



V Brazilian Symposium on Computing Systems Engineering

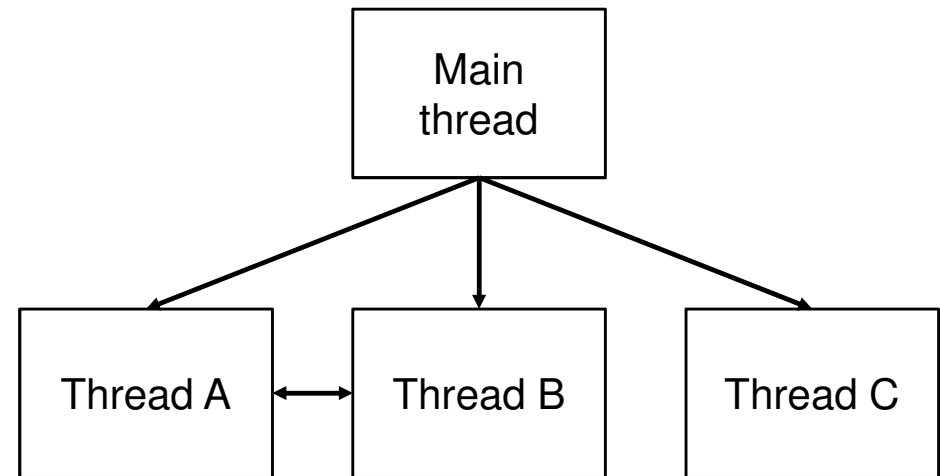


Fault Localization in Multi-threaded C Software using Bounded Model Checking

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

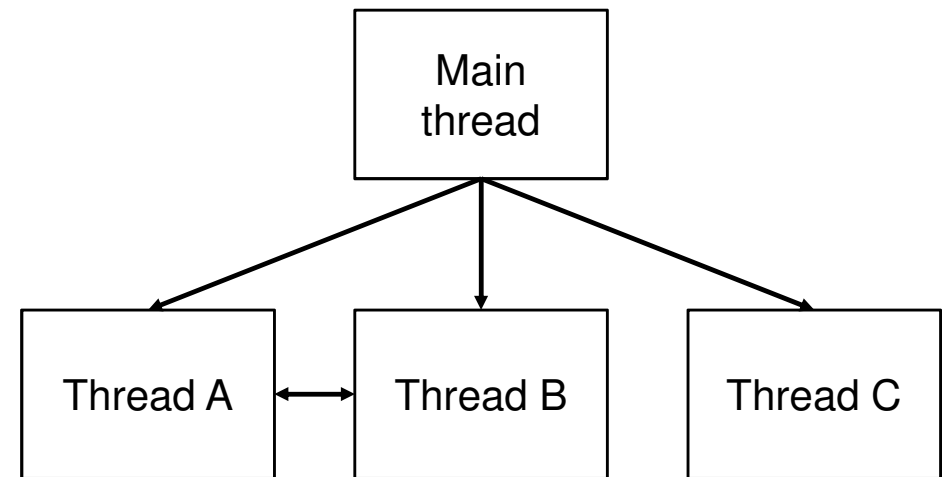
Multi-threaded Software and Difficulties

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



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- 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]

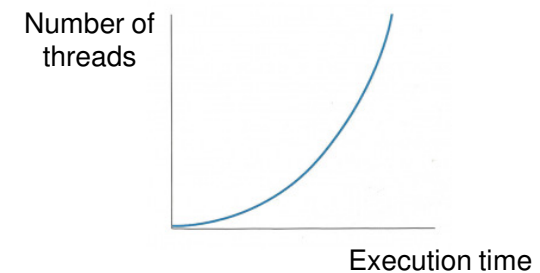
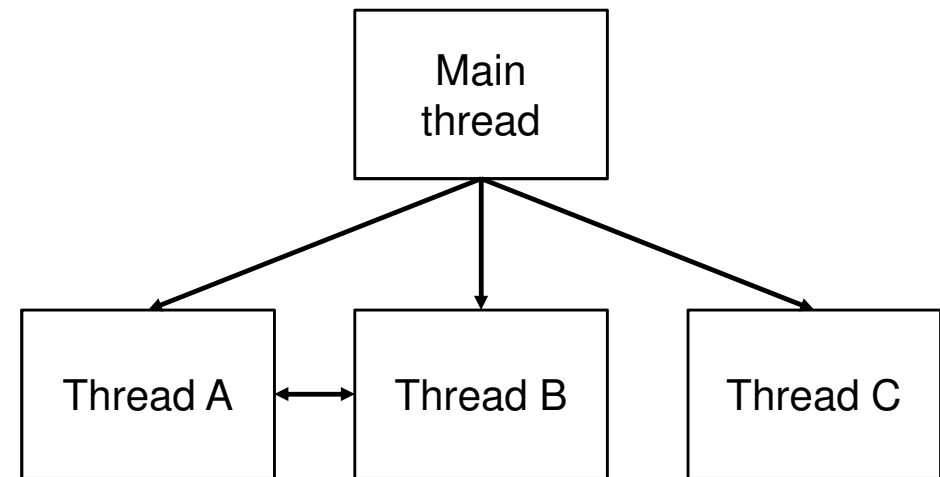


Possible Interleaving: $T_A \rightarrow T_B \rightarrow T_C \rightarrow T_B \rightarrow T_C \rightarrow T_A$



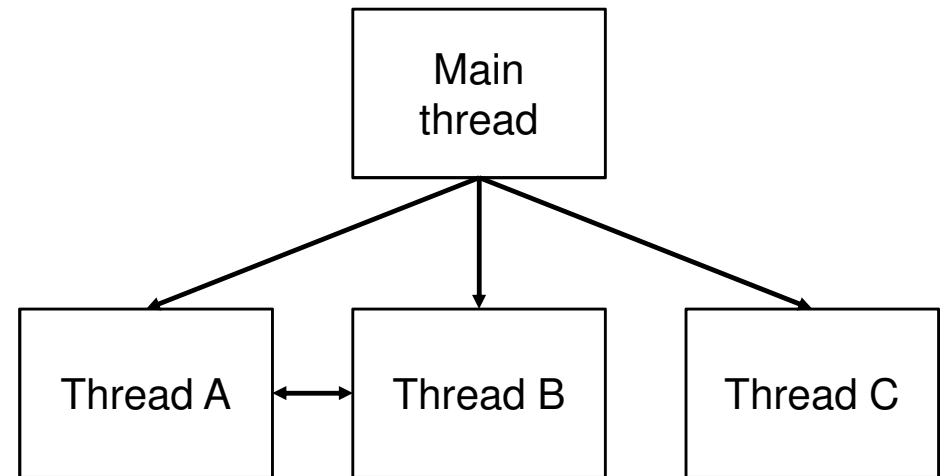
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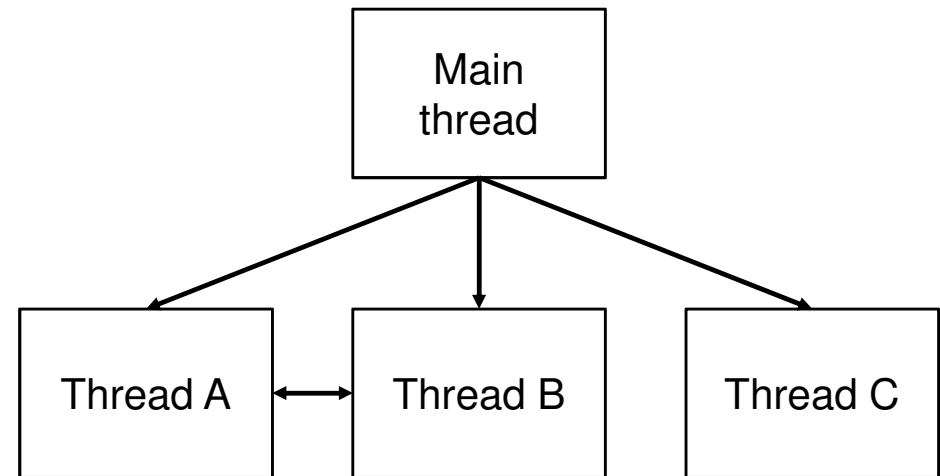
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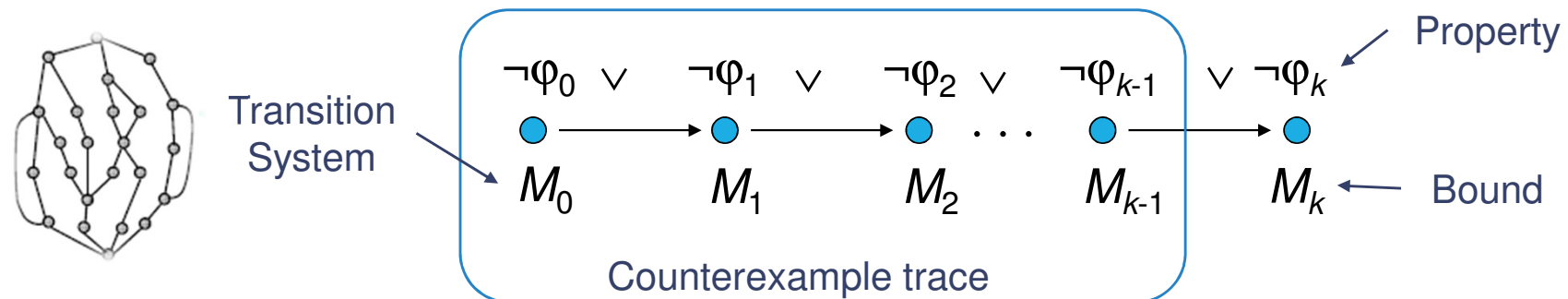
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Bounded Model Checking (BMC)

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



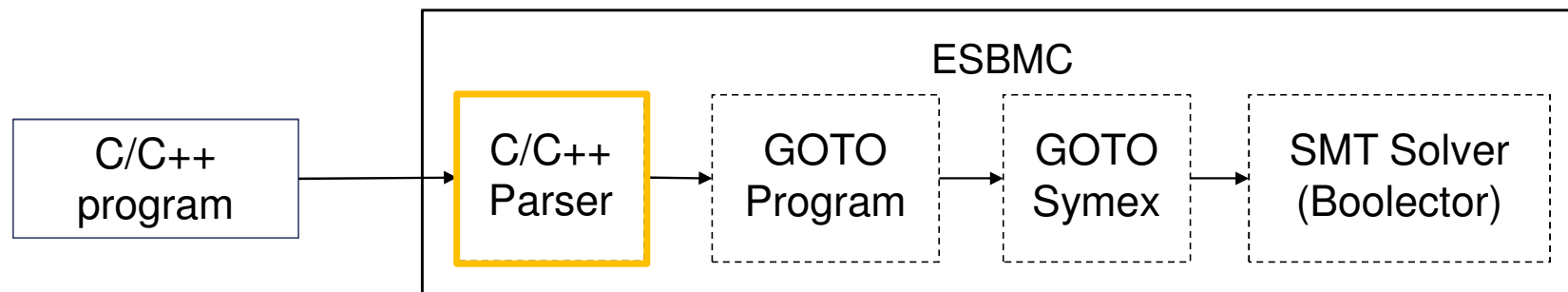
- Translated into a VC ψ such that: **ψ is satisfiable iff φ has counterexample of max. depth k**
- BMC has been applied successfully to verify multi-threaded software since 2005, but there are some limitations

Objectives

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

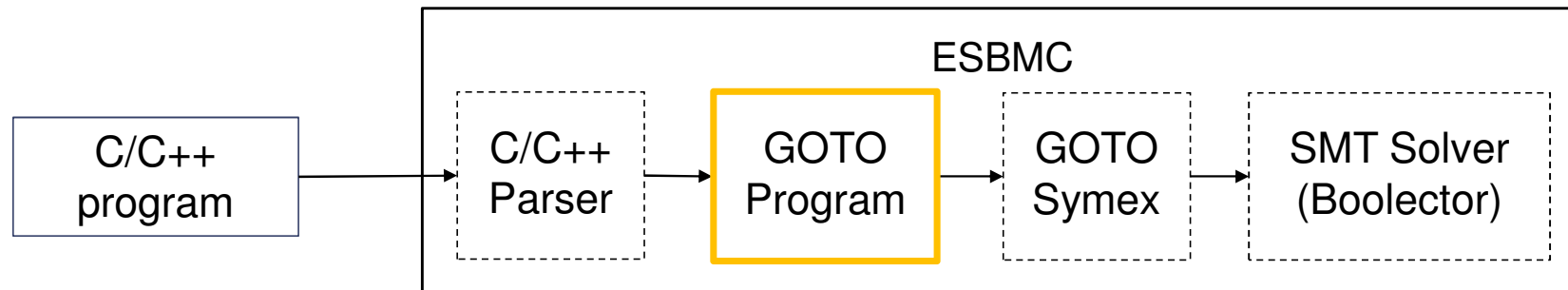
- Expand existing fault localization approaches to sequential programs to handle multi-threaded software and provide a sequentialization method to translate multi-threaded C software into sequential software
- Design a grammar to model functions and variables related to multi-threaded programming in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

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



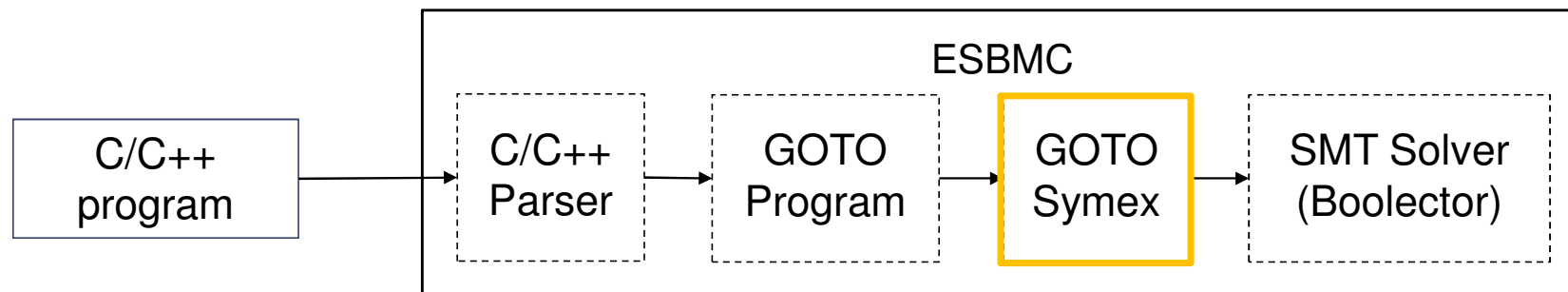
C parser: processes the ANSI-C file and builds an Abstract Syntax Tree (AST)

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



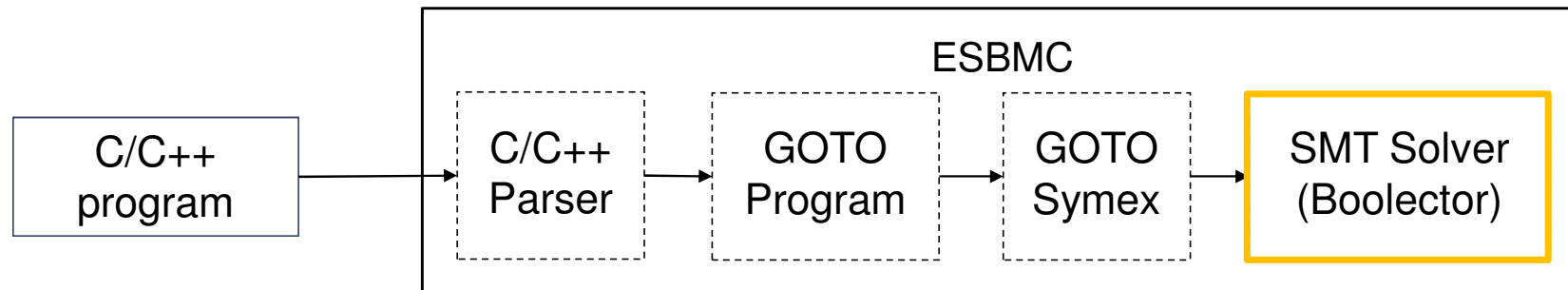
GOTO Program: converts an ANSI-C program into a GOTO-Program (replacement of *switch* and *while* by *if* and *goto* expressions)

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

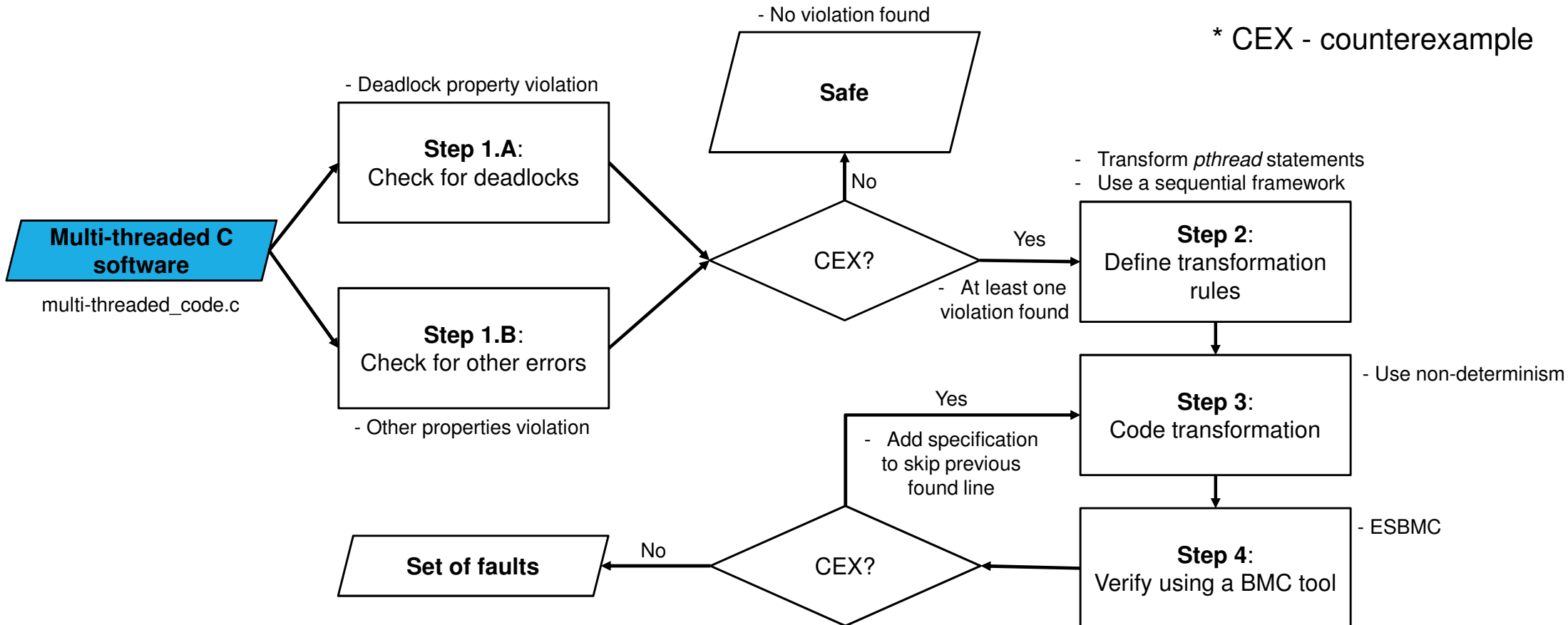
Fault Localization using Model Checking

- [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**

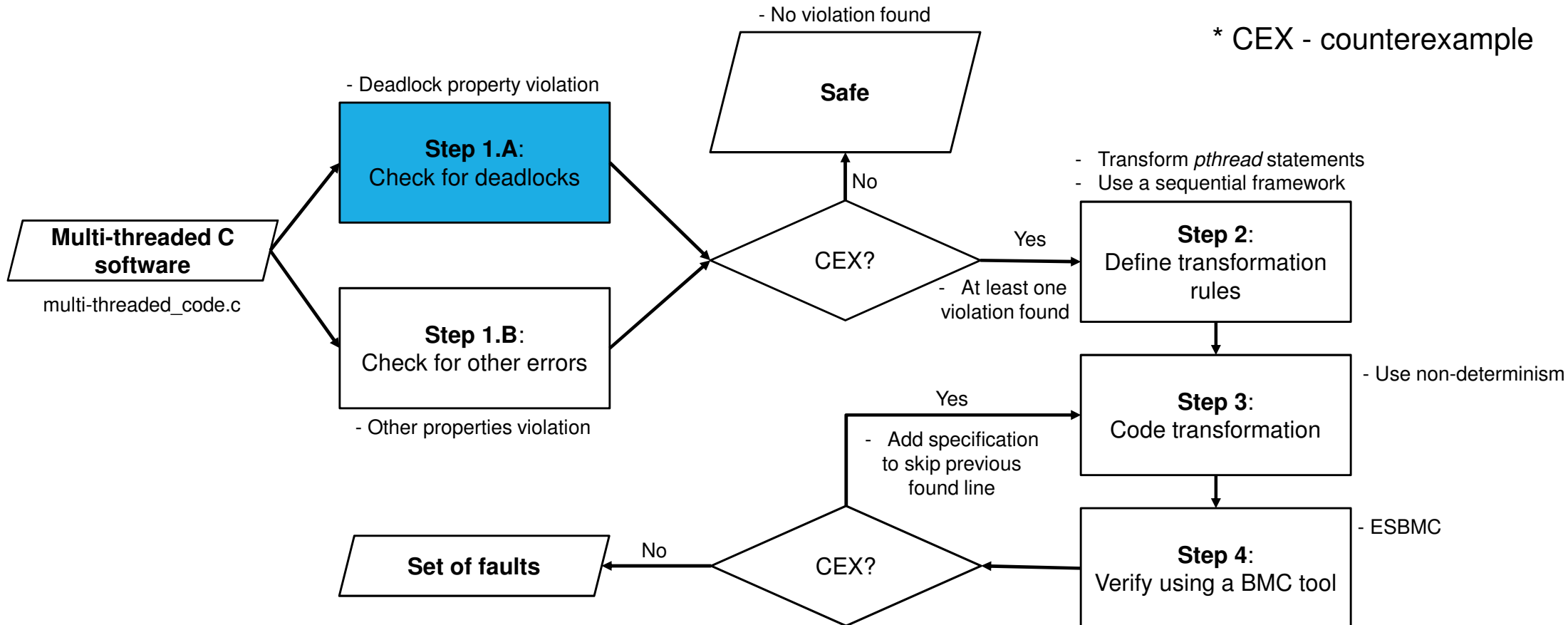
```
int non_det();
int diag;
...
int main(void *args) {
    diag = non_det();
    ...
    assert(0);
}
```

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

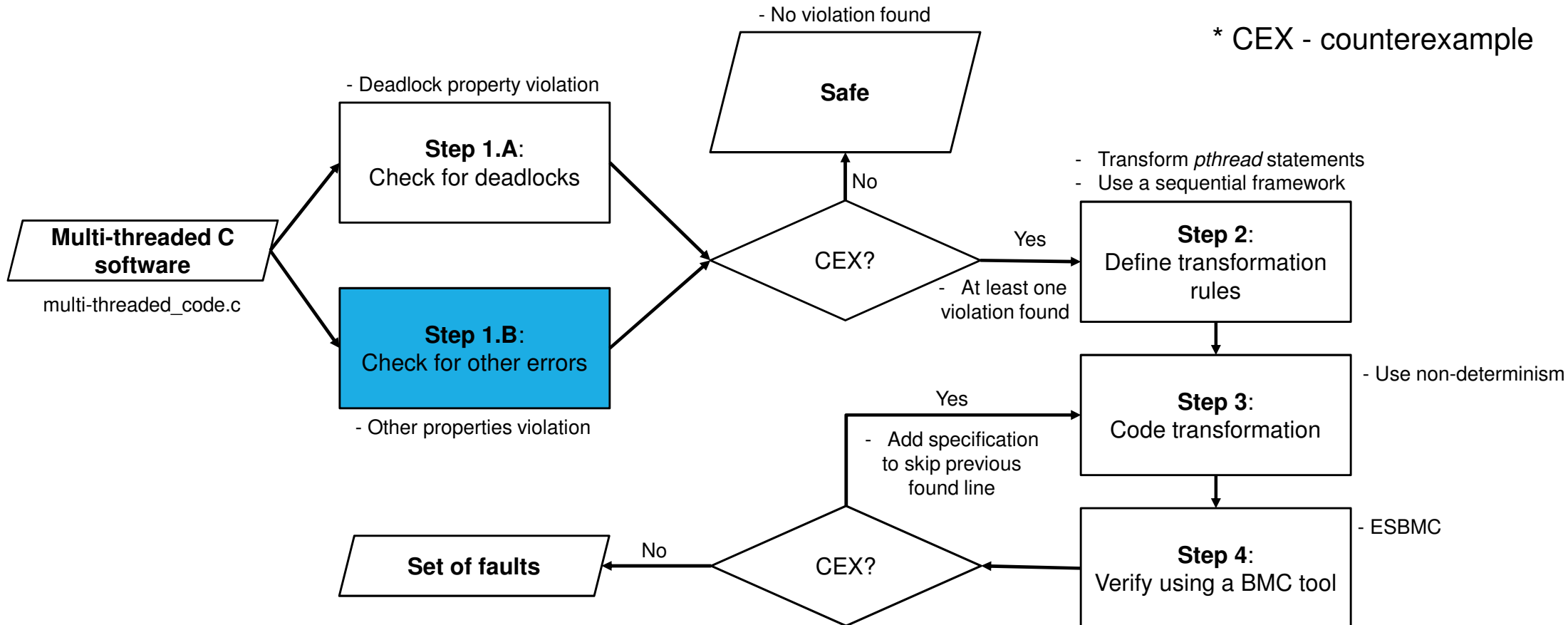
Our Proposed Methodology



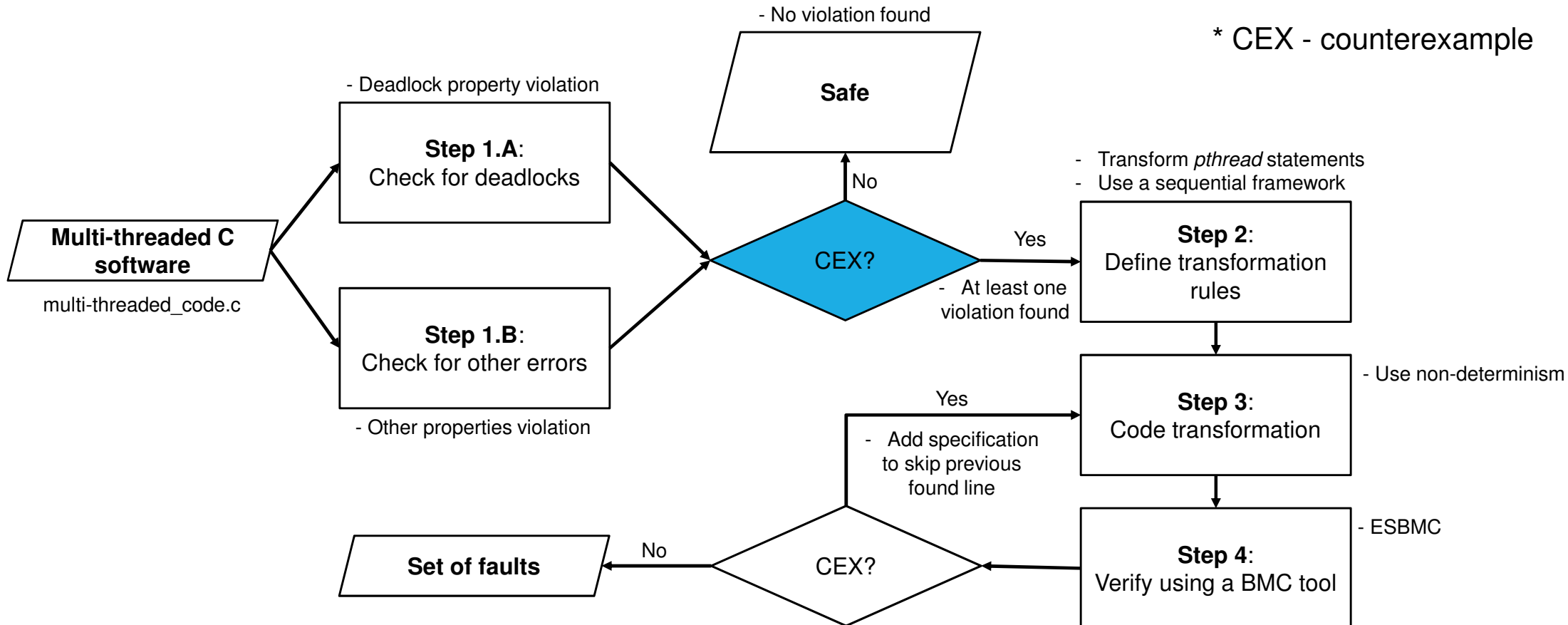
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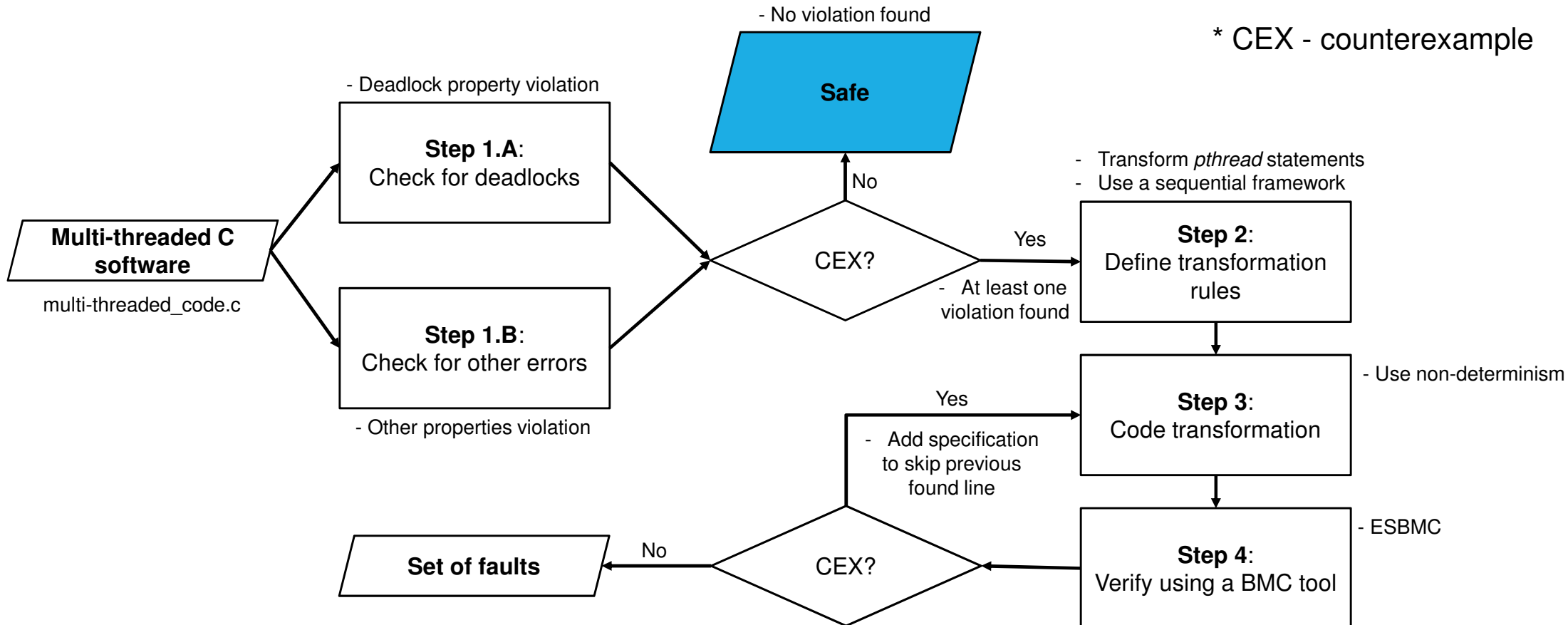
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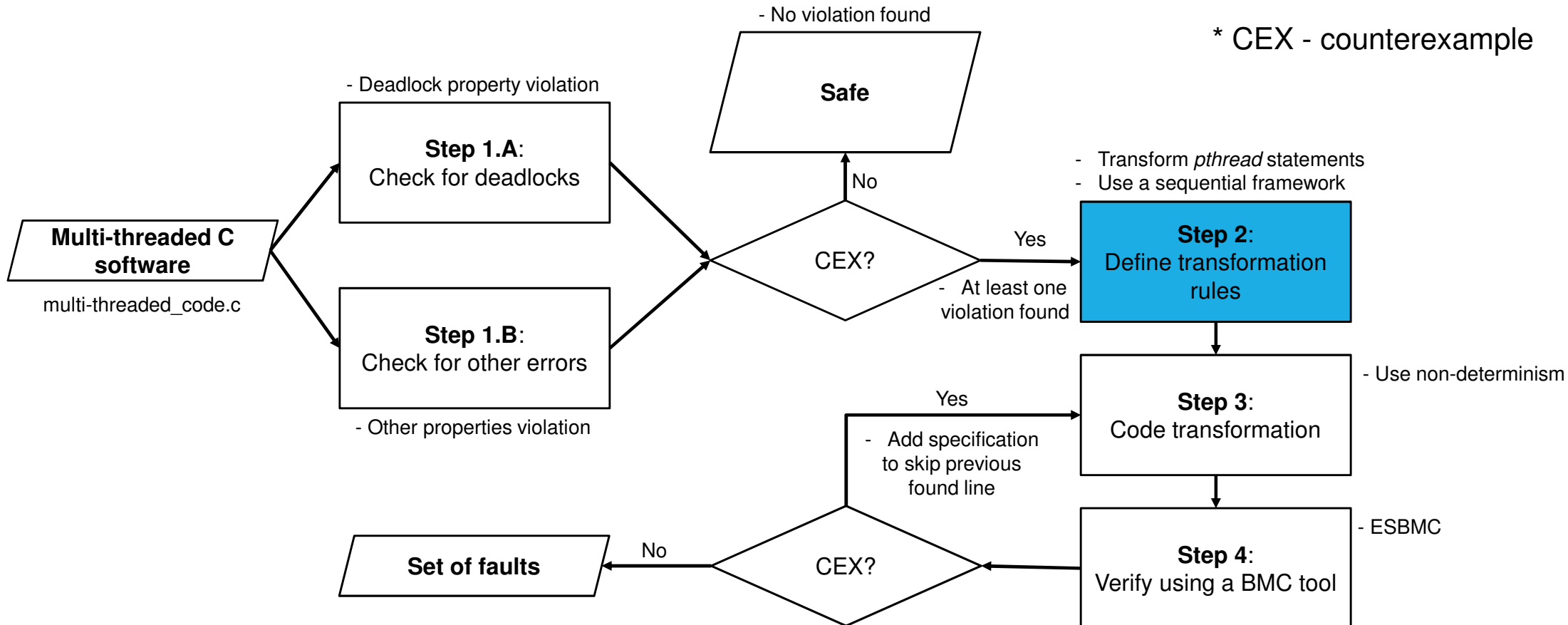
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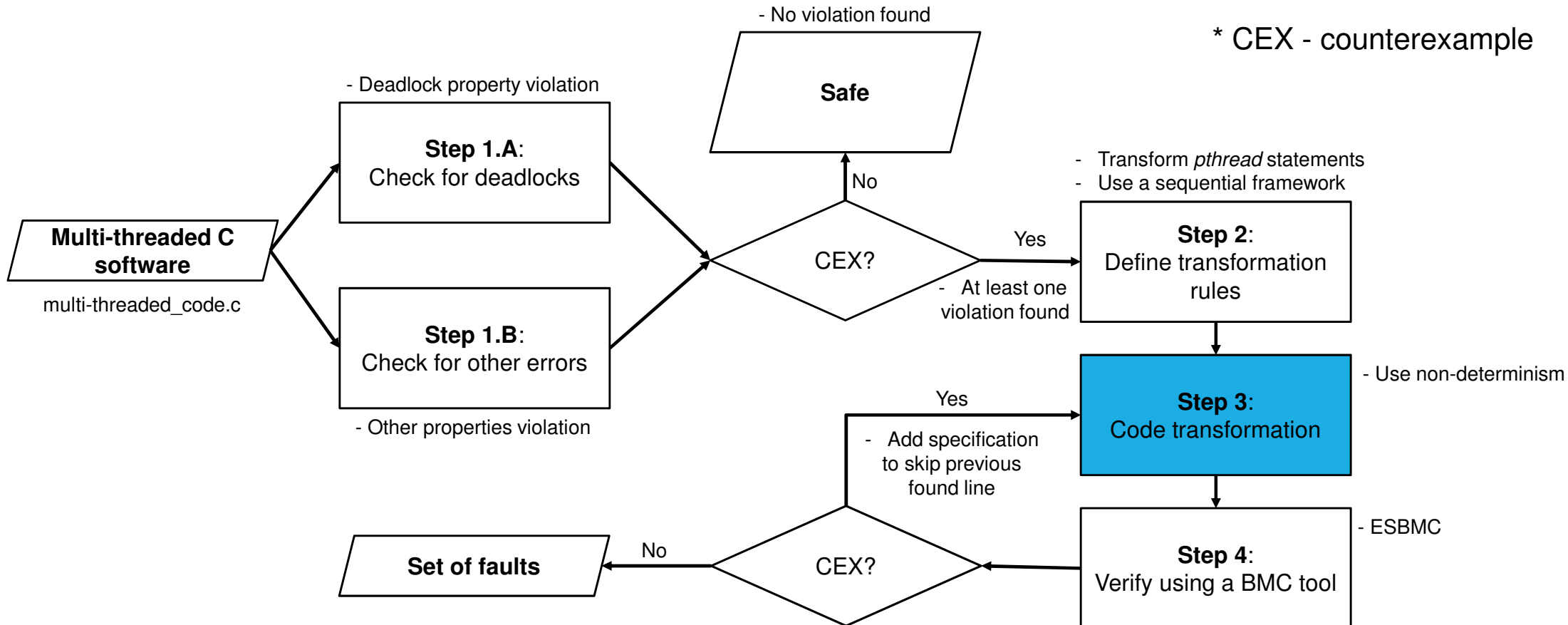
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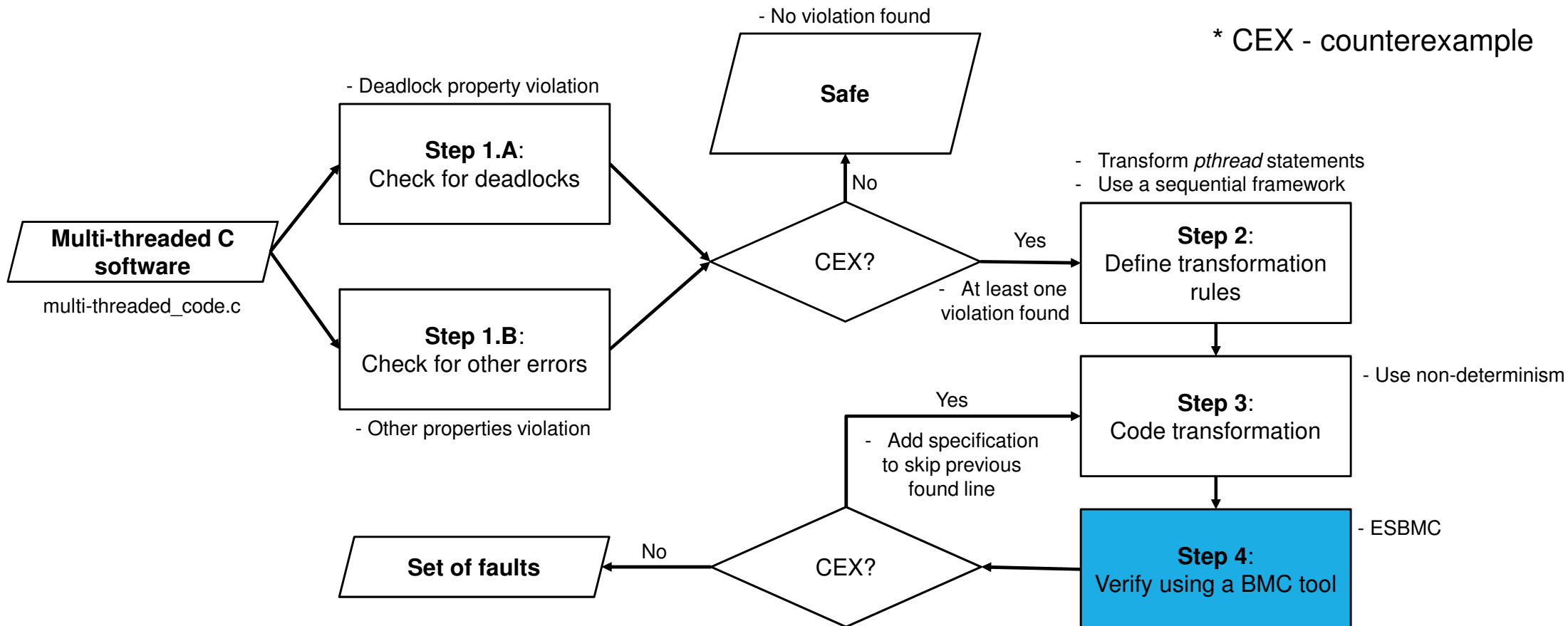
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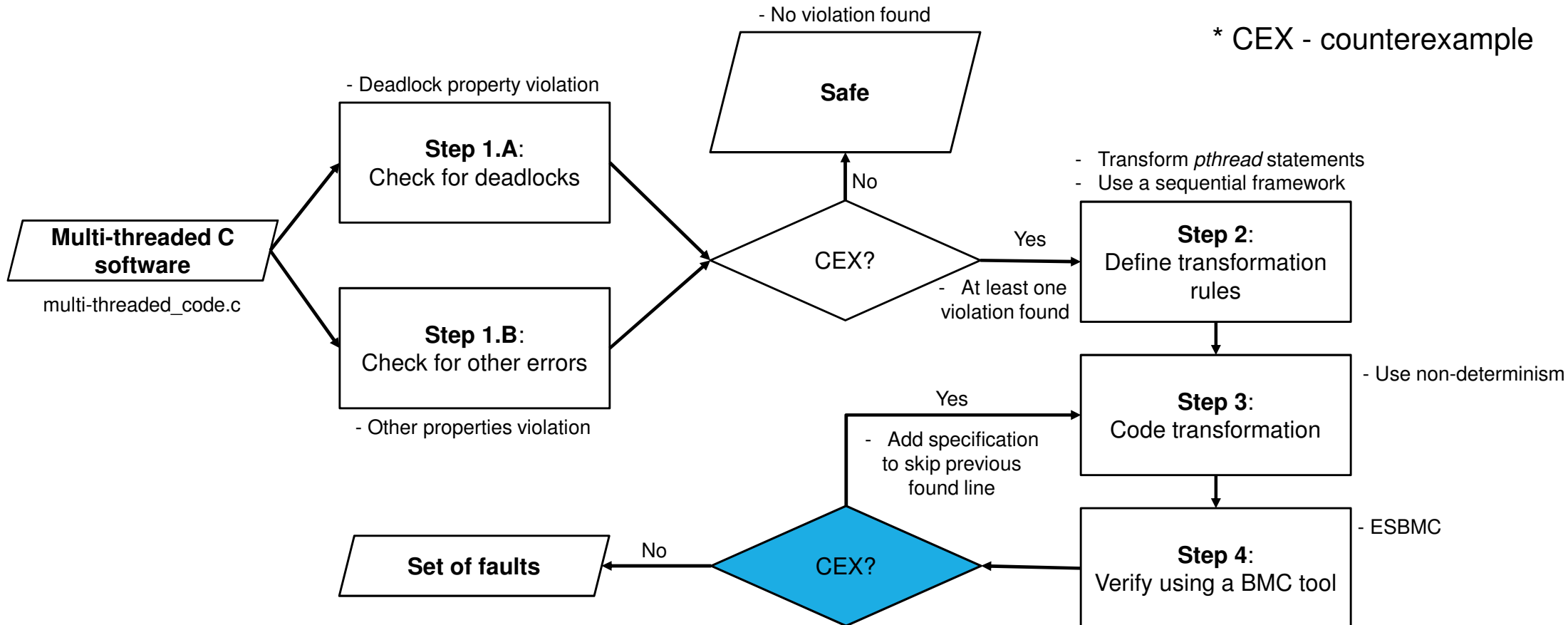
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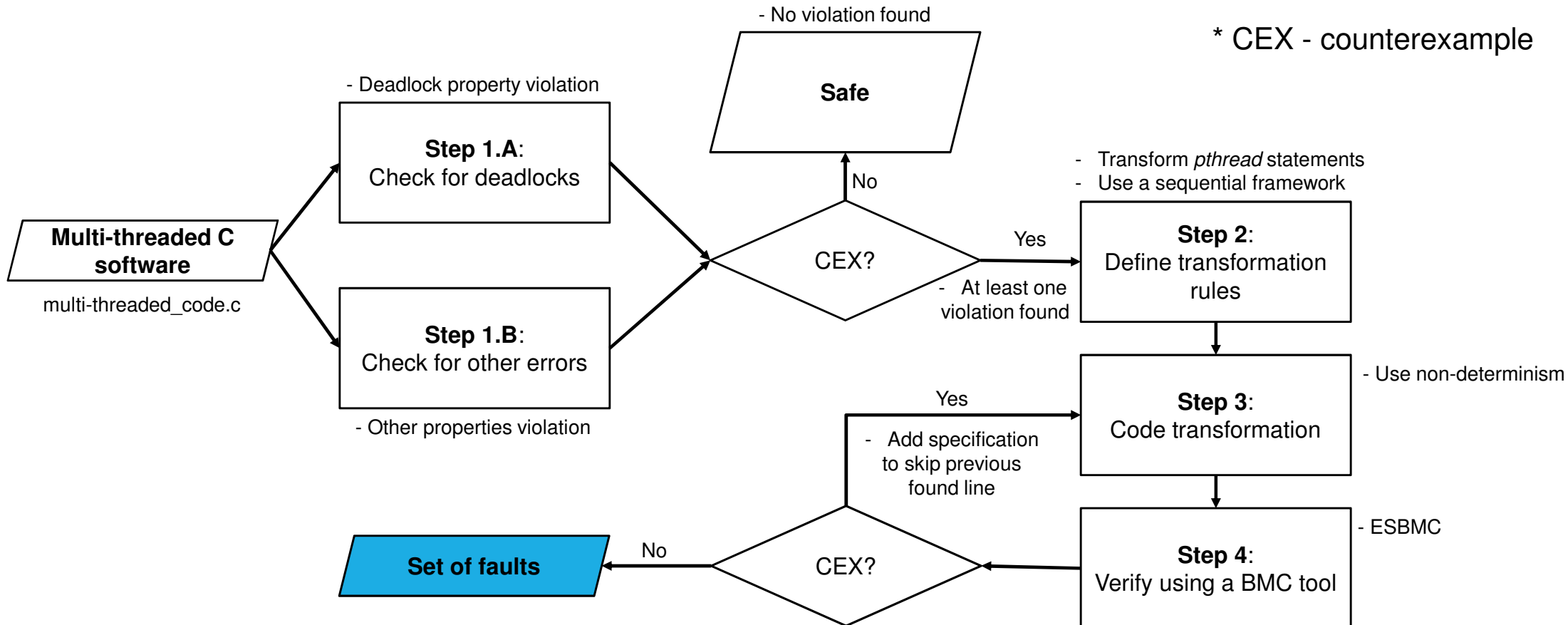
Our Proposed Methodology



Our Proposed Methodology



Our Proposed Methodology



Our Proposed Methodology – Grammar

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

cs[0]=11

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

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

cs[2]=31
NCS=3

Violated property:

file example.c line 16 function f2
assertion FALSE
VERIFICATION FAILED

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

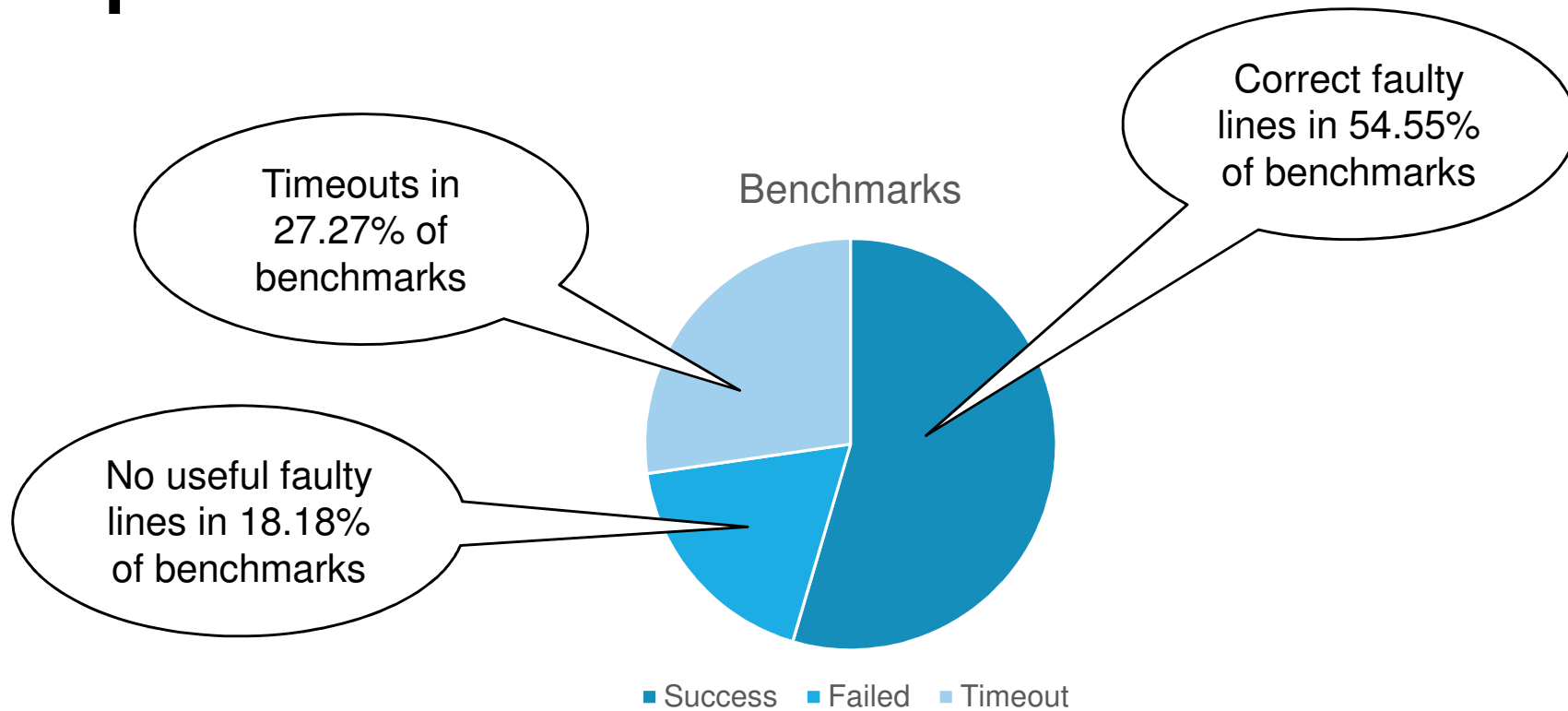
VERIFICATION SUCCESSFUL

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



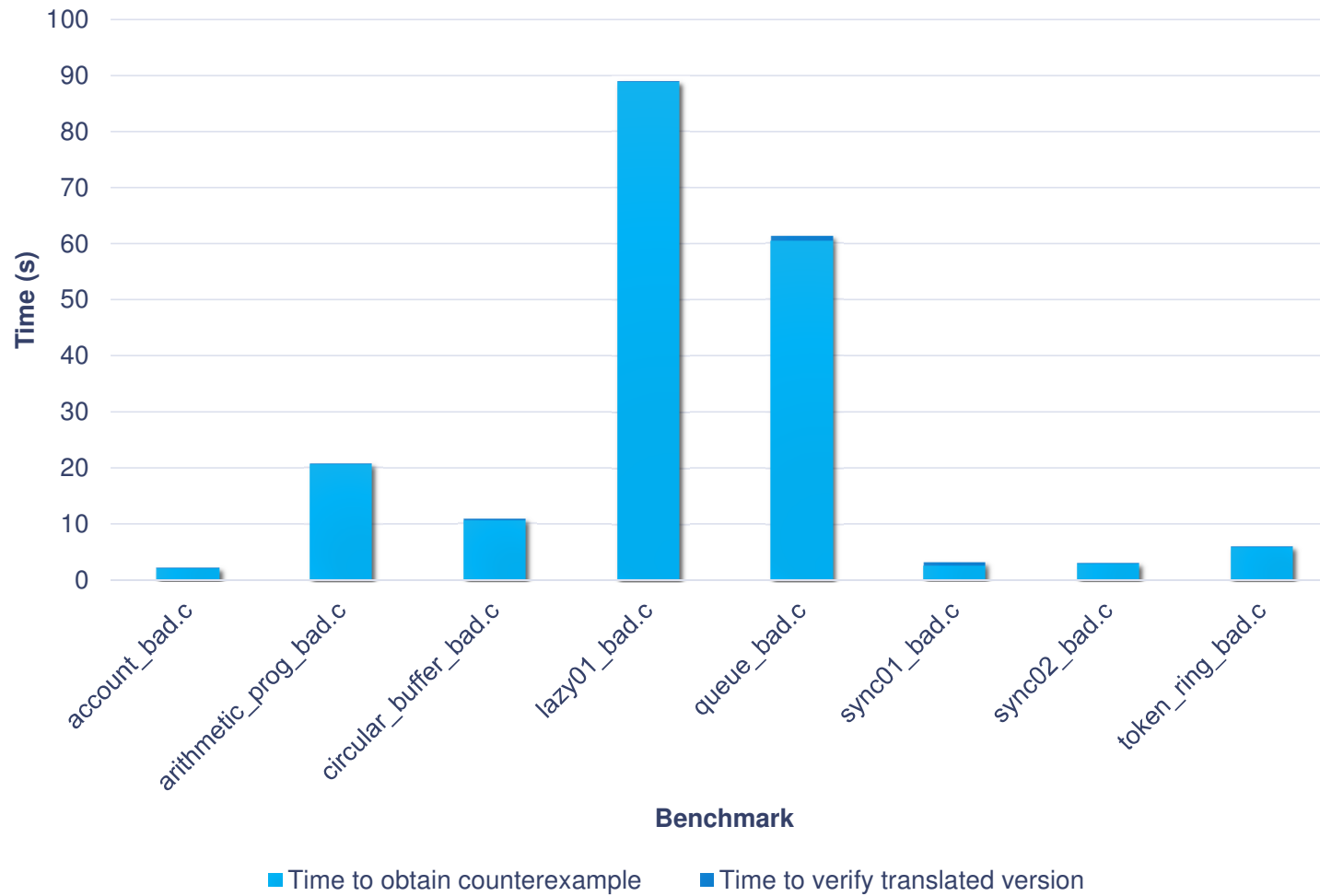
Experimental Results

- 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