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ESBMC v7.7： Automating Branch Coverage Analysis Using CFG-Based Instrumentation and SMT Solving

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ESBMC

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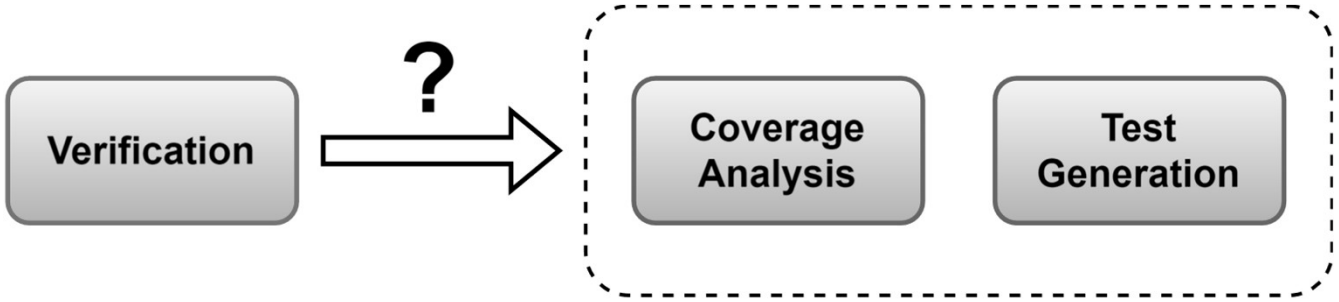
Motivation

ESBMC

ESBMC, a bounded model checking (BMC) verifier based on SMT solving, has proven its effectiveness in bug detection in recent competitions.

However, it has never participated in the evaluation of the Cover-Branches category due to the lack of:

- Branch coverage analysis
- Automated test suite generation



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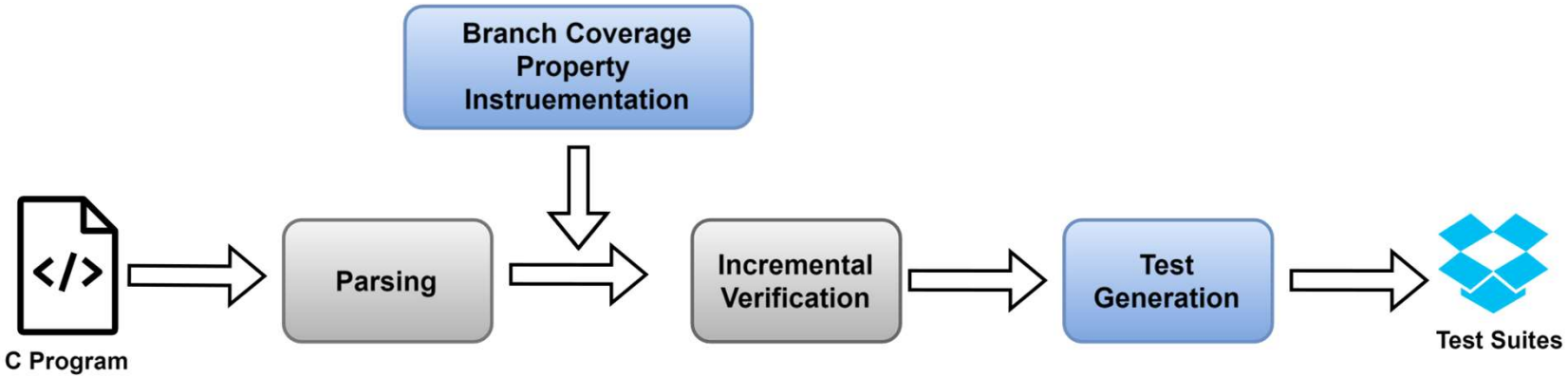
Contribution

ESBMC

To bridge this gap, we present **ESBMC v7.7** with the following key contributions:

- Branch Coverage Instrumentation
  - Instrumentation & Isolation
- Incremental Multiple Property Verification
  - Property Splitting & Incremental Reasoning
  - Re-verification & Termination
  - Test Generation



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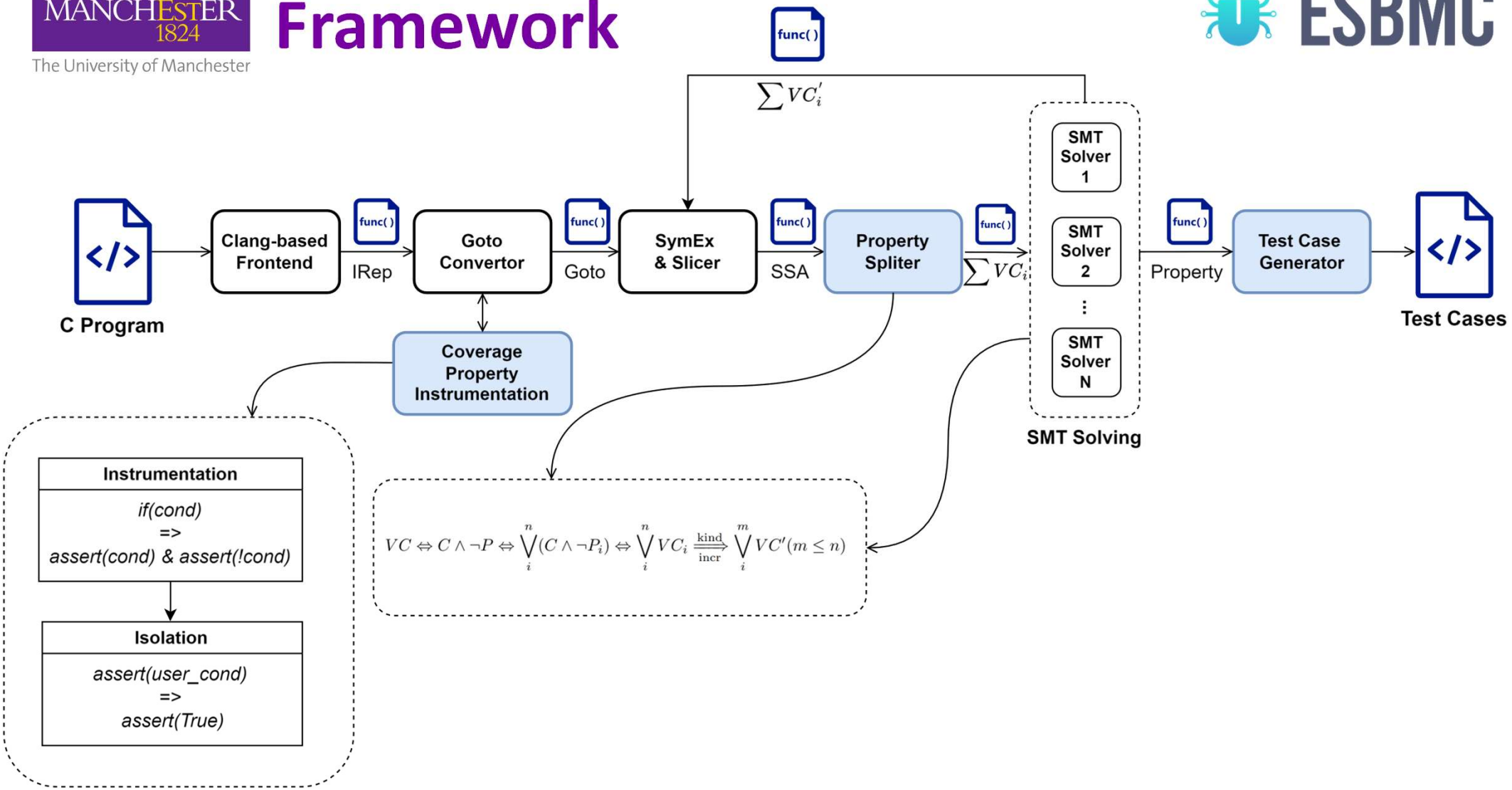
Framework

ESBMC



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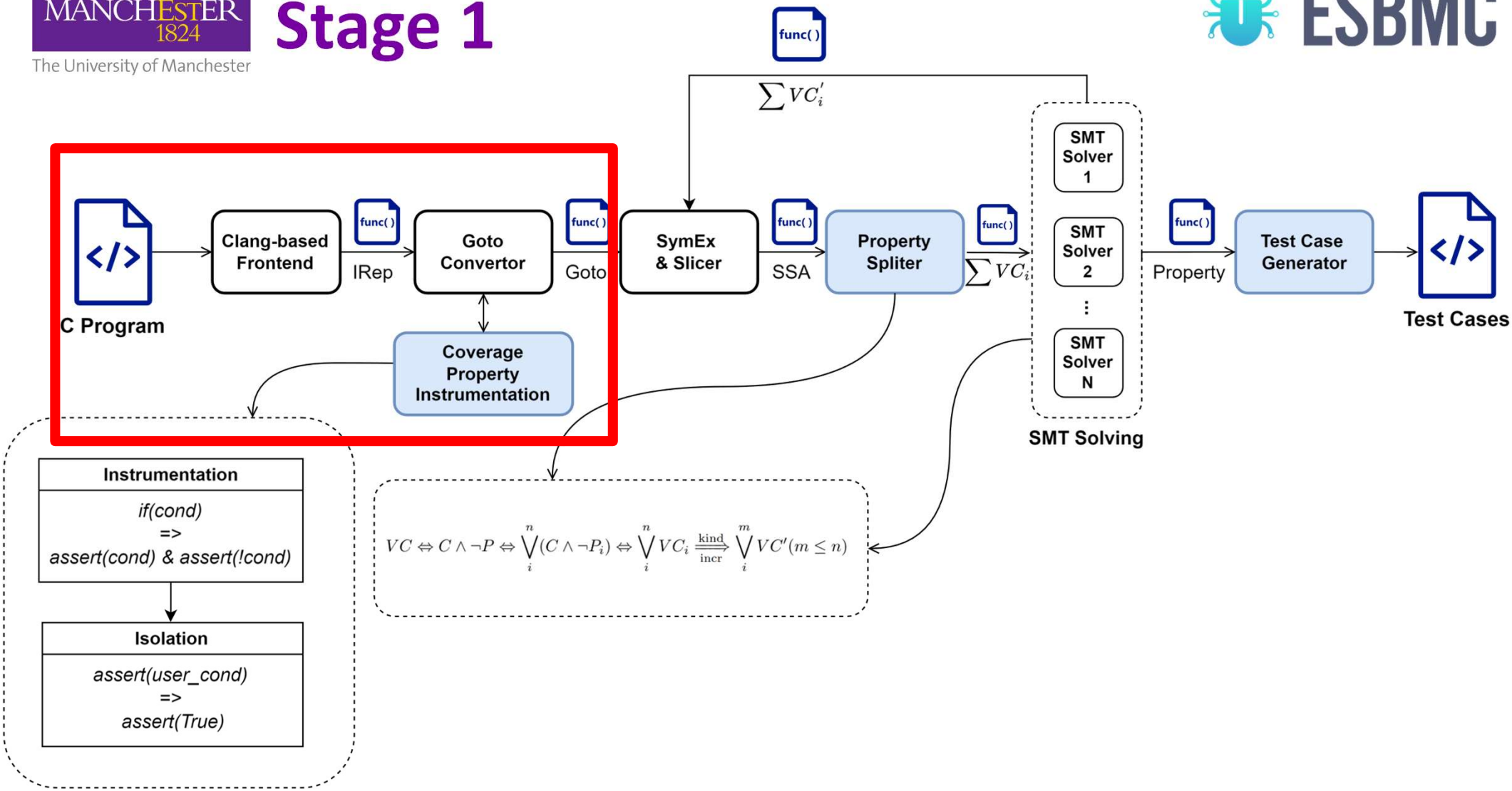
Stage 1

ESBMC



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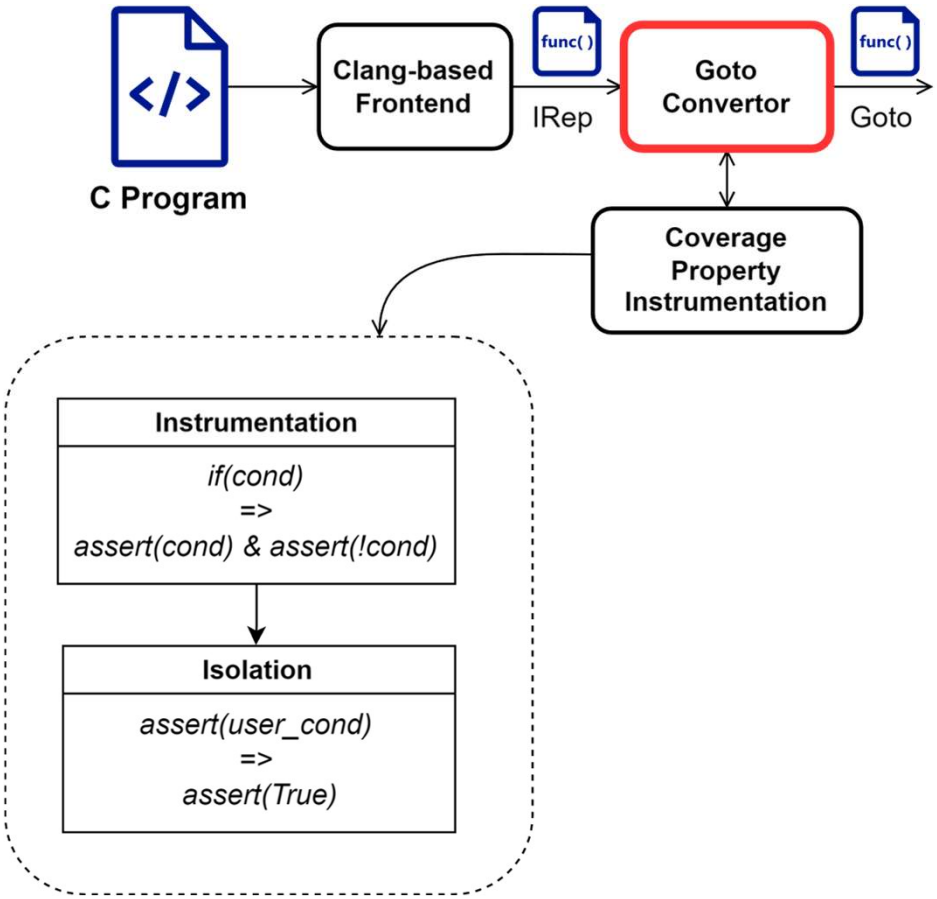
Simplification

ESBMC



We apply our algorithm upon **GOTO program,** i.e., Control Flow Graph (CFG).

Simplification: In the Goto program, control-flow constructs such as **if-else** statements, **while** loops, **for** loops, and **switch-case** statements are normalized into **if-goto** structures.

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```c
int main()
{
  int x = 0;
  while (__VERIFIER_nondet_bool())
  {
    if (!x)
    {
      assert(x == 0);
      ++x;
    }
    else if (x == 1)
    {
      assert(x > 0);
      x = 2;
    }
  }
  __VERIFIER_assert(x == 2);
}
```

```
esbmc exp.c --goto2c &> exp2.c
```

```c
int main()
{
    {
        int x = __VERIFIER_nondet_int();
    __ESBMC_goto_label_1:;
        _Bool return_value___VERIFIER_nondet_bool_1;
        return_value___VERIFIER_nondet_bool_1 = __VERIFIER_nondet_bool();
        if (!return_value___VERIFIER_nondet_bool_1) // while (nondet_bool())
            goto __ESBMC_goto_label_4;
        if (!(!(_Bool)x))                           // if (!x)
            goto __ESBMC_goto_label_2;
        assert(x == 0);
        assert(!overflow("+", x, 1));               // overflow-check
        x = x + 1;
        goto __ESBMC_goto_label_3;
    __ESBMC_goto_label_2:;
        if (!(x == 1))                              // else if (x == 1)
            goto __ESBMC_goto_label_3;
        assert(x > 0);
        x = 2;
    __ESBMC_goto_label_3:;
        goto __ESBMC_goto_label_1;
    __ESBMC_goto_label_4:;
        __VERIFIER_assert((int)(x == 2));
    }
}
```

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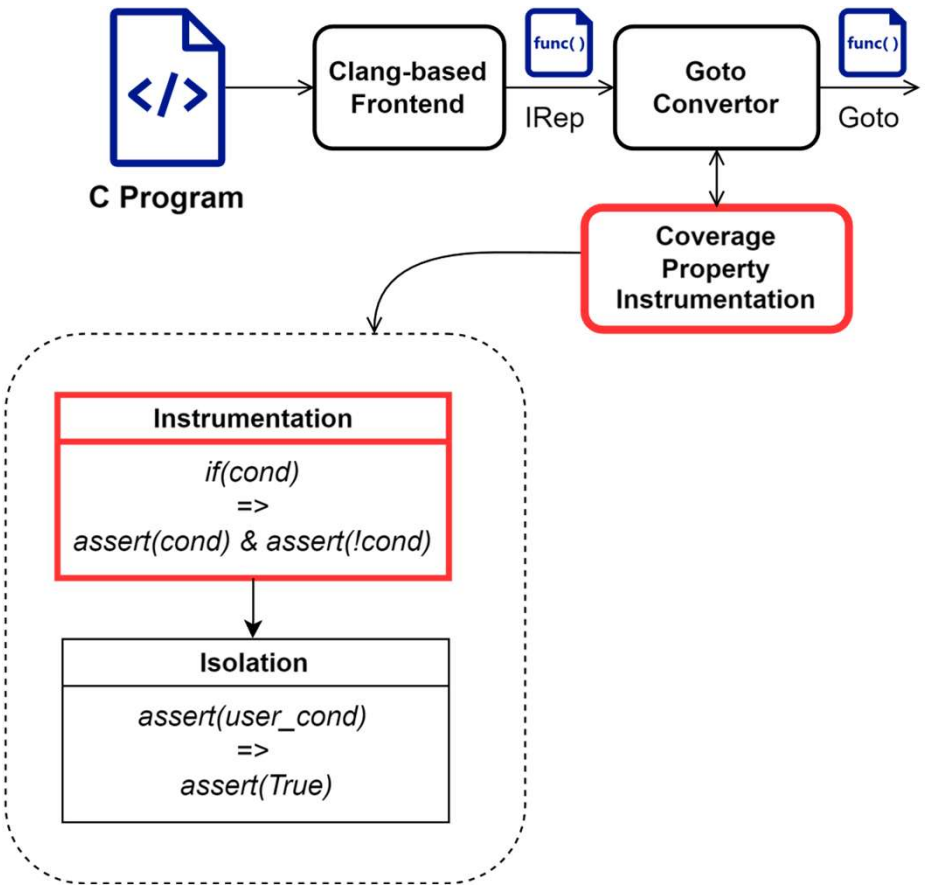
Instrumentation

ESBMC



Instrumentation: to entry a branch guarded by condition like `if(cond)`, there must exist an assignment that satisfies cond. This is equivalent to checking if a counterexample satisfies `assert(!cond)`

- True Branch: the body executes
- False Branch: the body is skipped

```
if(cond) => True branch:  assert(!cond)
         => False branch: assert(!(!cond))
```

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Instrumentation

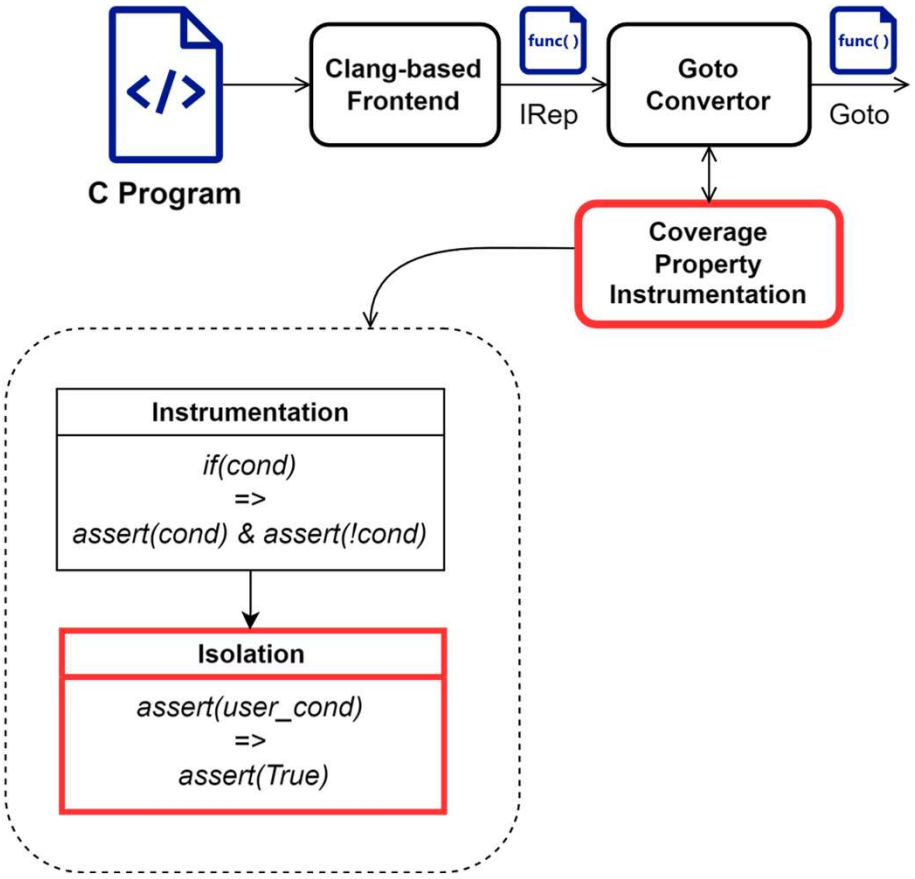
ESBMC

```
_Bool return_value___VERIFIER_nondet_bool_1;
return_value___VERIFIER_nondet_bool_1 = __VERIFIER_nondet_bool();
assert(!return_value___VERIFIER_nondet_bool_1);     // !return_value$___VERIFIER_nondet_bool$1
assert(!(!return_value___VERIFIER_nondet_bool_1)); // !(!return_value$___VERIFIER_nondet_bool$1)
if (!return_value___VERIFIER_nondet_bool_1)
    goto __ESBMC_goto_label_4;
```

```
assert(!(!(_Bool)x));     // !(!(_Bool)x)
assert(!(!(!(_Bool)x))); // !(!(!(_Bool)x))
if (!(!(_Bool)x))
    goto __ESBMC_goto_label_2;
```

```
assert(!(x == 1));     // !(x == 1)
assert(!(!(x == 1))); // !(!(x == 1))
if (!(x == 1))
    goto __ESBMC_goto_label_3;
```

Isolation



Isolation: Potential interferences are excluded to isolate the analysis of instrumented coverage properties from others.

- User-defined properties, i.e. assertions, are converted into tautologies

```
assert(a[i]>0) => assert(True)
```

- Internal safety checks within ESBMC are disabled

```
/* assert(y!=0) */
Double z = x / y
```

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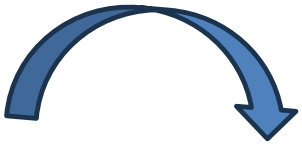
Isolation

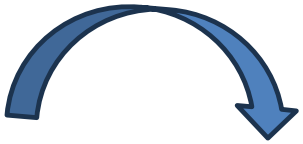
ESBMC

```
__ESBMC_goto_label_4:;
    __VERIFIER_assert((int)(x == 2));
}
```



```
__ESBMC_goto_label_4:;
    __VERIFIER_assert(1);  // x == 2
}
```

```
assert(x == 0);
assert(!overflow("+", x, 1));
x = x + 1;
```



```
assert(1);
/* assert(!overflow("+", x, 1)); */
x = x + 1;
```

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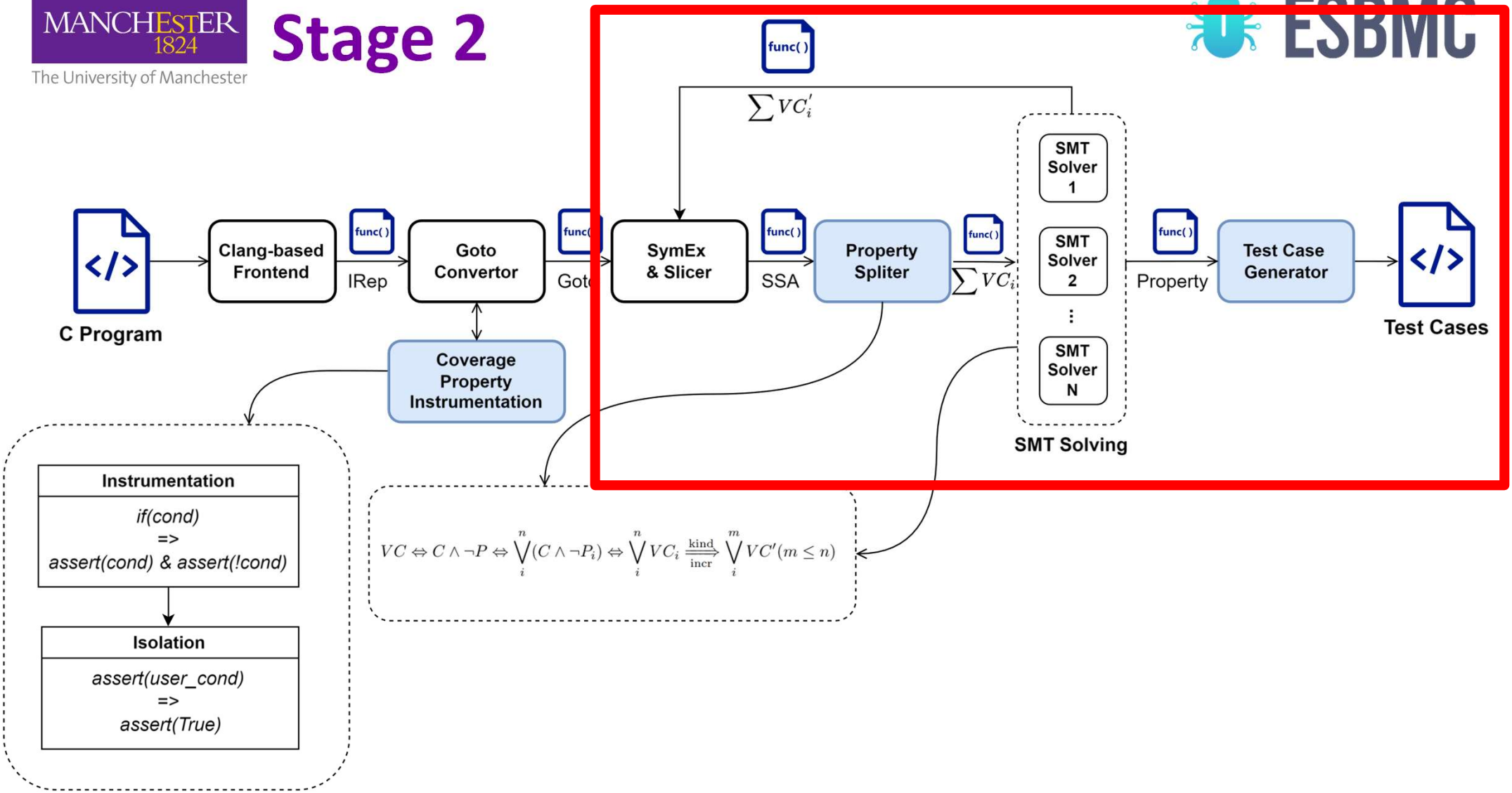
Stage 2

ESBMC



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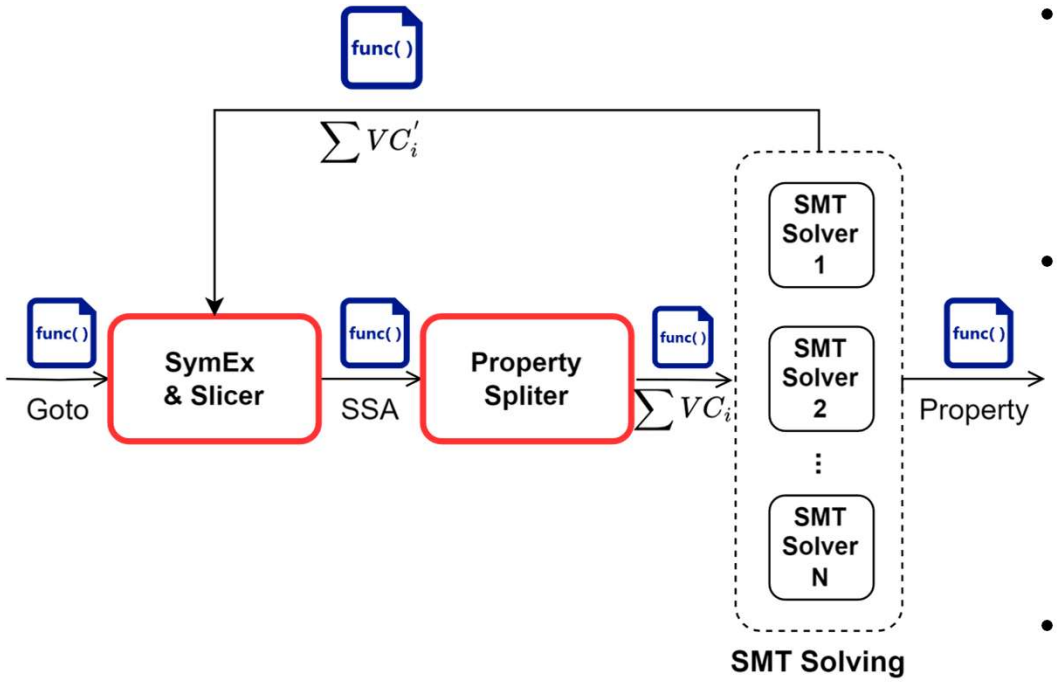
SymEx & Splitting

ESBMC



- The CFG get symbolic executed within defined bounds (e.g., through loop unrolling) and is eventually encoded as a **verification condition (VC)**.
- In ESBMC, the VC is an SMT formula incorporating:
  - **Constraints** (execution conditions, **C**)
  - **Properties** (expected behaviours, **P**)

$$VC \Leftrightarrow C \wedge \neg P$$

- To let ESBMC verify multiple properties, we split the property ***P*** into a set of unit properties $\boldsymbol{P_i}$

$$C \wedge \neg P \Leftrightarrow \bigvee_i^n (C \wedge \neg P_i) \Leftrightarrow \bigvee_i^n VC_i$$

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Incremental Reasoning

ESBMC

Issue:

- Normally, BMC verifies system behavior only up to a fixed bound ***k***, once this threshold is reached, it terminates. The verification result becomes unknown.
- As a consequence, some branch paths may be missed.

How about we set a relatively large ***k*** (e.g. ***100***)?

- **No guarantee of soundness**: Larger ***k*** increases depth but doesn't ensure that all paths are covered or that unreachability is proved.
- **Inefficiency**: Large bounds might lead to state-space explosion

https://ssvlab.github.io/esbmc/documentation.html#k-induction

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Incremental Reasoning

ESBMC

Aid: Use incremental reasoning (e.g. k-induction) to automatically extend verification beyond bound ***k***

- It checks that a property holds up to a bound (k)
- It proves that if it holds at (k), it also holds at $(k+1)$

In ESBMC, this can be summaries as three steps:

- **Base Case**: Check if the program is correct up to (k) steps (normal BMC).
- **Forward Reasoning**: prove that all loops in the program were fully unrolled.
- **Inductive Step**: If it is good up to (k), prove it's still good for $(k+1)$.

$$\begin{array}{rcrcl} & \neg & B(k) & \rightarrow & \text{program contains bug} \\ B(k) & \wedge & F(k) & \rightarrow & \text{program is correct} \\ B(k) & \wedge & I(k) & \rightarrow & \text{program is correct} \end{array}$$

https://ssvlab.github.io/esbmc/documentation.html#k-induction

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Recall: Instrumentation

ESBMC

```
_Bool return_value___VERIFIER_nondet_bool_1;
return_value___VERIFIER_nondet_bool_1 = __VERIFIER_nondet_bool();
assert(!return_value___VERIFIER_nondet_bool_1);     // !return_value$___VERIFIER_nondet_bool$1
assert(!(!return_value___VERIFIER_nondet_bool_1)); // !(!return_value$___VERIFIER_nondet_bool$1)
if (!return_value___VERIFIER_nondet_bool_1)
    goto __ESBMC_goto_label_4;
```

```
assert(!(!(_Bool)x));     // !(!(_Bool)x)
assert(!(!(!(_Bool)x))); // !(!(!(_Bool)x))
if (!(!(_Bool)x))
    goto __ESBMC_goto_label_2;
```

```
assert(!(x == 1));     // !(x == 1)
assert(!(!(x == 1))); // !(!(x == 1))
if (!(x == 1))
    goto __ESBMC_goto_label_3;
```

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Incremental Reasoning

ESBMC

```
!(!return_value$___VERIFIER_nondet_bool$1)

!return_value$___VERIFIER_nondet_bool$1

!(!(!(_Bool)x))

!(!(_Bool)x)

!(!(x == 1))

!(x == 1)
```

K=1

```
!(!(!(_Bool)x))

!(!(x == 1))

!(x == 1)
```

K=2

```
!(!(x == 1))
```

K=3

K=4 **Terminate**

Termination:

a) all remaining coverage properties are proven during forward reasoning

b) all properties are reduced to tautologies and removed through slicing, leaving no properties for further verification

Re-verification: if any property P_i remains unknown, a verification re-run is initiated

$$\bigvee_{i}^{n} VC_i \xrightarrow[\text{incr}]{\text{kind}} \bigvee_{i}^{m} VC'(m \leq n)$$

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Result

ESBMC

```
Solution found by the inductive step (k = 4)

[Coverage]

Branches : 6
Reached : 6
  !(!(!(_Bool)x))       file exp.c line 11 column 5 function main
  !(x == 1)     file exp.c line 16 column 10 function main
  !return_value$___VERIFIER_nondet_bool$1       file exp.c line 9 column 3 function main
  !(!return_value$___VERIFIER_nondet_bool$1)    file exp.c line 9 column 3 function main
  !(!(x == 1))  file exp.c line 16 column 10 function main
  !(!(_Bool)x)  file exp.c line 11 column 5 function main
Branch Coverage: 100%
```

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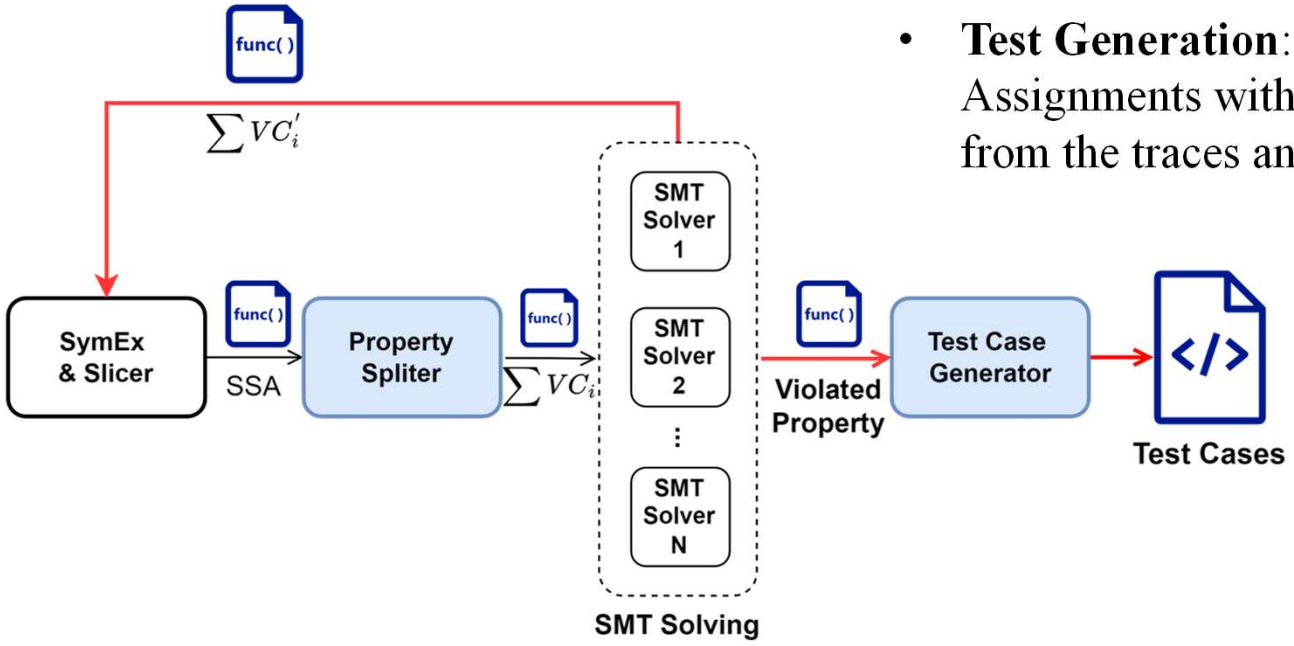
Test Generation



- **Test Generation**: whenever a property P_i violation is reported. Assignments with nondeterministic initial values are extracted from the traces and transformed into corresponding test suites.

```
testcase-0.xml
testcase-1.xml
testcase-2.xml
testcase-3.xml
testcase-4.xml
testcase-5.xml
```

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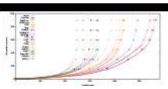
Result

ESBMC

ESBMC ranked around 7th–8th among all participants in Cover-Branches category at Test-Comp 2025.

Participants	Plots	cetfuzz	CoVeriTest	ESBMC-incr	ESBMC-kind	FDSE	Fizzer	FuSeBMC	FuSeBMC-AI	HybridTiger	KLEE	KLEEF	Owi	PRTest	Rizzer	Sikraken	Symbiotic	TracerX	TracerX-WP	UTestGen	WASP-C
Cover-Branches 10011 valid tasks		2524	4959	4380	4323	5468	5429	5656	4077	3866	3065	5734	2462	3191	–	2469	4207	3327	3275	4393	2740
CPU time		1800000 s	6000000 s	1500000 s	980000 s	7900000 s	7300000 s	8900000 s	3600000 s	4800000 s	2700000 s	5400000 s	6200000 s	8200000 s		7300000 s	2800000 s	2000000 s	2300000 s	5900000 s	3600000 s

Here, ESBMC-incr performs slightly better, mostly due to different unwinding configuration.

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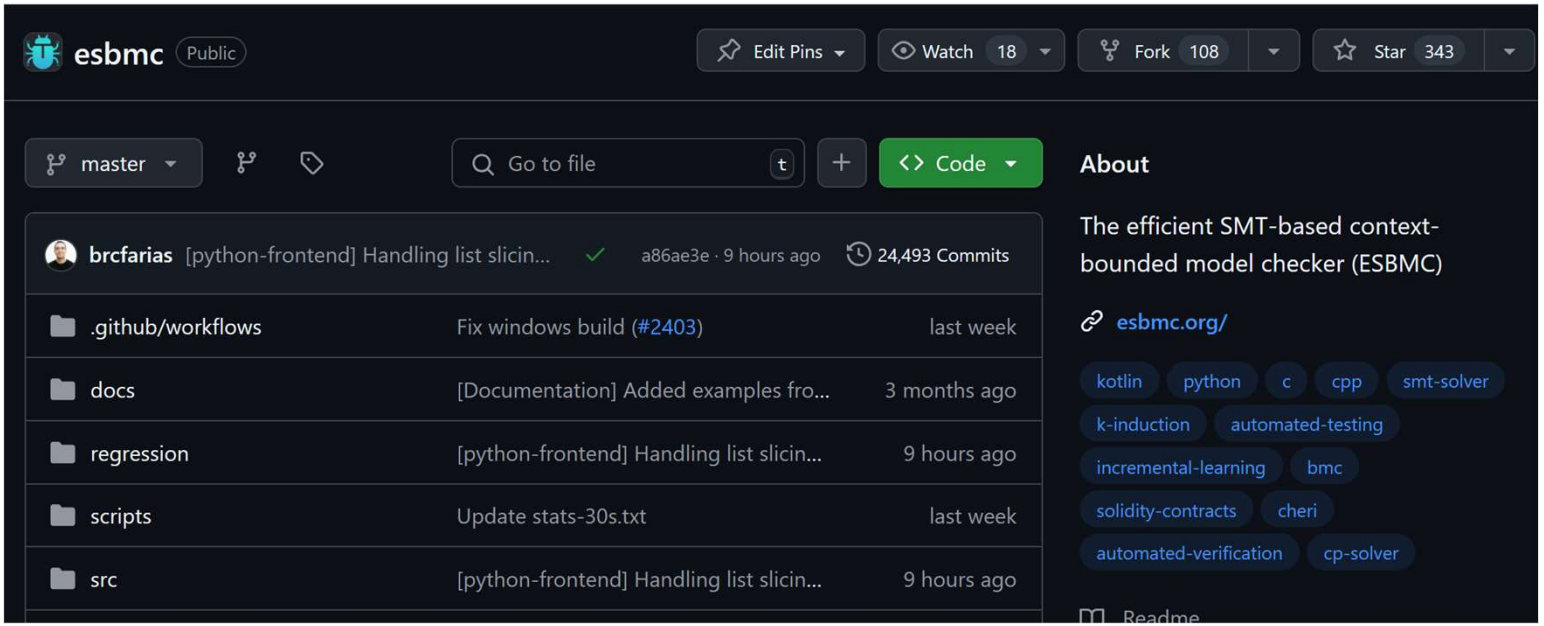
Software Project

ESBMC

ESBMC is open-source under the Apache License 2.0, and its C++ source code is publicly available on GitHub: https://github.com/esbmc/esbmc/

The official website is available at: https://esbmc.org



Software Project

ESBMC

Thank you!