CROWN Tutorial

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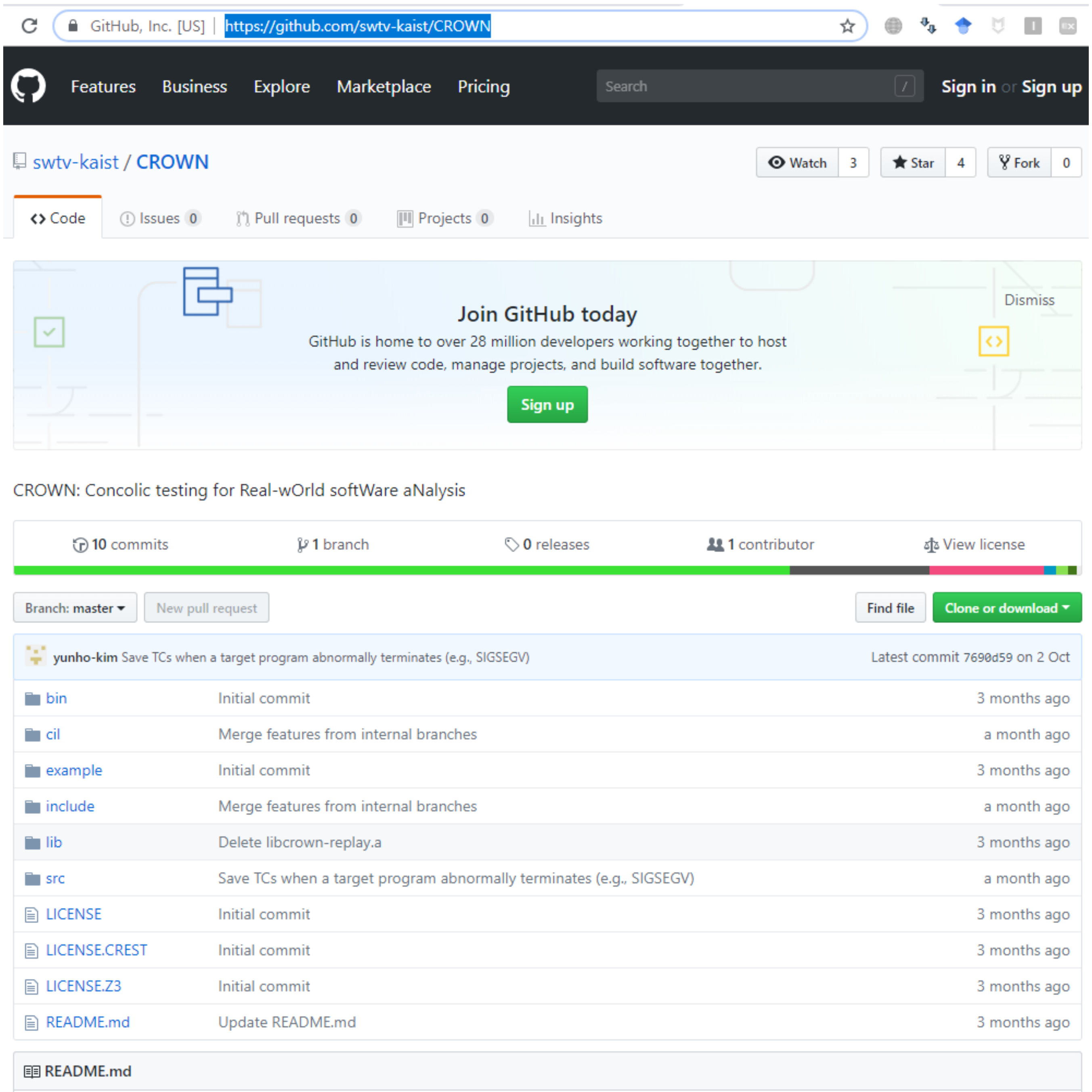

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CROWN: Concolic testing for Real-wOrld softWare aNalysis

10 commits | 1 branch | 0 releases | 1 contributor | View license

yunho-kim Save TCs when a target program abnormally terminates (e.g., SIGSEGV) Latest commit 7690d59 on 2 Oct

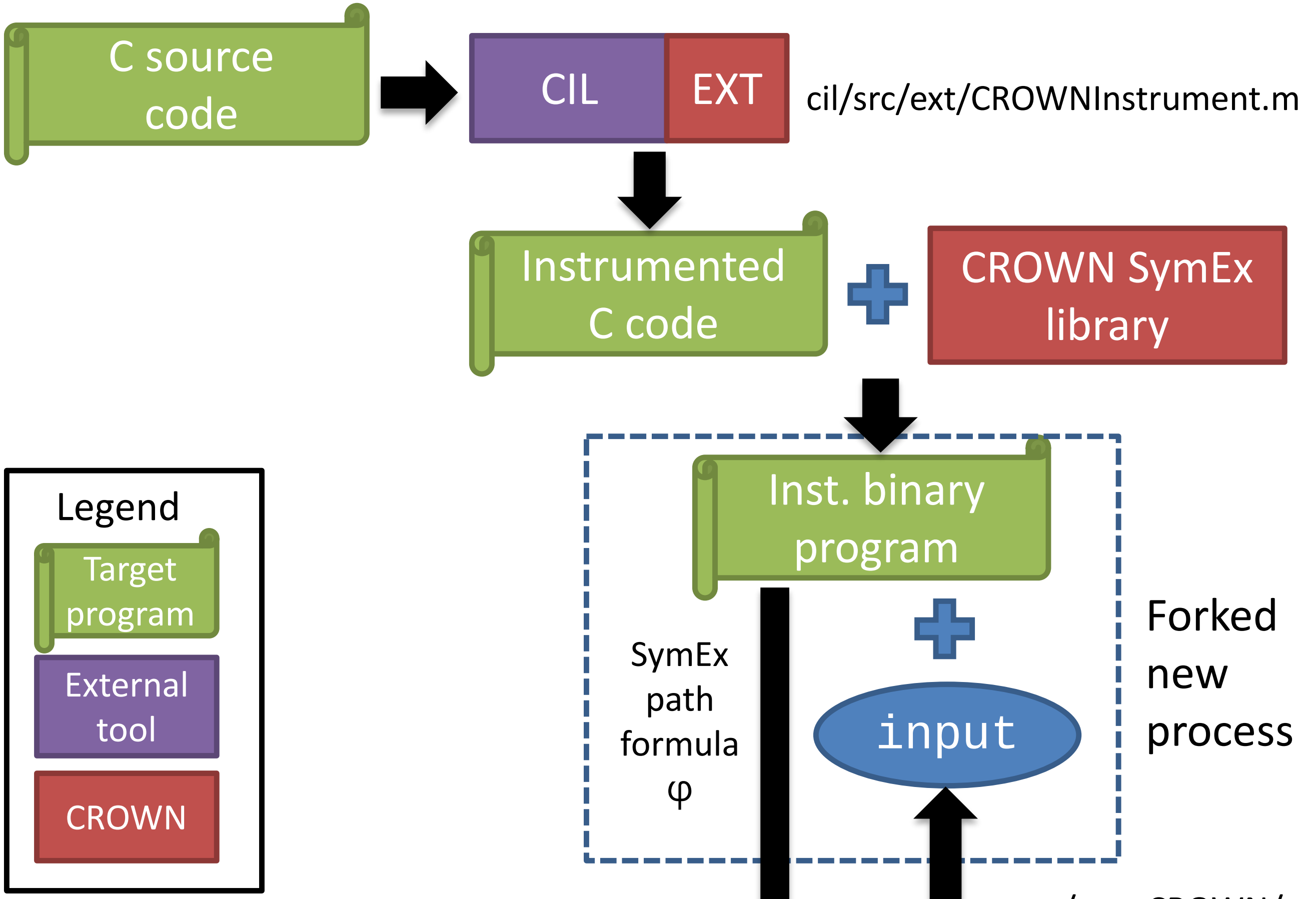
bin	Initial commit	3 months ago
cil	Merge features from internal branches	a month ago
example	Initial commit	3 months ago
include	Merge features from internal branches	a month ago
lib	Delete libcrown-replay.a	3 months ago
src	Save TCs when a target program abnormally terminates (e.g., SIGSEGV)	a month ago
LICENSE	Initial commit	3 months ago
LICENSE.CREST	Initial commit	3 months ago
LICENSE.Z3	Initial commit	3 months ago
README.md	Update README.md	3 months ago

README.md

CROWN

- CROWN is a concolic testing tool for C programs
  - Generate test inputs automatically
  - Execute target under test on generated test inputs
  - Explore all possible execution paths of a target systematically
- CROWN is a open-source extension of CREST
  - mainly written in C++
    - CROWN's instrumentation is implemented as a module of CIL (C Intermetiate Language) written in Ocaml
- https://github.com/swtv-kaist/CROWN/

Overview of CROWN code



C source code

CIL

EXT

cil/src/ext/CROWNInstrument.ml

Instrumented C code

CROWN SymEx library

src/libCROWN/CROWN.cc
src/base/symbolic_interpreter.cc
src/base/symbolic_execution.cc
src/base/symbolic_expression.cc
src/base/symbolic_path.cc
src/base/symbolic_predicate.cc

Legend

Target program

External tool

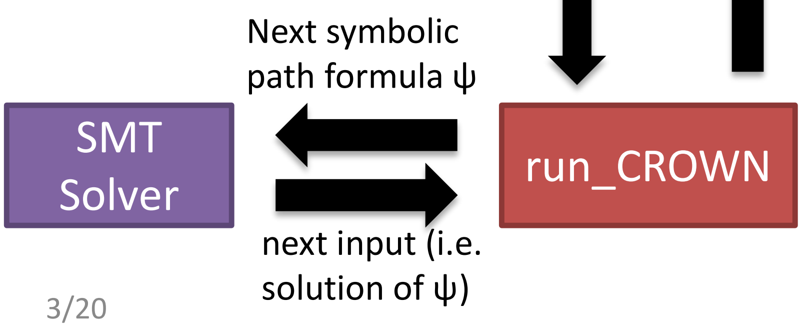
CROWN

Inst. binary program

SymEx path formula φ

input

Forked new process



Next symbolic path formula ψ

SMT Solver

run_CROWN

next input (i.e. solution of ψ)

src/run_CROWN/run_CROWN.cc
src/run_CROWN/concolic_search.cc
src/base/yices_solver.cc
src/base/symbolic_execution.cc
src/base/symbolic_expression.cc
src/base/symbolic_path.cc
src/base/symbolic_predicate.cc
src/base/basic_types.cc

4 Main Tasks of Human Engineers

1. Adding proper assert() statements
   – W/o assert(), no test results obtained
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 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);
}
```

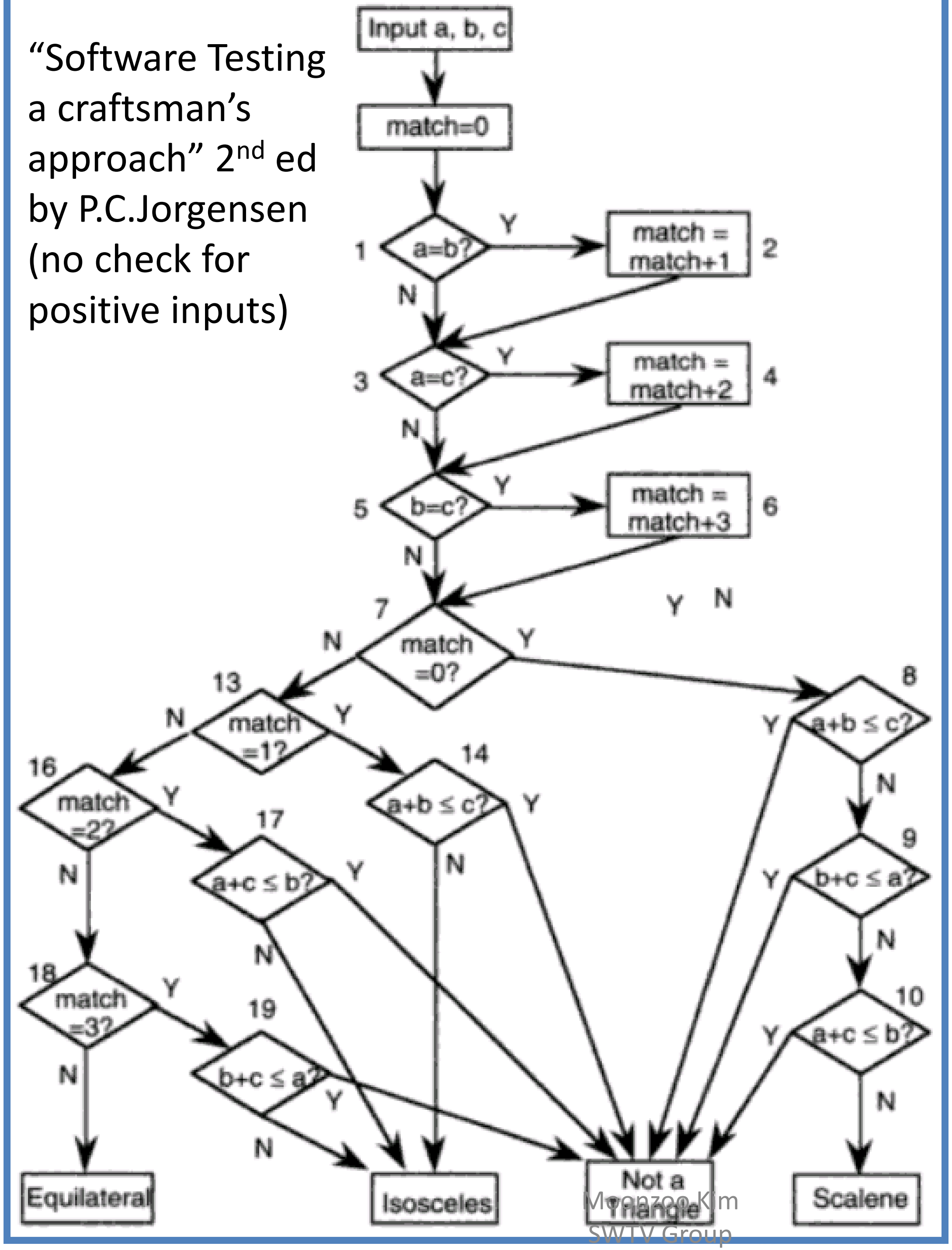
```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <crown.h>
int main() {
   int a,b,c, match=0;
   SYM_int(a); SYM_int(b); SYM_int(c);

/*printf("Please type 3 integers:\n");
   scanf("%d", &a);
   scanf("%d", &b);
   scanf("%d", &c);  */

   //filtering out invalid inputs
   SYM_assume(a>0 && b>0 && c>0);
   printf("a,b,c = %d,%d,%d\n",a,b,c);

   //0: Equilateral, 1:Isosceles,
   // 2: Not a triangle, 3:Scalene
   int result=-1;
   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) {
```

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



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

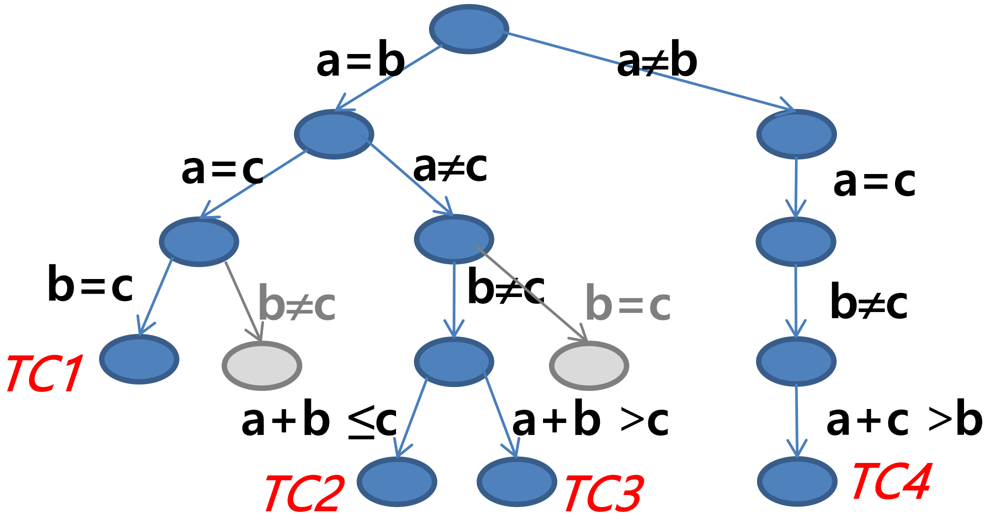
Execution Snapshot (1/2)

```
…$ run_crown ./triangle-crown  100  -rev-dfs -TCDIR test
       cases
-------------------------
### SYM_assume(a>0 && b>0 && c>0) is violated at Line
       15 (main in triangle-crown.c) ###
-------------------------
### SYM_assume(a>0 && b>0 && c>0) is violated at Line
       15 (main in triangle-crown.c) ###
-------------------------
### SYM_assume(a>0 && b>0 && c>0) is violated at Line
       15 (main in triangle-crown.c) ###
-------------------------
a,b,c = 1,1,1
This triangle is an equilateral.
Iteration 1 (0s, 0.42s): covered 11 branches [1 reach funs
       , 42 reach branches].(11, 0)
-------------------------
a,b,c = 1610612736,536870912,1
This triangle is not a triangle.
Iteration 2 (0s, 0.56s): covered 19 branches [1 reach funs
       , 42 reach branches].(19, 11)
-------------------------
a,b,c = 1610612736,536870912,1610612736
This triangle is not a triangle.
Iteration 3 (0s, 0.68s): covered 21 branches [1 reach funs
       , 42 reach branches].(21, 19)
-------------------------
a,b,c = 2,1,2
This triangle is an isoscele.
Iteration 4 (0s, 0.104s): covered 23 branches [1 reach fu
       ns, 42 reach branches].(23, 21)
-------------------------
a,b,c = 1610612736,536870912,536870912
This triangle is not a triangle.
Iteration 5 (0s, 0.118s): covered 25 branches [1 reach
       funs, 42 reach branches].(25, 23)
```

```
-------------------------
a,b,c = 1,2,2
This triangle is an isoscele.
Iteration 6 (0s, 0.133s): covered 26 branches [1 reach funs,
       42 reach branches].(26, 25)
-------------------------
a,b,c = 272629760,1346371584,809500672
This triangle is not a triangle.
Iteration 7 (0s, 0.149s): covered 28 branches [1 reach funs,
       42 reach branches].(28, 26)
-------------------------
a,b,c = 1108719680,34977856,1108457536
This triangle is not a triangle.
Iteration 8 (0s, 0.169s): covered 30 branches [1 reach funs,
       42 reach branches].(30, 28)
-------------------------
a,b,c = 427818799,427818767,377487598
This triangle is a scalene.
Iteration 9 (0s, 0.195s): covered 33 branches [1 reach funs,
       42 reach branches].(33, 30)
-------------------------
a,b,c = 1610612736,1610612736,536870912
This triangle is not a triangle.
Iteration 10 (0s, 0.209s): covered 35 branches [1 reach funs,
       42 reach branches].(35, 33)
-------------------------
a,b,c = 2,2,1
This triangle is an isoscele.
Iteration 11 (1s, 0.234s): covered 36 branches [1 reach funs,
       42 reach branches].(36, 35)
```

Concolic Testing the Triangle Program

Test case	Input (a,b,c)	Executed symbolic path formula w/ a test case φ	Next symbolic path formula ψ	Solution for the next sym. path formula
1	1,1,1	a=b Æa=c Æ b=c	a=b Æ a=c Æ b≠c	Unsat
			a=b Æ a≠c	1,1,2
2	1,1,2	a=b Æ a≠c Æ b≠c Æ a+b ≤c	a=b Æ a≠c Æ b≠c Æ a+b > c	2,2,3
3	2,2,3	a=b Æ a≠c Æ b≠c Æ a+b >c	a=b Æ a≠c Æ b=c	Unsat
			a≠b	2,1,2
4	2,1,2	a≠b Æ a=c Æ b≠c Æ a+c>b	a≠bÆ a=c Æ b≠c Æ a+c ≤b	2,5,2



Execution Snapshot (2/2)

```
…$ cat branches
1 21 /* branch IDs */
6 11
7 10
8 9
13 14
20 21
23 24
26 27
29 36
30 31
32 33
34 35
37 40
38 39
41 44
42 43
45 48
46 47
51 52
54 55
57 58
60 61
```

```
…$ cat coverage
6 /*covered branch IDs*/
7
8
20
21
23
24
26
27
29
30
31
32
33
34
35
36
37
38
39
40
…
```

```
…$ cat testcases/input.11
5 /* type of a symbolic input variable */
2 /* value of a symbolic input variable */
5
2
5
1

moonzoo@checker6:~/cs492d/CROWN/example$
print_execution

Symbolic variables & input values
(a_1 = 2)      [ Line: 7, File: triangle-crown.c ]
(b_1 = 2)      [ 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 ]
! ((a_1 + b_1) <= c_1)  [ Line: 31, 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 ]
24     [ Line: 22, File: triangle-cro ]
27     [ Line: 23, File: triangle-cro ]
36     [ Line: 24, File: triangle-cro ]
37     [ Line: 30, File: triangle-cro ]
39     [ Line: 31, File: triangle-cro ]
53     [ Line: 46, File: triangle-cro ]
```

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`"
3. Run an instrumented executable target program
   - Note that an instrumented executable target program reads "`input`" file as an initial test case
   - Ex. ./triable
4. See symbolic information of `input.[n]` by using `print_execution`

Symbolic Debugging (2/2)

```
…$ cat testcases/input.1
5 /* type of a symbolic input variable */
1 /* a: value of a symbolic input variable */
5
1
5
1

checker$ cp testcases/input.1 input

checker$ ./triangle-crown
a,b,c = 1,1,1:result=0
```

```
…$ 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]
```

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

Decision/Condition Coverage Analysis by CROWN

```
int main(){
    int A, B, C, D;
    if (A && B || C && D){
        printf("Yes\n");
    }else{
        printf("No\n");
    }
}
```

```
if (A != 0) {
    __CrownBranch(5, 2, 1); A == T
    if (B != 0) {
      __CrownBranch(10, 3, 1);A == T && B == T
      printf("Yes\n");
    } else {
      __CrownBranch(11, 4, 0);A == T && B != T
      goto _L;
    }
  } else {
    __CrownBranch(6, 5, 0);A != TRUE
    _L: /* CIL Label */
    if (C != 0) {                (A != T || A == T && B != T)
      __CrownBranch(16, 6, 1);   && C == T
      if (D != 0) {                 (A != T || A == T && B != T)
        __CrownBranch(21, 7, 1);    && C == T && D == T
        printf("Yes\n");
      } else {
        __CrownBranch(22, 8, 0);    (A != T || A == T && B != T)
        printf("No\n");             && C == T && D != T
      }
    } else {
      __CrownBranch(17, 9, 0);    (A != T || A == T && B != T)
      printf("No\n");             && C != T
    }
  }
```

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

Measure Branch Coverage w/ TCs generated by crown_replay

```
…$ 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 testcases/input.4 input
…$ ./triangle-crown_replay
a,b,c = 2,1,2
This triangle is an isoscele.

…$ gcov -b triangle-crown
File 'triangle-crown.c'
Lines executed:56.67% of 30
Branches executed:64.10% of 39
Taken at least once:28.21% of 39
Calls executed:50.00% of 10
Creating 'triangle-crown.c.gcov'
…

…$ crown_replay ./triangle-crown_replay -d testcases -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
ile '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'
```