CROWN Tutorial

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CROWN

- CROWN is a concolic testing tool for C programs
  - Explore all possible execution paths of a target systematically
  - To extract symbolic path formulas from concrete executions, it inserts probes into target C code
    - CROWN's instrumentation is implemented as a module of CIL (C Intermetiate Language) written in Ocaml
    - CIL provides convenient features to analyze/modify target C code
  - Generate test inputs automatically by solving symbolic path formulas by using a SMT solver

- CROWN is the core engine of the commercial automated testing tool CROWN 2.0
  - https://www.vpluslab.kr/crown2

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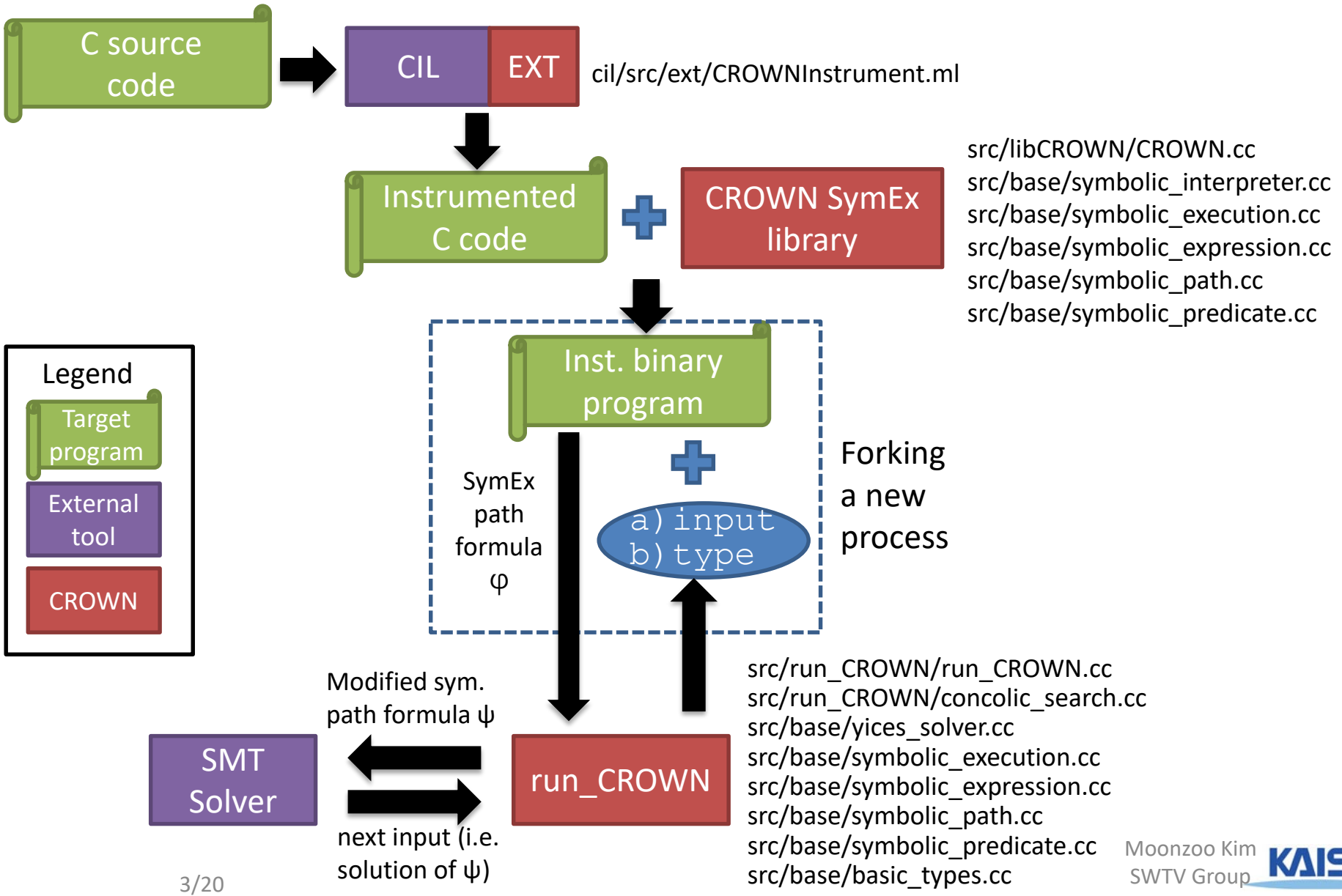
Overview of CROWN code



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Instrumented C Code

```
#line 10
 { /* Creates symbolic expression a==b */
  __CrownLoad(36, (unsigned long )(& a), (long long )a);
  __CrownLoad(35, (unsigned long )(& b), (long long )b);
  __CrownApply2(34, 12, (long long )(a == b));
  if (a == b) {

    __CrownBranch(37, 11, 1); //extern void __CrownBranch(int id , int bid , unsigned char b )
    __CrownLoad(41, (unsigned long )(& match), (long long )match);
    __CrownLoad(40, (unsigned long )0, (long long )1);
    __CrownApply2(39, 0, (long long )(match + 1));
    __CrownStore(42, (unsigned long )(& match));
     match ++;

  } else {
    __CrownBranch(38, 12, 0);
  } }
```

Control dependency v.s. Data dependency
- match has control dependency on a and b
- match does not have data dependency on a and b

CROWN Commands

- `crownc <filename>.c`
  - Output
    - `<filename>.cil.c` // instrumented C file
    - `branches` // lists of paired branches
    - `<filename>` // executable file
- `run_crown ./filename <n> -[dfs|cfg|random|random_input|hybrid] [-TCDIR <tc_folder>] [-INIT_TC]`
  - `<n>`: # of iterations/testings
  - Concolic search strategies
    - `dfs`: depth first search
    - `rev-dfs` : reverse depth first search
    - `cfg`: uncovered branch first
    - `random`: negated branch is randomly selected
    - `random_input`: pure random input
    - `hybrid`: combination of dfs and random
  - `-INIT_TC`: to use "`input`" file in a target directory as an initial test case
    - if "`input`" file does not exist, `run_CROWN` terminates with an error message
  - Output (updating at each iteration)
    - `input`: containing concrete types and values of symbolic variables
    - `szd_execution`: symbolic execution path
    - `coverage`: coverage achieved so far
    - A test case file in <tc_folder> if –TCDIR option is given

4 Main Tasks of Human Engineers

1. Adding proper assert() statements
   - W/o assert(), only runtime crash can be detected
2. Selection of symbolic variables in a target program
   - Identify which parts of a target program are most important
3. Construction of symbolic external environment
   - To reduce false alarms and detect real bugs
4. Performance tuning and debugging
   - To obtain better concolic testing results

Supported Symbolic Data-types

- #define **SYM_unsigned_char(x)** __CrownUChar(&x)
- #define **SYM_unsigned_short(x)** __CrownUShort(&x)
- #define **SYM_unsigned_int(x)** __CrownUInt(&x)
- #define **SYM_char(x)** __CrownChar(&x)
- #define **SYM_short(x)** __CrownShort(&x)
- #define **SYM_int(x)** __CrownInt(&x)
- #define **SYM_float(x)** __CrownFloat(&x)
- #define **SYM_double(x)** __CrownDouble(&x)

Symbolic Variable w/ Initial Value

- SYM_unsigned_char_init (x, 7)
- SYM_unsigned_short_init(x, 7)
- SYM_unsigned_int(x, 7)
- SYM_char_init(x, 7)
- SYM_short(x, 7)
- SYM_int(x, 7)
- SYM_float(x, 7.0)
- SYM_double(x, 7.0)

```
#include<crown.h>
int main() {
  int x;
  SYM_int_init(x, 7);
  printf("x=%d\n", x);
  if ( x > 10)
    printf("x>10\n");
  else
    printf("x<=10\n");
}
```

Symbolic Assumption

- You can describe symbolic assumption using `SYM_assume(exp)`
  - exp is **guaranteed to be true** right after `SYM_assume(exp)`
  - similar to `__CPROVER_assume(exp)` in CBMC
- Ex.

```
#include <crown.h>
#include <stdio.h>
#include <assert.h>

void main() {
    int x, y;
    SYM_int(x);
    SYM_int(y);
    SYM_assume( x + y > 10);
    printf("x=%d, y=%d\n", x, y);
    assert( x + y > 10);
}
```


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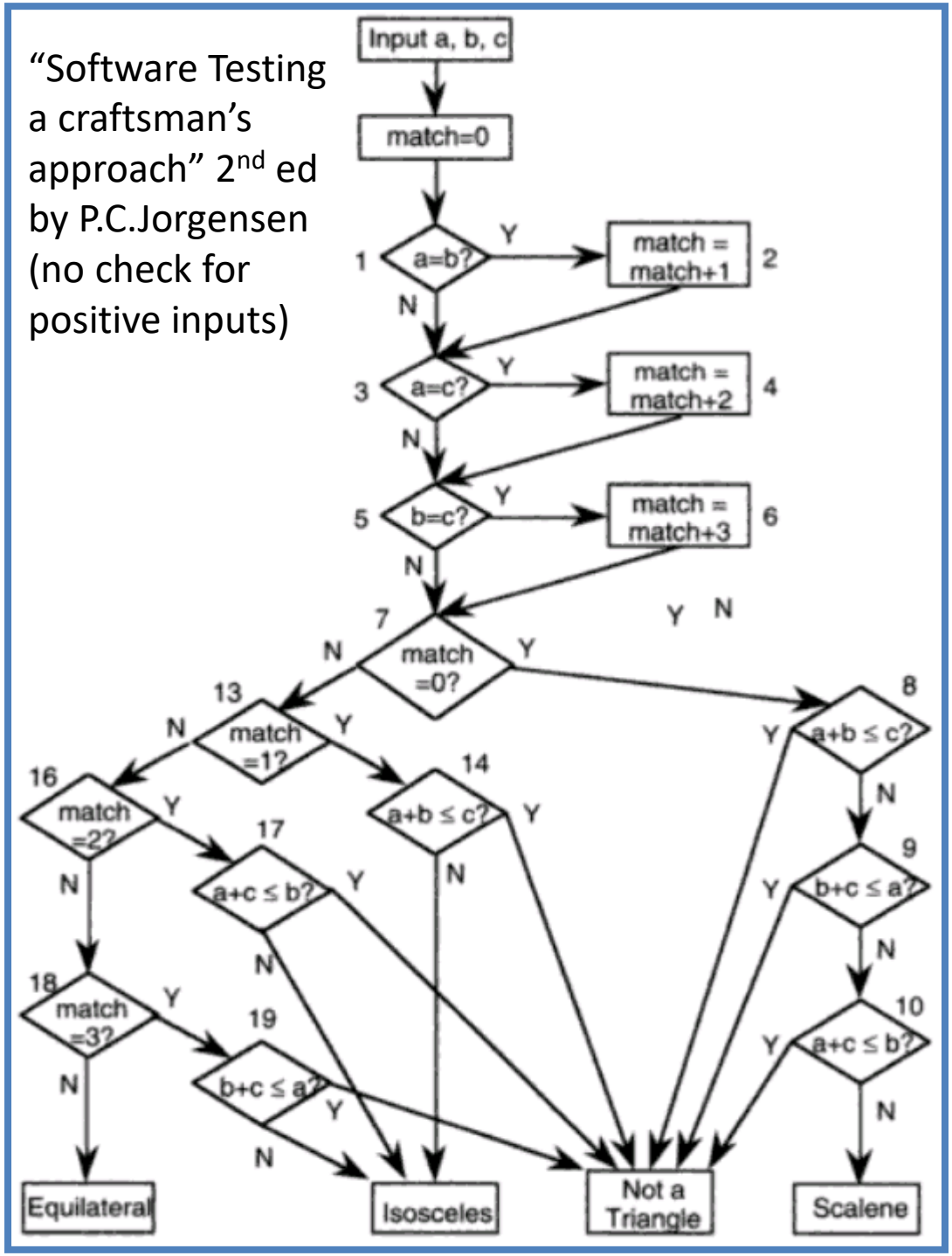
"Software Testing a craftsman's approach" 2nd ed by P.C.Jorgensen (no check for positive inputs)



```c
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <crown.h>

#define CROWN // to apply concolic test

int triangle(int, int, int);

int main() {
    int a,b,c, result;

#ifdef CROWN
    SYM_int(a); SYM_int(b); SYM_int(c);
#ifndef CROWN_REPLAY
    //filtering out invalid inputs
    SYM_assume(a>0 && b>0 && c>0);
#endif
    printf("a,b,c = %d,%d,%d\n",a,b,c);
#else
    printf("Please type 3 integers:\n");
    scanf("%d,%d,%d",&a,&b,&c);
#endif

    result=triangle(a,b,c);

    char triangle_type[20];
    switch(result) {
       case 0: strcpy(triangle_type,
               "an equilateral"); break;
       case 1: strcpy(triangle_type,
               "an isoscele"); break;
       case 2: strcpy(triangle_type,
               "not a triangle"); break;
       case 3: strcpy(triangle_type,
               "a scalene"); break;
       defaults: break;    }
    printf("Type: %s.\n",triangle_type);
}
```

```c
// Return value:
// 0: Equilateral, 1:Isosceles,
// 2: Not a triangle, 3:Scalene
int triangle(int a, int b, int c) {
    int result=-1, match=0;

    if(a==b) match=match+1;
    if(a==c) match=match+2;
    if(b==c) match=match+3;

    if(match==0) {
        if( a+b <= c) result=2;
        else if( b+c <= a) result=2;
        else if(a+c <= b) result =2;
        else result=3;
    } else {
        if(match == 1) {
            if(a+b <= c) result =2;
            else result=1;
        } else {
            if(match ==2) {
                if(a+c <=b) result = 2;
                else result=1;
            } else {
                if(match==3) {
                    if(b+c <= a) result=2;
                    else result=1;
                } else result = 0;
            } }}

    return result;
}
```

Compile/Instrumentation Snapshot

```
verifier3:~/crown/triangle$ crownc triangle.c

>>> cilly command:  /usr/bin/../cil/bin/cilly triangle.c -o t
    riangle --save-temps --doCrownInstrument -I/usr/bin
    /../include -L/usr/bin/../lib -L/usr/bin/../lib -lcrown-f
    p -lstdc++ -g -lrt -Wno-attributes -lpthread
gcc -D__GNUCC -E -I/usr/bin/../include -g -DCIL=1 triangle
    .c -o ./triangle.i
/usr/cil/bin/cilly.native --out ./triangle.cil.c --doCrownInst
    rument ./triangle.i
triangle.c:34: Warning: Body of function main falls-throu
    gh. Adding a return statement
gcc -D__GNUCC -E -I/usr/bin/../include -g ./triangle.cil.c -o
    ./triangle.cil.i
gcc -D__GNUCC -c -I/usr/bin/../include -g -g -Wno-attribut
    es -o ./triangle.o ./triangle.cil.i
gcc -D__GNUCC -o triangle -I/usr/bin/../include -g -g -Wno
    -attributes ./triangle.o -L/usr/bin/../lib -L/usr/bin/../li
    b -lcrown-fp -lstdc++ -g -lrt -lpthread
>>> Check cilly
>>> cilly - success!
>>> Find the file(triangle)
>>> start: 2022-11-17 12:02:26
>>> end: 2022-11-17 12:02:26
>>> gcc command(sanitizer none):  gcc -o triangle_replay
    triangle.c -I/usr/bin/../include -L/usr/bin/../lib -lcrow
    n-replay --coverage -Wno-attributes -lpthread
>>> Check gcc
>>> gcc - success
>>> Find the file(triangle_replay)
>>> start: 2022-11-17 12:02:26
>>> end: 2022-11-17 12:02:26
```

```
Complied with FP option
Read 42 branches.
Read 78 nodes.
Wrote 48 branch edges.

verifier3:~/crown/triangle$ ls

triangle.c
triangle.i
triangle.cil.c
triangle.cil.i

triangle.gcno
triangle.o

triangle
triangle_replay

branches
cfg_branches
funcount
cfg
cfg_func_map
idcount
stmtcount
```

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Execution Snapshot (1/2)

```
$ run_crown ./triangle  50 -dfs -TCDIR tcs
------------------------
program command is triangle
### SYM_assume(a>0 && b>0 && c>0) is violated
      at Line 17 (main in triangle.c) ###
...
------------------------
program command is triangle
a,b,c = 1,1,1
This triangle is an equilateral.
Iteration 1 (0s, 0s, 0.018s): covered 11 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1610612736,1610612736,536870912
This triangle is not a triangle.
Iteration 2 (1s, 1s, 0.043s): covered 18 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 2,2,1
This triangle is an isoscele.
Iteration 3 (1s, 0s, 0.050s): covered 20 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1610612736,536870912,1
This triangle is not a triangle.
Iteration 4 (1s, 0s, 0.060s): covered 23 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 272629760,1346371584,809500672
This triangle is not a triangle.
Iteration 5 (1s, 0s, 0.067s): covered 25 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1108719680,34977856,1108457536
This triangle is not a triangle.
Iteration 6 (1s, 0s, 0.074s): covered 27 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 427818799,427818767,377487598
This triangle is a scalene.
Iteration 7 (1s, 0s, 0.085s): covered 30 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1610612736,536870912,536870912
This triangle is not a triangle.
Iteration 8 (1s, 0s, 0.091s): covered 32 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1,2,2
This triangle is an isoscele.
Iteration 9 (1s, 0s, 0.098s): covered 33 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 1610612736,536870912,1610612736
This triangle is not a triangle.
Iteration 10 (1s, 0s, 0.104s): covered 35 branches
      [2 reach funs, 42 reach branches]
------------------------
a,b,c = 2,1,2
This triangle is an isoscele.
Iteration 11 (1s, 0s, 0.111s): covered 36 branches
      [2 reach funs, 42 reach branches]
```

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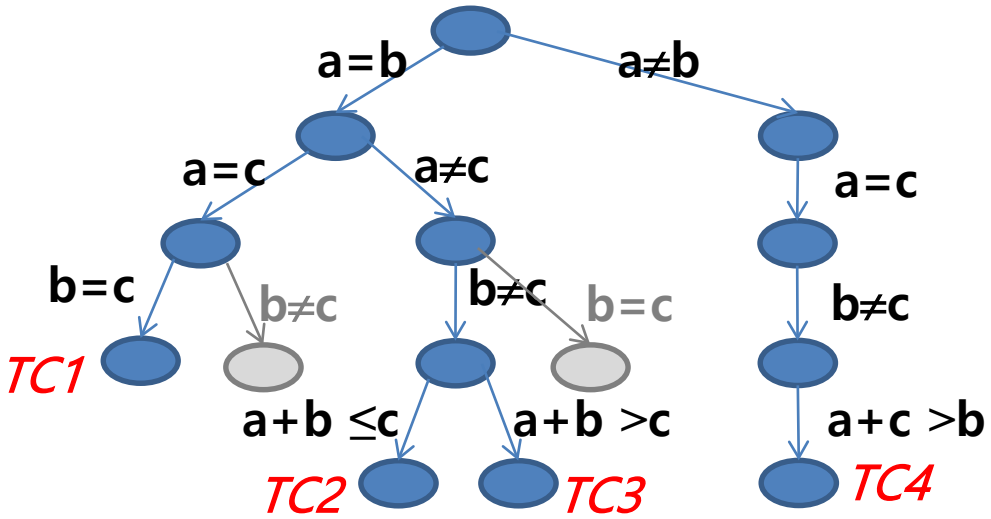
Concolic Testing the Triangle Program

Test case	Input (a,b,c)	Executed symbolic path formula (SPF) φ	Modified symbolic path formula φ'	Solution for the modified SPF
TC1	1,1,1	a=b Æa=c Æb=c	a=b Æa=c Æb≠c	Unsat
			a=b Æa≠c	1,1,2
TC2	1,1,2	a=b Æa≠c Æb≠c Æa+b ≤c	a=b Æa≠c Æb≠c Æa+b > c	2,2,3
TC3	2,2,3	a=b Æa≠c Æb≠c Æa+b >c	a=b Æa≠c Æb=c	Unsat
			a≠b	2,1,2
TC4	2,1,2	a≠b Æa=c Æb≠c Æa+c>b	a≠bÆa=c Æb≠c Æa+c ≤b	2,5,2



Execution Snapshot (2/2)

```
…$ cat branches
1 8 /* branch IDs */
6 11
7 10
8 9
13 14
21 22
24 25
27 28
30 31
2 13
48 49
51 52
54 55
57 64
58 59
60 61
62 63
65 68
66 67
69 72
70 71
73 76
74 75
```

```
…$ cat coverage
6 /*covered branch IDs*/
7
8
21
22
24
25
27
28
30
48
49
51
52
54
55
57
58
59
60
61
62
…
```

```
…$ l tcs
input.1 ...  input.11  type.1 ...  type.11

…$ print_execution

Symbolic variables & input values
(a_1 = 2)       [ Line: 14, File: triangle.c ]
(b_1 = 1)       [ Line: 14, File: triangle.c ]
(c_1 = 2)       [ Line: 14, File: triangle.c ]

Symbolic path formula
(a_1 > 0)       [ Line: 17, File: triangle.c ]
(b_1 > 0)       [ Line: 17, File: triangle.c ]
(c_1 > 0)       [ Line: 17, File: triangle.c ]
! (a_1 == b_1)  [ Line: 43, File: triangle.c ]
(a_1 == c_1)    [ Line: 44, File: triangle.c ]
! (b_1 == c_1)  [ Line: 45, File: triangle.c ]
! ((a_1 + c_1) <= b_1)  [ Line: 58, File: triangle.c ]

Sequence of reached branch ids
-1      [main enters]
6       [ Line: 17, File: triangle.cil.c ]
7       [ Line: 17, File: triangle.cil.c ]
8       [ Line: 17, File: triangle.cil.c ]
-1      [triangle enters]
49      [ Line: 43, File: triangle.cil.c ]
51      [ Line: 44, File: triangle.cil.c ]
55      [ Line: 45, File: triangle.cil.c ]
64      [ Line: 47, File: triangle.cil.c ]
68      [ Line: 53, File: triangle.cil.c ]
69      [ Line: 57, File: triangle.cil.c ]
71      [ Line: 58, File: triangle.cil.c ]
-2      [triangle exits]
22      [ Line: 28, File: triangle.cil.c ]
24      [ Line: 29, File: triangle.cil.c ]
-2      [main exits]
```

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Symbolic Debugging [1/2]

1. Select `[TCDIR]/input.[n]` whose symbolic path formula you would like to know
2. Copy `[TCDIR]/input.[n]` to a target directory with a name "`input`"
   - Also copy `type.[n]`
3. Run an instrumented executable target program
   - Note that an instrumented executable target program reads "`input`" file w/ "`type`" as an initial test case
   - Ex. ./triable
4. See symbolic information of `input.[n]` by using `print_execution`

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Symbolic Debugging (2/2)

```
...$ run_crown ./triange...
...
----------------
program command is triangle
a,b,c = 1,1,1
This triangle is an equilateral.
Iteration 1 (0s, 0s, 0.018s):
covered 11 branches
[2 reach funs, 42 reach branches]
-----------------
...
...$ cp tcs/input.1 input
...$ cp tcs/type.1 type
...$ ./triangle
a,b,c = 1,1,1
This triangle is an equilateral.
```

```
...$ print_execution
Symbolic variables & input values
(a_1 = 1)      [ Line: 7, File: triangle-crown.c ]
(b_1 = 1)      [ Line: 7, File: triangle-crown.c ]
(c_1 = 1)      [ Line: 7, File: triangle-crown.c ]

Symbolic path formula
(a_1 > 0)      [ Line: 15, File: triangle-crown.c ]
(b_1 > 0)      [ Line: 15, File: triangle-crown.c ]
(c_1 > 0)      [ Line: 15, File: triangle-crown.c ]
(a_1 == b_1)   [ Line: 21, File: triangle-crown.c ]
(a_1 == c_1)   [ Line: 22, File: triangle-crown.c ]
(b_1 == c_1)   [ Line: 23, File: triangle-crown.c ]

Sequence of reached branch ids
-1     [main enters]
6      [ Line: 15, File: triangle-cro ]
7      [ Line: 15, File: triangle-cro ]
8      [ Line: 15, File: triangle-cro ]
20     [ Line: 21, File: triangle-cro ]
23     [ Line: 22, File: triangle-cro ]
26     [ Line: 23, File: triangle-cro ]
36     [ Line: 24, File: triangle-cro ]
40     [ Line: 30, File: triangle-cro ]
44     [ Line: 34, File: triangle-cro ]
48     [ Line: 38, File: triangle-cro ]
51     [ Line: 46, File: triangle-cro ]
-2     [main exits]
```

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Decision/Condition Coverage Analysis by CROWN

```
1 int main(){
2     int A, B, C, D;
3     if (A && B || C && D){
4         printf("Yes\n");
5     }else{
6         printf("No\n");
7     }
8 }
```

- CROWN transforms a compound predicate into atomic ones with nested conditional statements
- CROWN consider all possible cases with short-circuit
- Thus, branch coverage reported by CROWN might be lower than actual branch coverage

```
1   if (A != 0) {
2     __CrownBranch(5, 2, 1);
3     if (B != 0) {
4       __CrownBranch(10, 3, 1);
5       printf("Yes\n");
6     } else {
7       __CrownBranch(11, 4, 0);
8       goto _L;
9     }
10  } else {
11    __CrownBranch(6, 5, 0)
12    _L: /* CIL Label */
13    if (C != 0) {
14      __CrownBranch(16, 6, 1);
15      if (D != 0) {
16        __CrownBranch(21, 7, 1);
17        printf("Yes\n");
18      } else {
19        __CrownBranch(22, 8, 0);
20        printf("No\n");
21      }
22    } else {
23      __CrownBranch(17, 9, 0);
24      printf("No\n");
25    }
26  }
```

A == T

A == T && B == T

A == T && B != T

A != TRUE

(A != T || A == T && B != T) && C == T

(A != T || A == T && B != T) && C == T && D == T

(A != T || A == T && B != T) && C == T && D != T

(A != T || A == T && B != T) && C != T

Measure Branch Coverage by Using `gcov` (1/2)

```
…$ crown_replay
Usage : crown_replay <PROGRAM_CMD> [OPTION]...
Options:
   -d <DIR>  Use test inputs in the directory <DIR>.
             (Default : testdir)
   -s <ITER_START>
      Start the iteration from the <ITER_START>th test.
      (Default : 1)
   -e <ITER_END>
      End the iteration to the <ITER_END>th test.
      (Default : # of test inputs in <DIR>)
```

- `crownc` generates `<target>_replay` which is an original target program (i.e., conditional stmts *not* transformed, symbolic execution *not* extracted) that can read TCs generated by CROWN
  - Ex> `triangle_replay`
- `<target>_replay` reads "`input`" file in the same directory to replay
- `crown_replay` replays `<target>_replay` to measure branch coverage of the original target program with TCs in <DIR> generated by CROWN

```
…$ cp tcs/input.4 input .
…$ cp tcs/type.4 type .
…$ ./triangle_replay
a,b,c = 2,1,2
This triangle is an isoscele.
…$ gcov -b -f triangle
Function 'triangle'
Lines executed:61.90% of 21
Branches executed:61.54% of 26
Taken at least once:42.31% of 26
No calls

File 'triangle.c'
Lines executed:68.75% of 32
Branches executed:69.23% of 39
Taken at least once:41.03% of 39
Calls executed:54.55% of 11
```

```
…$ crown_replay ./triangle_replay -d tcs -s 5 -e 7
a,b,c = 1610612736,536870912,536870912
This triangle is not a triangle.
Iteration 5
------------------------
a,b,c = 1,2,2
This triangle is an isoscele.
Iteration 6
------------------------
a,b,c = 272629760,1346371584,809500672
This triangle is not a triangle.
Iteration 7
------------------------
… $ gcov –b triangle-crown
File 'triangle-crown.c'
Lines executed:76.67% of 30
Branches executed:84.62% of 39
Taken at least once:53.85% of 39
Calls executed:50.00% of 10
Creating 'triangle-crown.c.gcov'
```

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Measure Branch Coverage by Using `gcov` (2/2)

- To correctly measure branch coverage of a target program, you should make `SYM_assume()` ineffective, since `SYM_assume(exp)` adds additional branches to a target program to check if `exp` is true or not.

- You can make `SYM_assume()` ineffective by using the following directives in a concolic testing driver code:

```
#ifndef CROWN_REPLAY
  SYM_assume(...);
#endif
```

- Note that `crownc` builds `<target>_replay` binary file with `-DCROWN_REPLAY` flag.