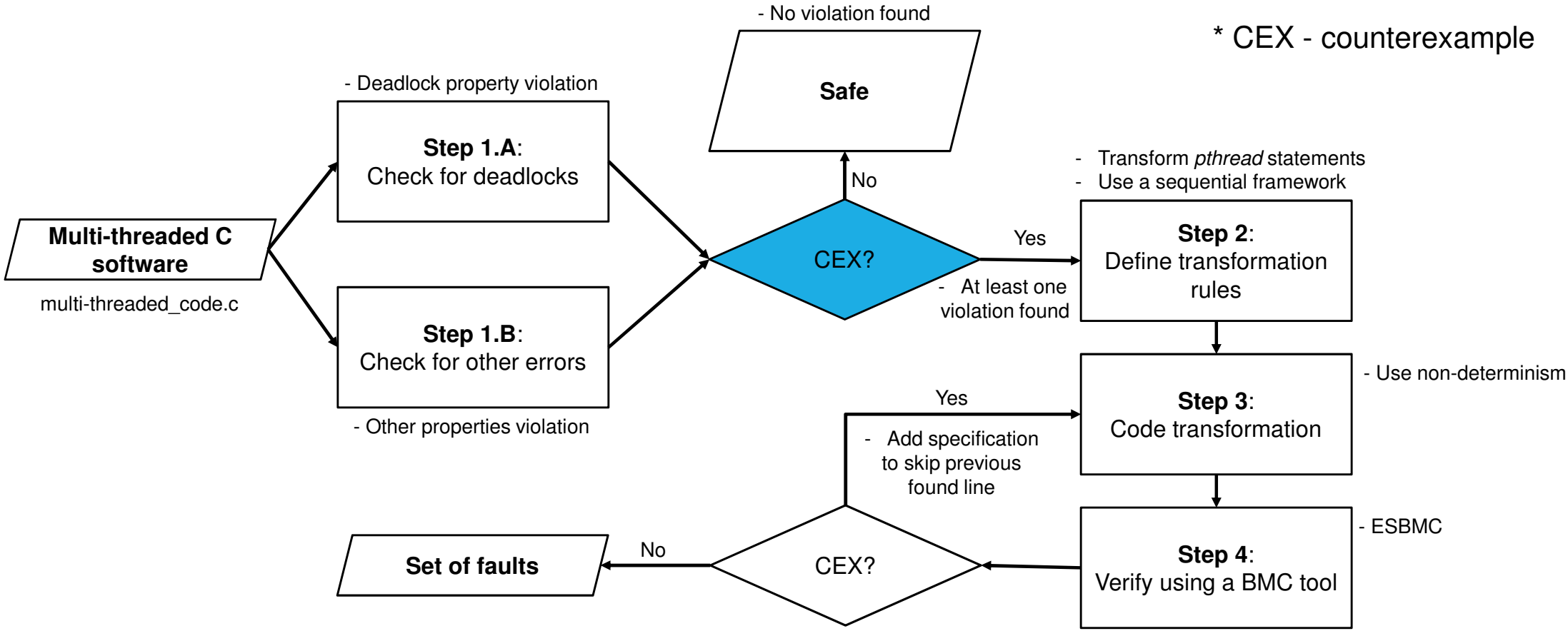
Our Proposed Methodology



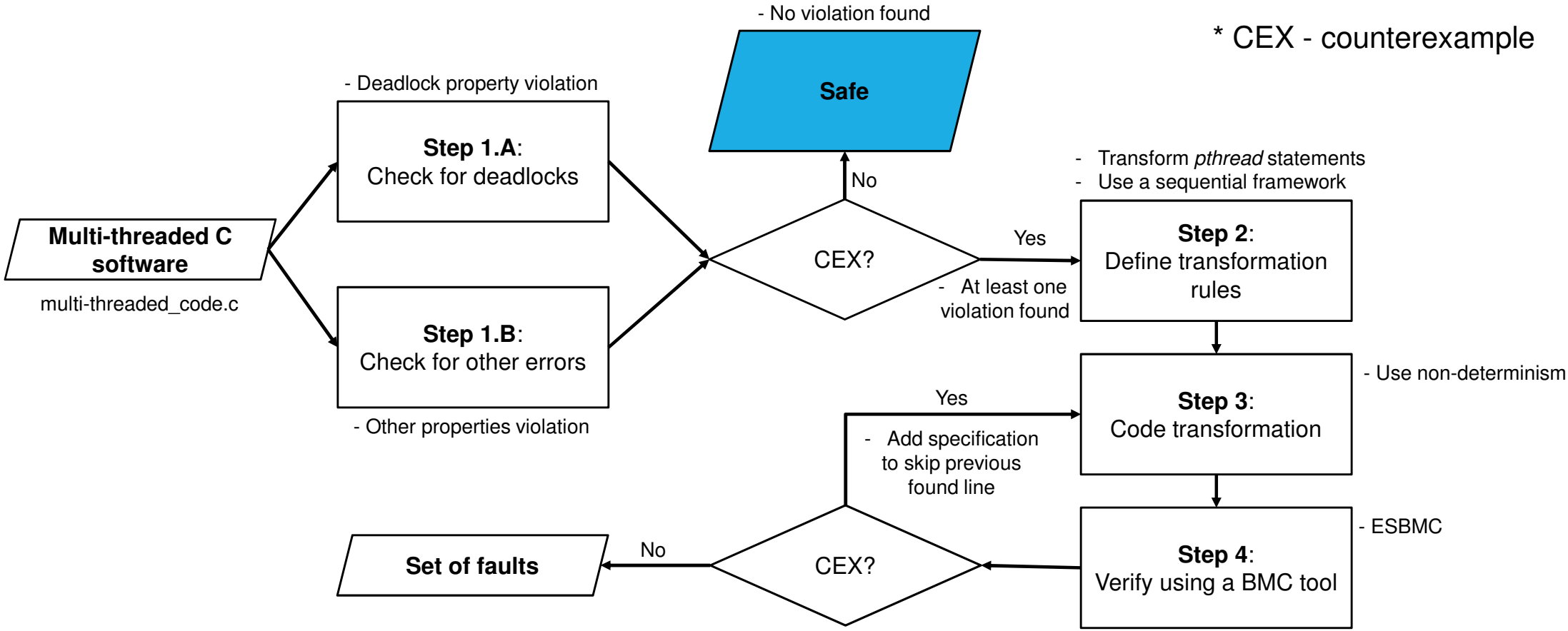
Our Proposed Methodology



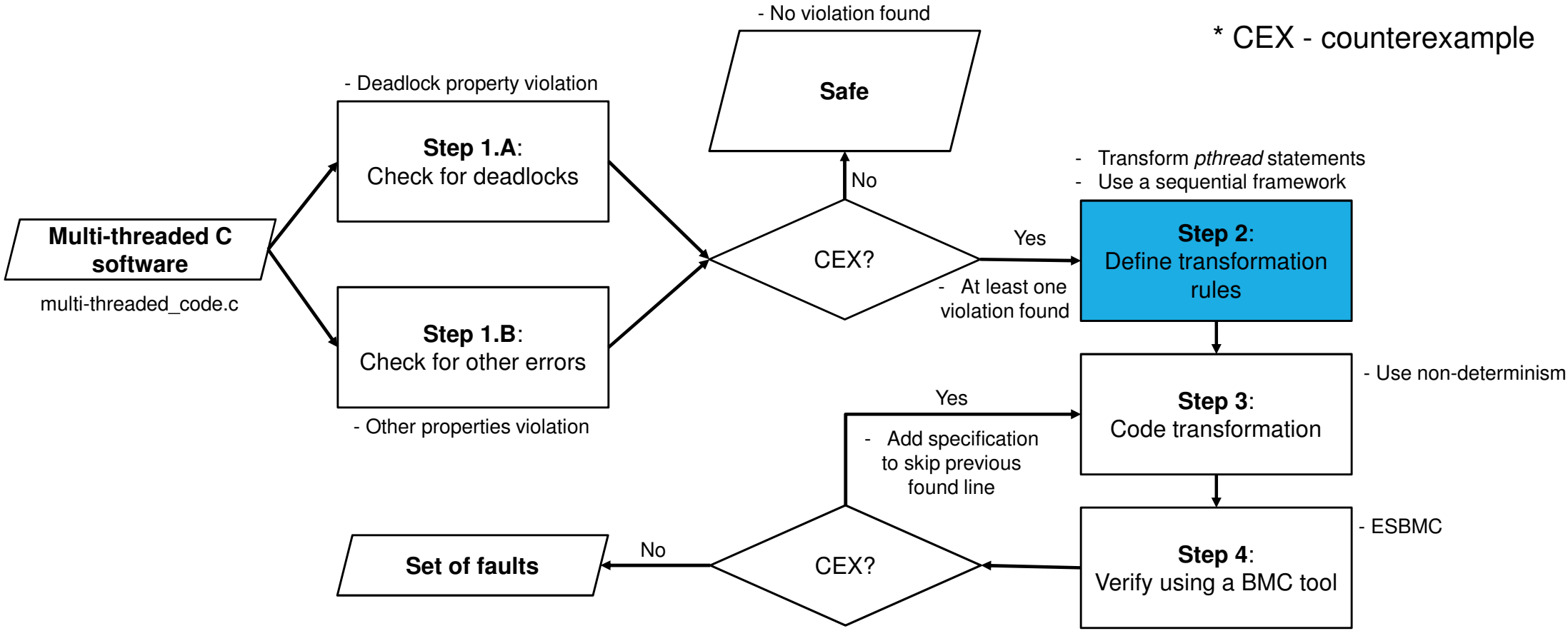
Our Proposed Methodology



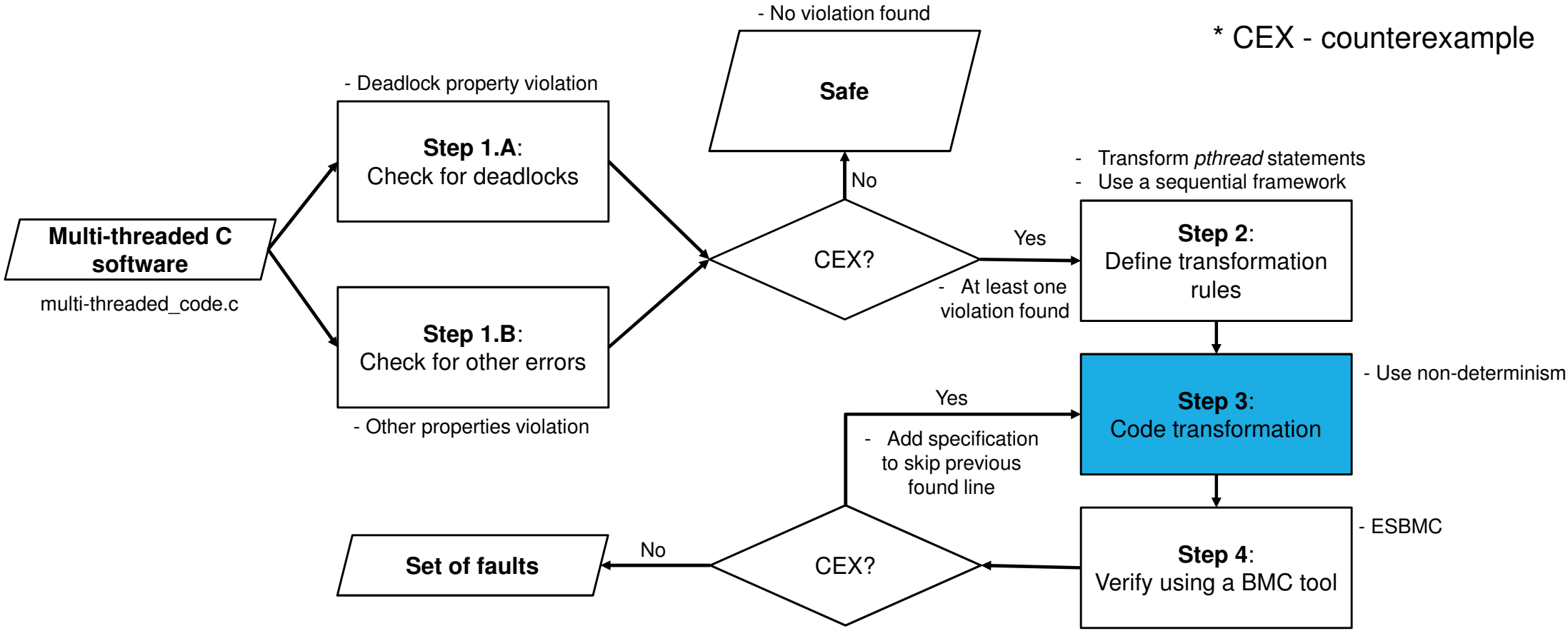
Our Proposed Methodology



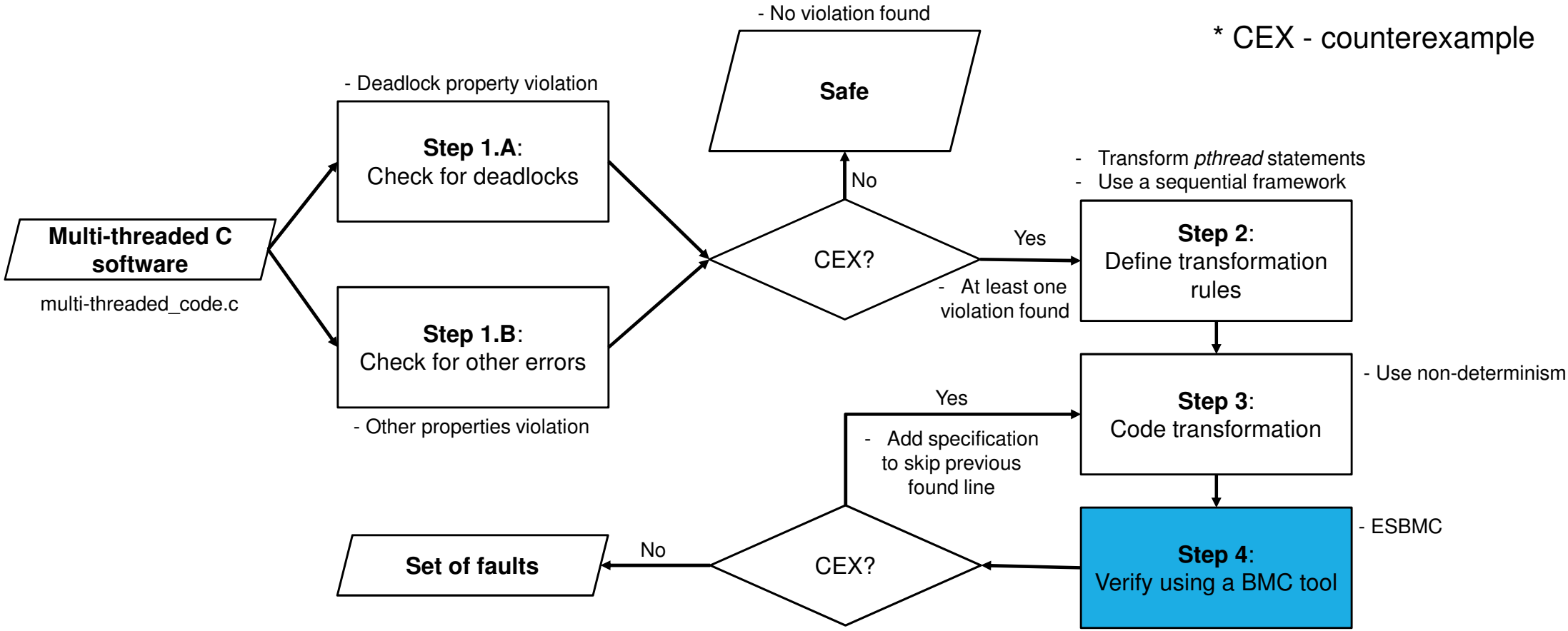
Our Proposed Methodology



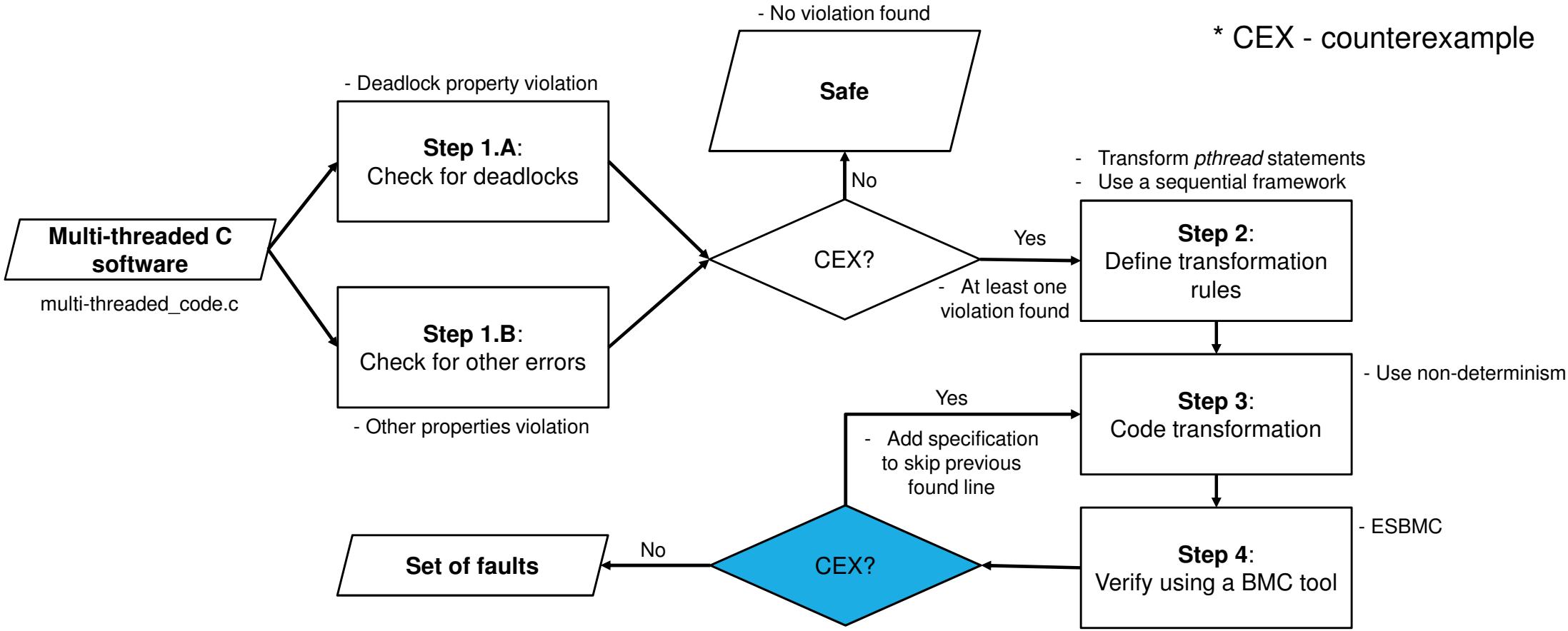
Our Proposed Methodology



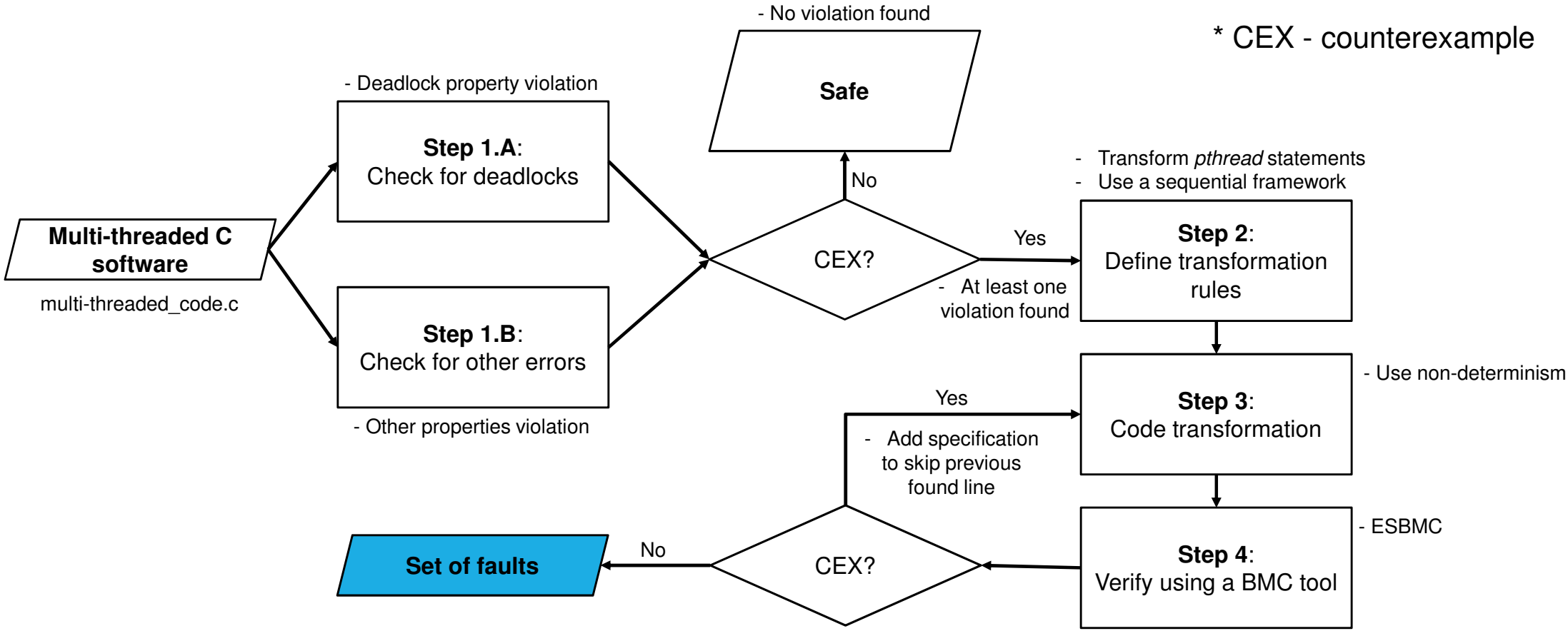
Our Proposed Methodology



Our Proposed Methodology



Our Proposed Methodology



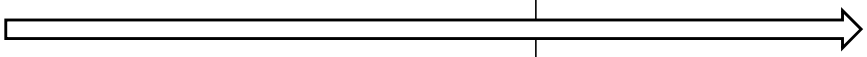
Our Proposed Methodology – Grammar

Statement	Transformation
pthread_t	ε
pthread_attr_t	ε
pthread_cond_attr_t	ε
pthread_create	ε
pthread_join	ε
pthread_exit	ε
pthread_mutex_t	Integer variable is declared
pthread_mutex_lock	**1** is assigned to variable
pthread_mutex_unlock	**0** is assigned to variable
pthread_cond_t	Integer variable is declared
pthread_cond_wait	**1** is assigned to variable
pthread_cond_signal	**0** is assigned to variable

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```



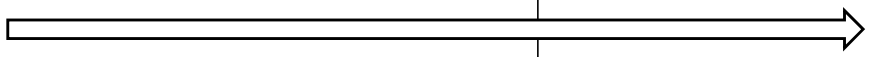
```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Thread 0

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```



```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Context switch 1

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```

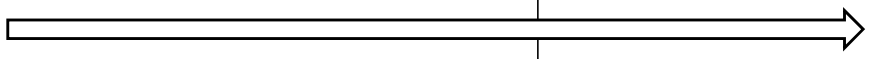
```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Context switch 2

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```



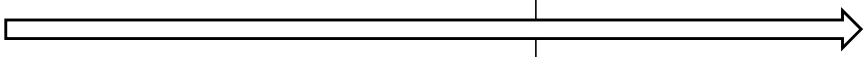
```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Context switch 10

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```



```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Thread 1

Our Proposed Methodology – Rules

- Then, we have to use a framework that simulates multi-threaded programs execution

```
#define NCS X
int cs[NCS] = {...};
int main(void *args) {
    for (int i = 0; i < NCS; i++) {
        switch (cs[i]) {
            ...
        }
    }
    return 0;
}
```

```
case 1: {
    case 11: { ... }
    case 12: { ... }
    ...
    case 20: { ... }
} break;

case 2: {
    case 21: { ... }
    case 22: { ... }
    ...
    case 30: { ... }
} break;
...
```

Thread 2..N

Note: we can model up to 10 context switches for each thread

Running Example


```
(1) #include <pthread.h>
(2) #include <assert.h>
(3)
(4) pthread_mutex_t m;
(5) int c = 0;
(6)
(7) void *f1(void *arg) {
(8)    pthread_mutex_lock(&m);
(9)    c = c + 1;
(10)  pthread_mutex_unlock(&m);
(11) }
...
```

```
...
(12)
(13) void *f2(void *arg) {
(14)    pthread_mutex_lock(&m);
(15)    c = c - 1;
(16)    assert(c == 1);
(17)    pthread_mutex_unlock(&m);
(18) }
(19)
...
```

```
...
(20) int main() {
(21)    pthread_mutex_init(&m, NULL);
(22)    pthread_t t1, t2;
(23)    pthread_create(&t1, NULL, f1, NULL);
(24)    pthread_create(&t2, NULL, f2, NULL);
(25)    return 0;
(26) }
```

Running Example

esbmc --no-bounds-check --no-div-by-zero-check --no-pointer-check --deadlock-check --no-slice --boolector example.c

```
*** Thread interleavings 122 ***
Symex completed in: 0.001s
size of program expression: 110 assignments
Slicing time: 0.000s
Generated 0 VCC(s), 0 remaining after simplification
VERIFICATION SUCCESSFUL
BMC program time: 0.001s
```

Running Example

esbmc --no-bounds-check --no-div-by-zero-check --no-pointer-check --no-slice --boolector example.c

```
Counterexample:
...
State 99 file example.c line 16 function f2 thread 2
c::f2 at /tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
-------------------------------------------------
Violated property:
  file example.c line 16 function f2
  assertion
  FALSE

VERIFICATION FAILED
```

Running Example


```
Counterexample:
...
State 56 file /tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 101
function pthread_create thread 0 c::pthread_create at example.c line 24 <main invocation>
------------------------------------------------
State 75 file example.c line 11 function f1 thread 1 c::f1 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
State 99 file example.c line 16 function f2 thread 2 c::f2 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
Violated property:
  file example.c line 16 function f2
  assertion FALSE
  VERIFICATION FAILED
```

cs[0]=11

Running Example


```
Counterexample:
...
State 56 file /tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 101
function pthread_create thread 0 c::pthread_create at example.c line 24 <main invocation>
------------------------------------------------
State 75 file example.c line 11 function f1 thread 1 c::f1 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
State 99 file example.c line 16 function f2 thread 2 c::f2 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
Violated property:
  file example.c line 16 function f2
  assertion FALSE
  VERIFICATION FAILED
```

cs[1]=21

Running Example


```
Counterexample:
...
State 56 file /tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 101
function pthread_create thread 0 c::pthread_create at example.c line 24 <main invocation>
------------------------------------------------
State 75 file example.c line 11 function f1 thread 1 c::f1 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
State 99 file example.c line 16 function f2 thread 2 c::f2 at
/tmp/esbmc_release_n70Swf/buildrelease/ansi-c/library/pthread_lib.c line 67
------------------------------------------------
Violated property:
  file example.c line 16 function f2
  assertion FALSE
  VERIFICATION FAILED
```

cs[2]=31
NCS=3

Running Example


```
#include <pthread.h>
#include <assert.h>
#define NCS 3
int cs[NCS] = {11, 21, 31}, nondet(), diag, c = 0;

void f1_1() {
   int t = c + 1;
   c = (diag == 9 ? nondet() : t);
}

void f2_1() {
   int t = c - 1;
   c = (diag == 15 ? nondet() : t);
   __ESBMC_assume(c == 1);
}
...
```

```
...
int main() {
   int i; diag = nondet();
   for (i = 0; i < NCS; i++) {
      switch (cs[i]) {
         case 1: {
            case 11: {
               if (cs[i] == 11) break;
            }
         } break;
         case 2: {
            case 21: {
               f1_1();
               if (cs[i] == 21) break;
            } break;
         } break;
...
```

```
...
         case 3: {
            case 31: {
               f2_1();
               if (cs[i] == 31) break;
            } break;
         } break;
      }
   }
   assert(0);
   return 0;
}
...
```

Running Example

esbmc --no-bounds-check --no-div-by-zero-check --no-pointer-check --no-slice --boolector transformed_example.c

```
Counterexample:
...
State 9 file example-hawk.c line 5 thread 0
------------------------------------------------
  diag=15 (15)
...
State 26 file example-hawk.c line 13
function f2_1 thread 0
c::f2_1 at example-hawk.c line 35
<main invocation>
------------------------------------------------
  example-hawk::f2_1::1::t=0 (0)
...
...
State 27  thread 0
c::f2_1 at example-hawk.c line 35
<main invocation>
------------------------------------------------
  c::f2_1::$tmp::tmp$1=TRUE
...
State 29 file example-hawk.c line 14
function f2_1 thread 0
c::f2_1 at example-hawk.c line 35
<main invocation>
------------------------------------------------
  c=1 (1)
...
------------------------------------------------
Violated property:
  file example-hawk.c line 41 function main
  assertion
  FALSE

VERIFICATION FAILED
```

Running Example

F = <Line=15, Correct Value=1>

esbmc --no-bounds-check --no-div-by-zero-check --no-pointer-check --no-slice --boolector repaired_example.c

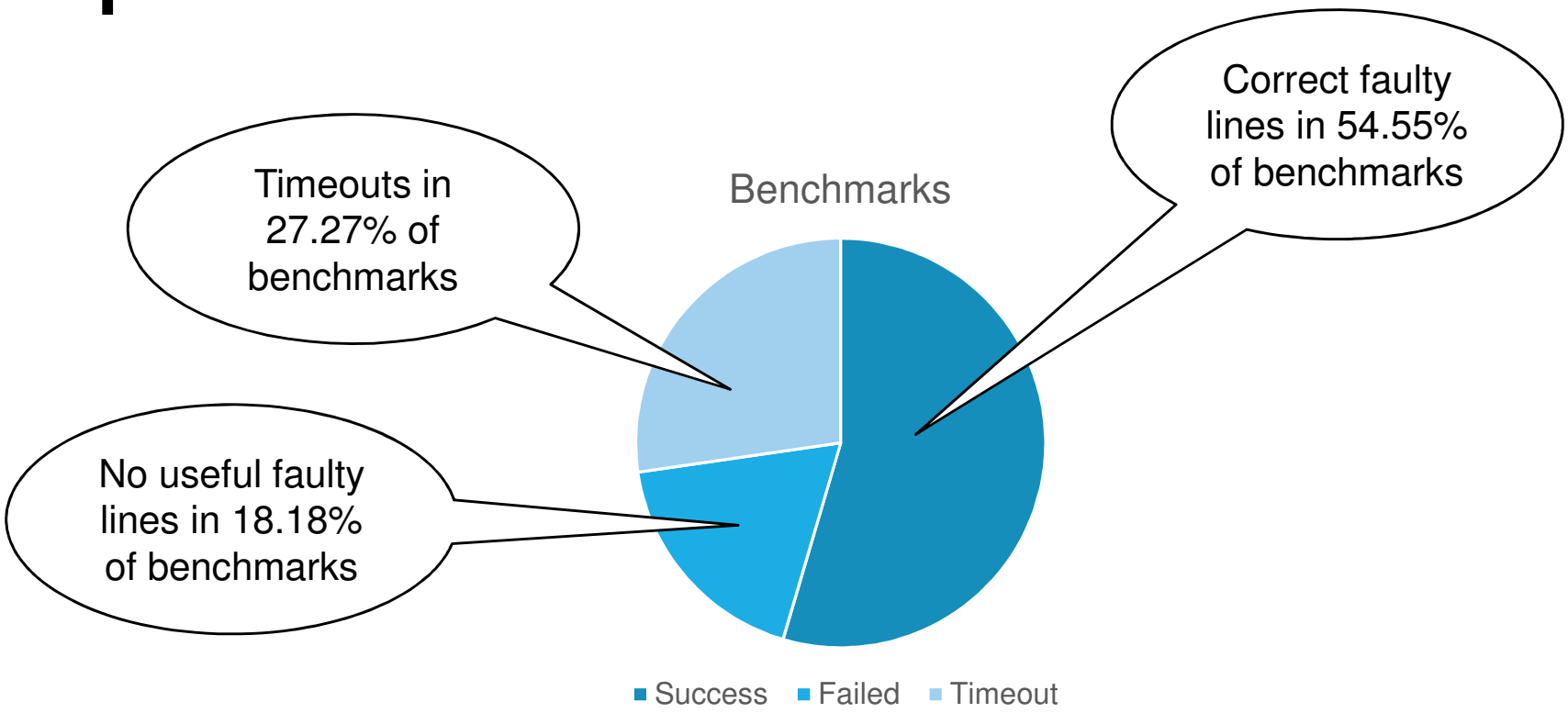
```
...
(15) c = 1;
...
```

```
*** Thread interleavings 197 ***
Symex completed in: 0.004s
size of program expression: 120 assignments
Slicing time: 0.000s
Generated 0 VCC(s), 0 remaining after simplification
VERIFICATION SUCCESSFUL
BMC program time: 0.004s
```

Experimental Objectives and Setup

- Objectives
  - Verify and validate our method using standard multi-threaded C software
- Specs
  - ESBMC v1.24.1 with SMT solver Boolector version 2.1.0
  - Core i7 4500 1.8 GHz
  - 8 GB of RAM
  - Fedora 21 64-bits
- Benchmarks
  - 11 benchmarks extracted from the Software Verification Competition, and the same used to evaluate ESBMC for multi-threaded C code

Experimental Results



Experimental Results

- No useful faulty lines occur when ESBMC retrieves unreasonable **diag** in the counterexample for the translated software under verification
  - E.g. **diag == 0**, since there is no line 0 in the code, we cannot say anything about this fault

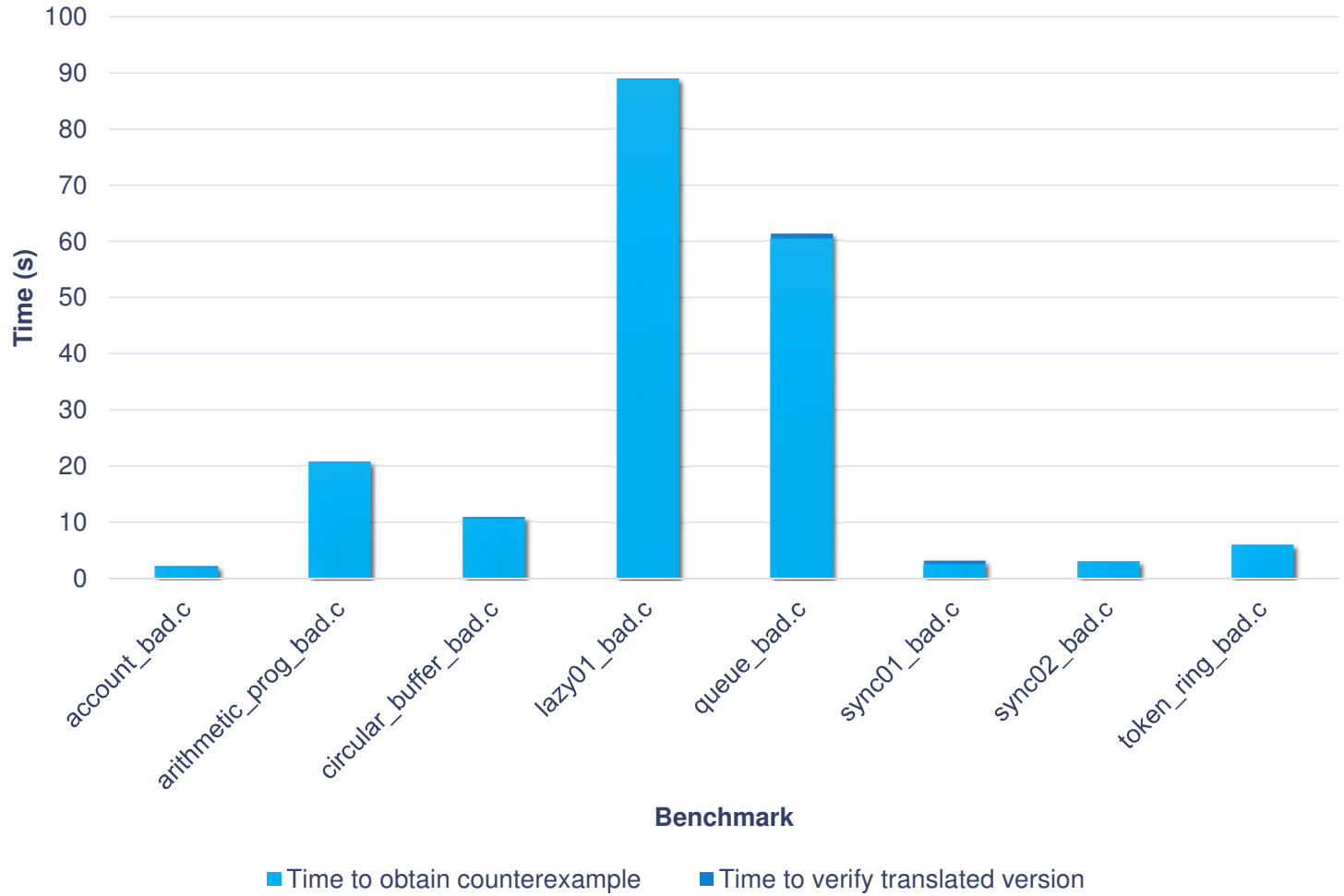
- Timeouts
  - If we run out of memory when first checking a benchmark using ESBMC, we denote that execution as a timeout
  - Thus, we cannot state it is a safe program, neither model it using our methodology

Experimental Results

- However, since we entirely rely on BMC tools to provide counterexamples to then translate the program under verification, timeouts are not due to our methodology

- This way, correct faulty lines are found in 6 out of 8 (**75%**) benchmarks

Experimental Results



Conclusions

- A novel method for localizing faults in multi-threaded C programs was proposed
  - It is based in BMC techniques and is also an extension to a sequential method to localize faults [Griesmeyer'07]
  - Useful for embedded systems
- Our methodology showed itself to be useful to assist in fault localization in standard multi-threaded software

Future Work

- Improve our code transformation
  - Use GOTO structure to model iterations
  - Model **pthread** statements more accurately
- Develop a tool to automate this process, such as an Eclipse plugin