Symbolic Execution

Ejecución Simbólica Dinámica

Ingeniería del Software 2

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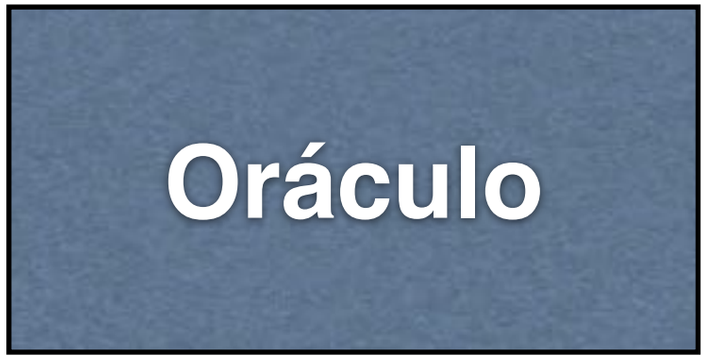
ICC Instituto de Ciencias de la Computación

Random Testing

Programa bajo Test

Oráculo

Random Testing



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3.       return -x
4.   else:
5.       z = x - y
6.       if (y+z=10000):
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8.       else:
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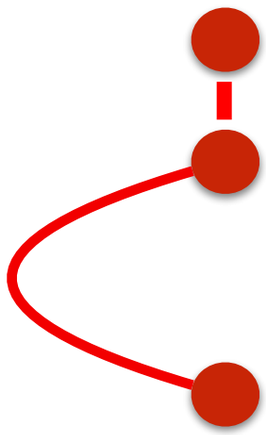

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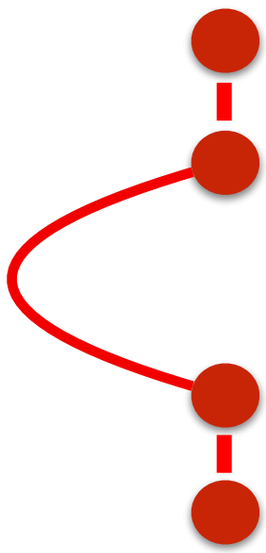

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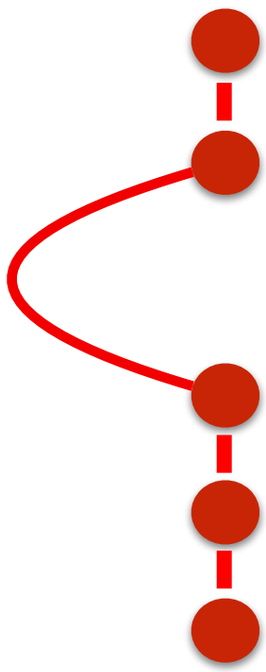

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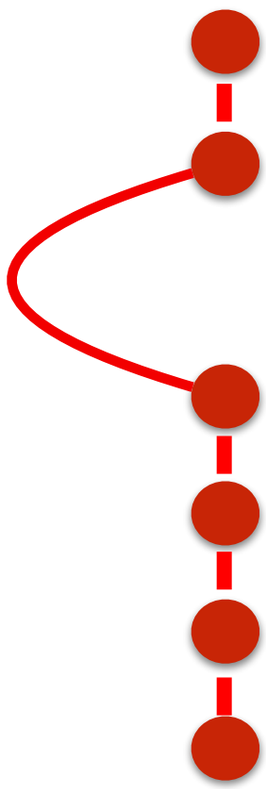

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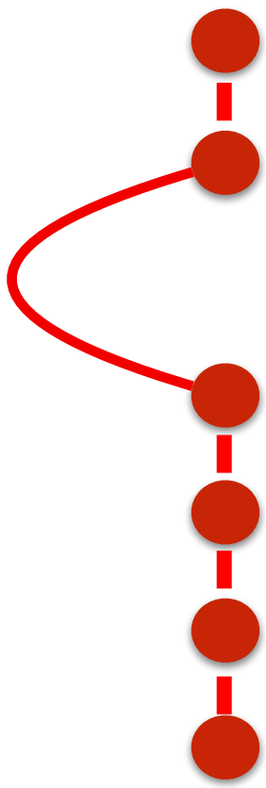

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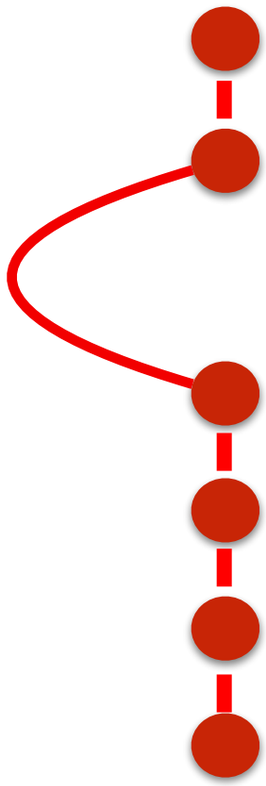

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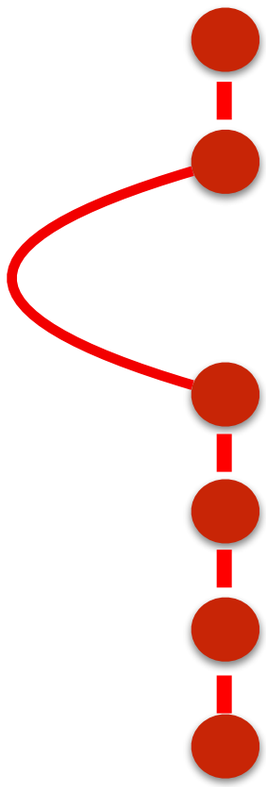
y>=0
x=10000



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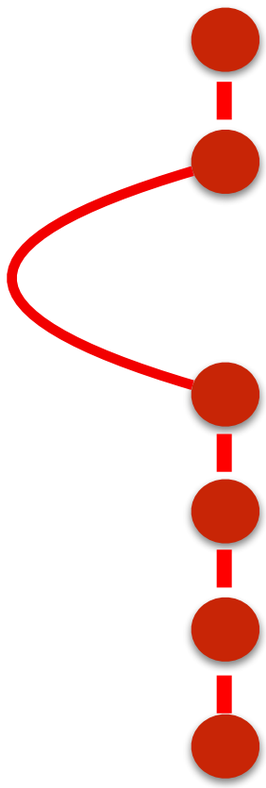
y>=0
x=10000

2^31 / 2^32 = 50%



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```

y>=0

x=10000

2^31 / 2^32 = 50%

1 / 2^32 ~ 0%

↓

extremadamente improbable que random choice pueda el test llegue 7

Ejecución Simbólica

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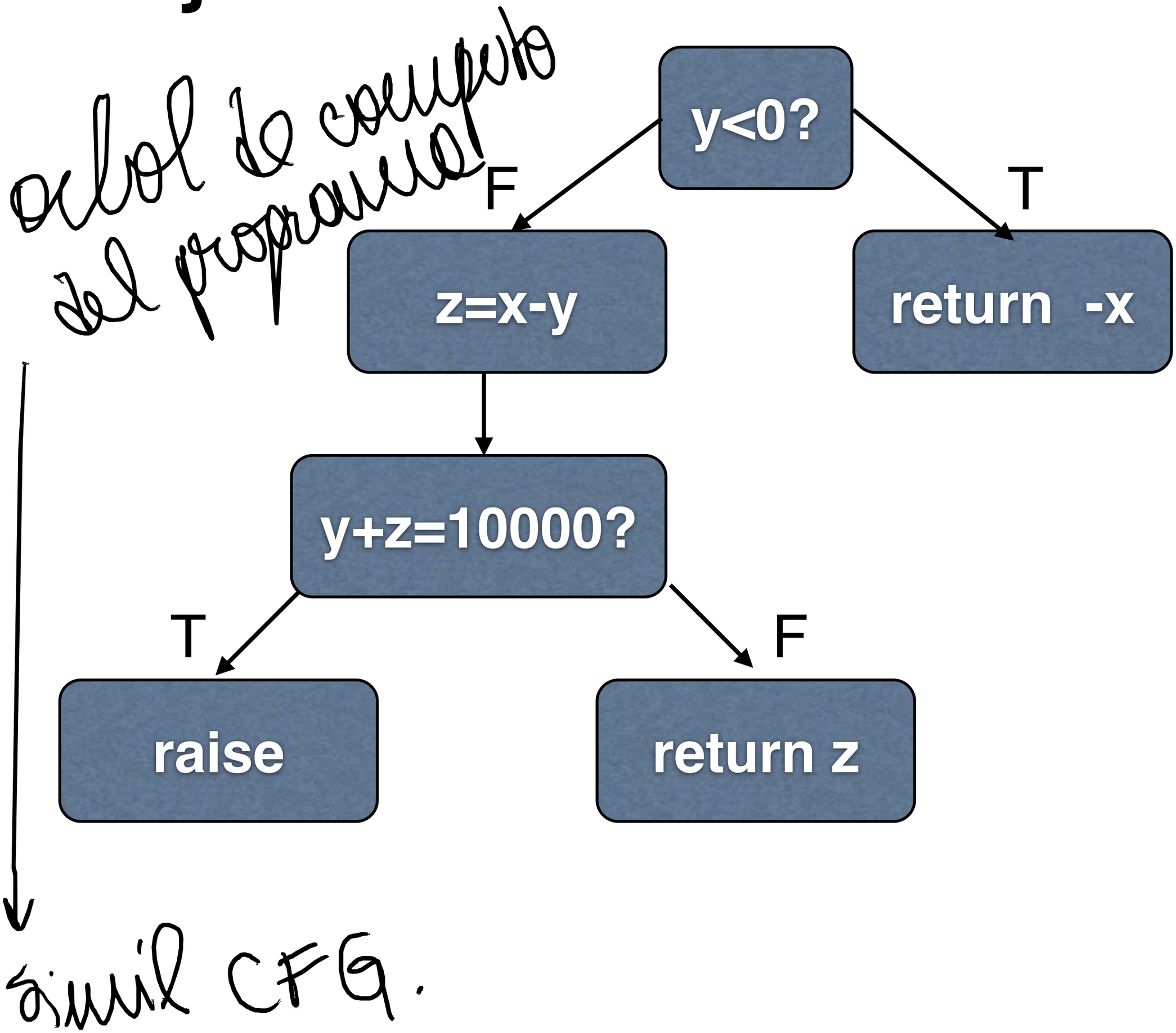
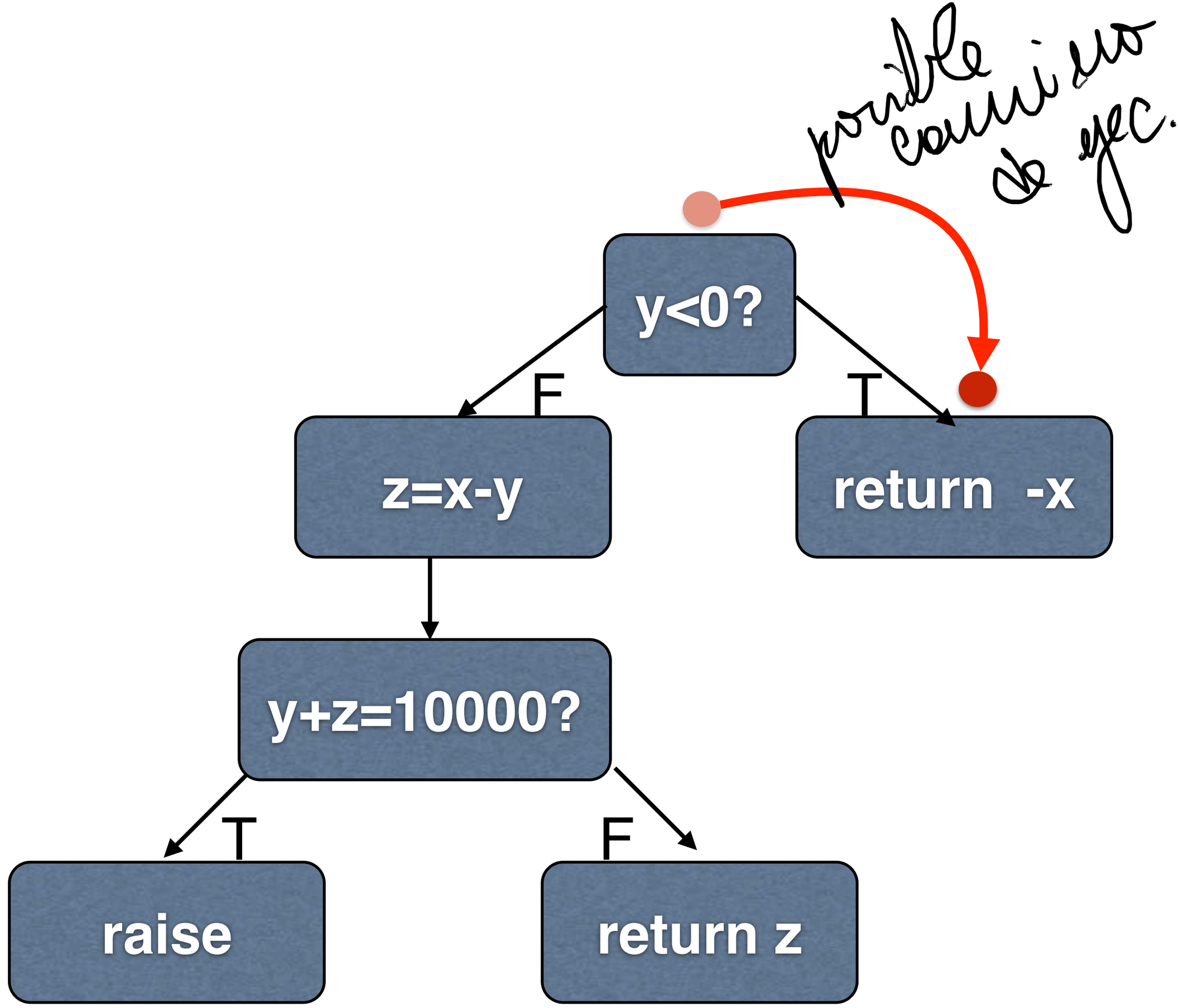
Ejecución Simbólica




possible execution
y<0?
F
T
z=x-y
return -x
y+z=10000?
T
F
raise
return z

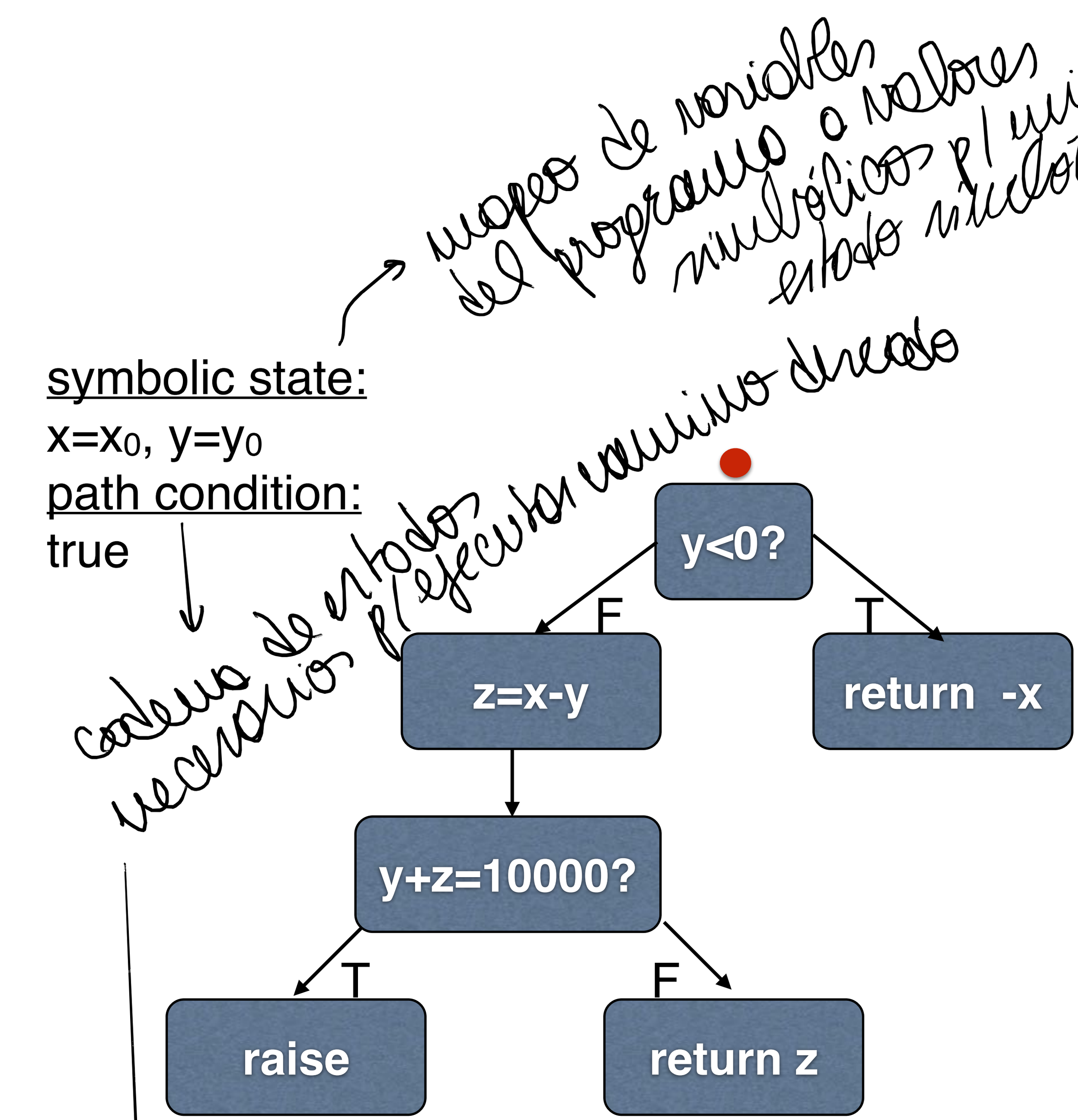
mapeo de variables del programa a valores simbólicos p/ un estado alcanzado

<u>symbolic state:</u>

$x=x_0$, $y=y_0$

<u>path condition:</u>

true



cadena de estados alcanzados durante la ejecución

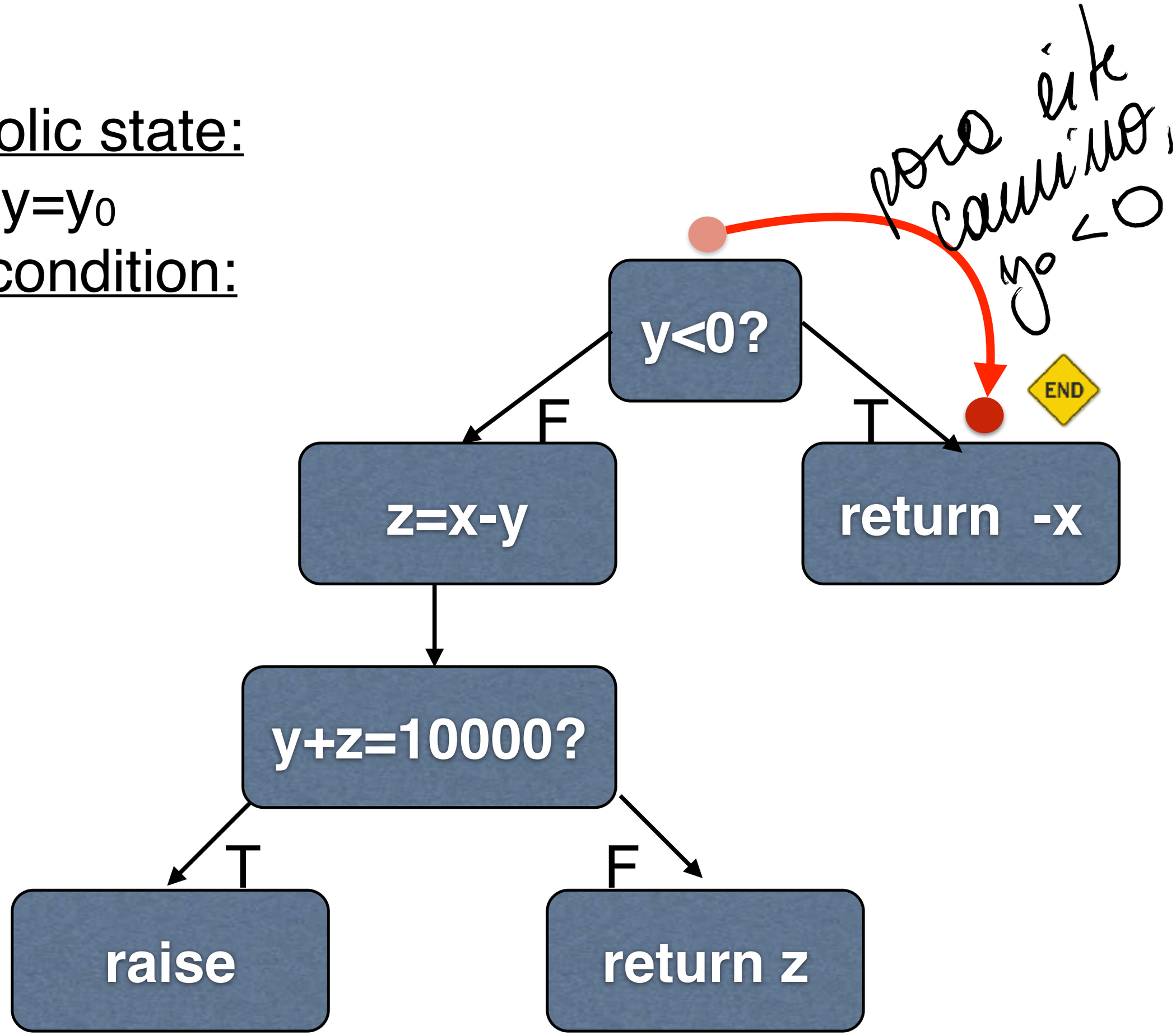
conjunto condiciones p/ que todo camino sea correcto

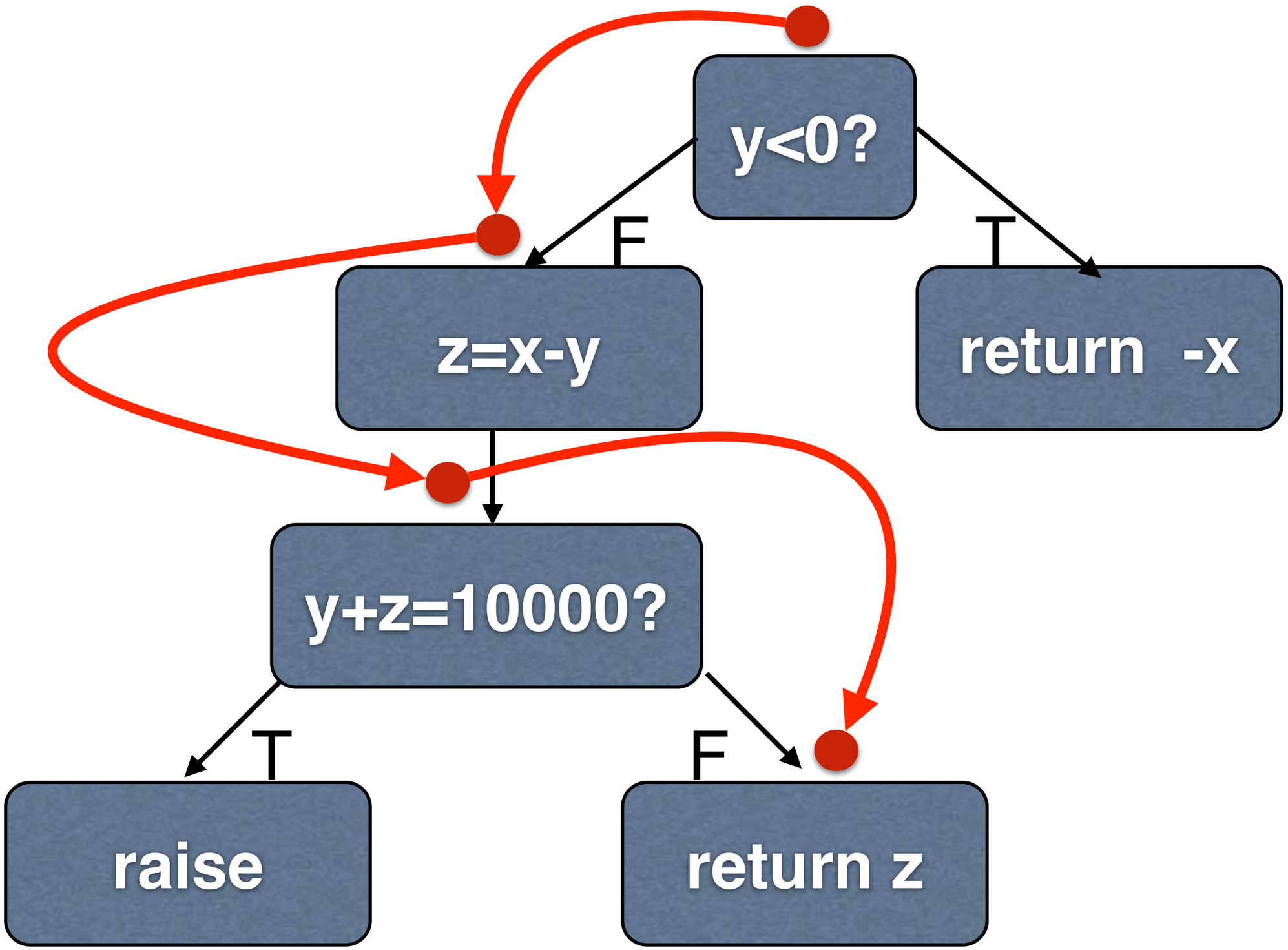
<u>symbolic state:</u>

$x=x_0$, $y=y_0$

<u>path condition:</u>

$y_0<0$



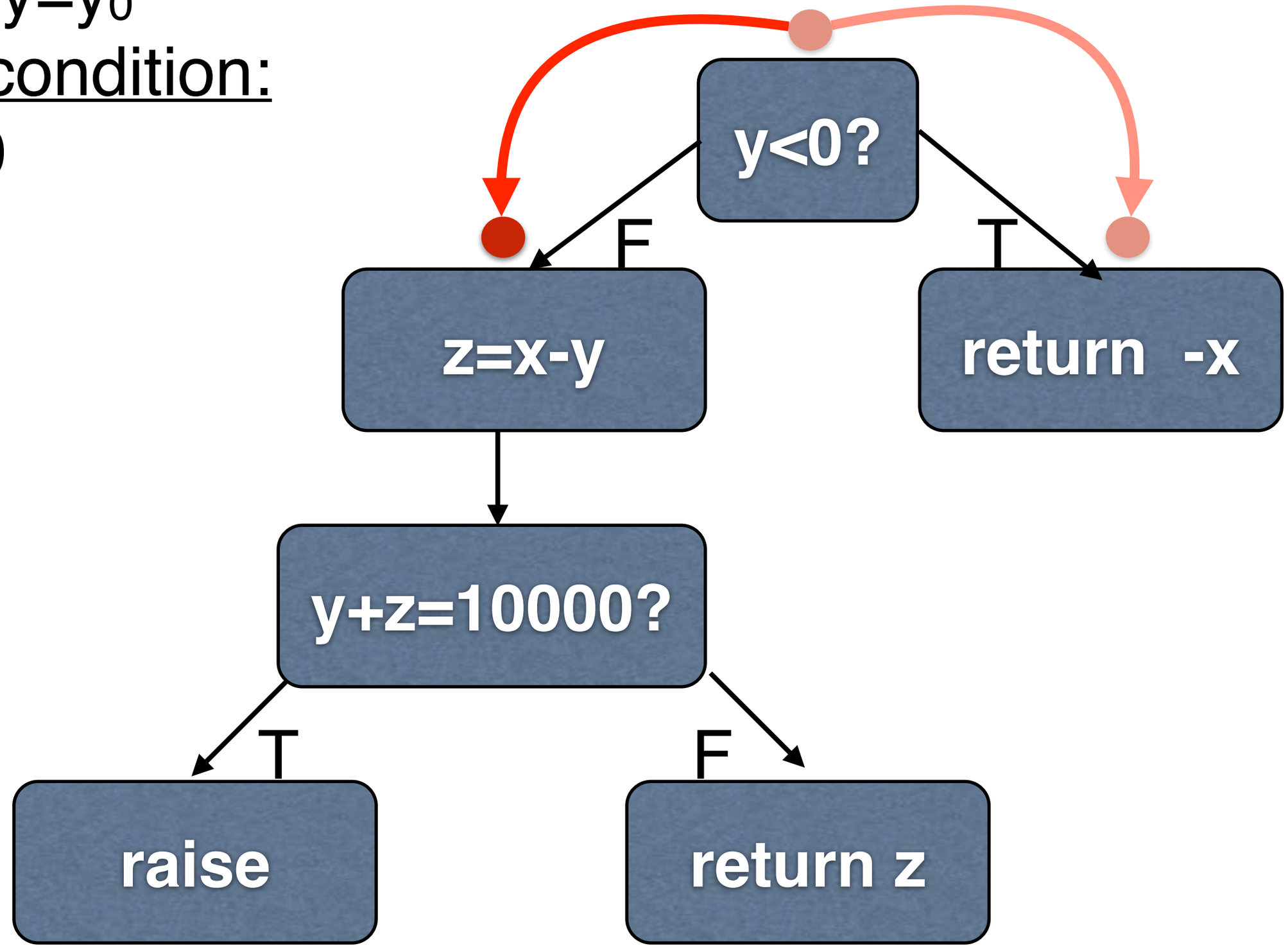

y<0?
F
T
z=x-y
return -x
y+z=10000?
T
F
raise
return z

<u>symbolic state:</u>

$x=x_0$, $y=y_0$

<u>path condition:</u>

$y_0>=0$

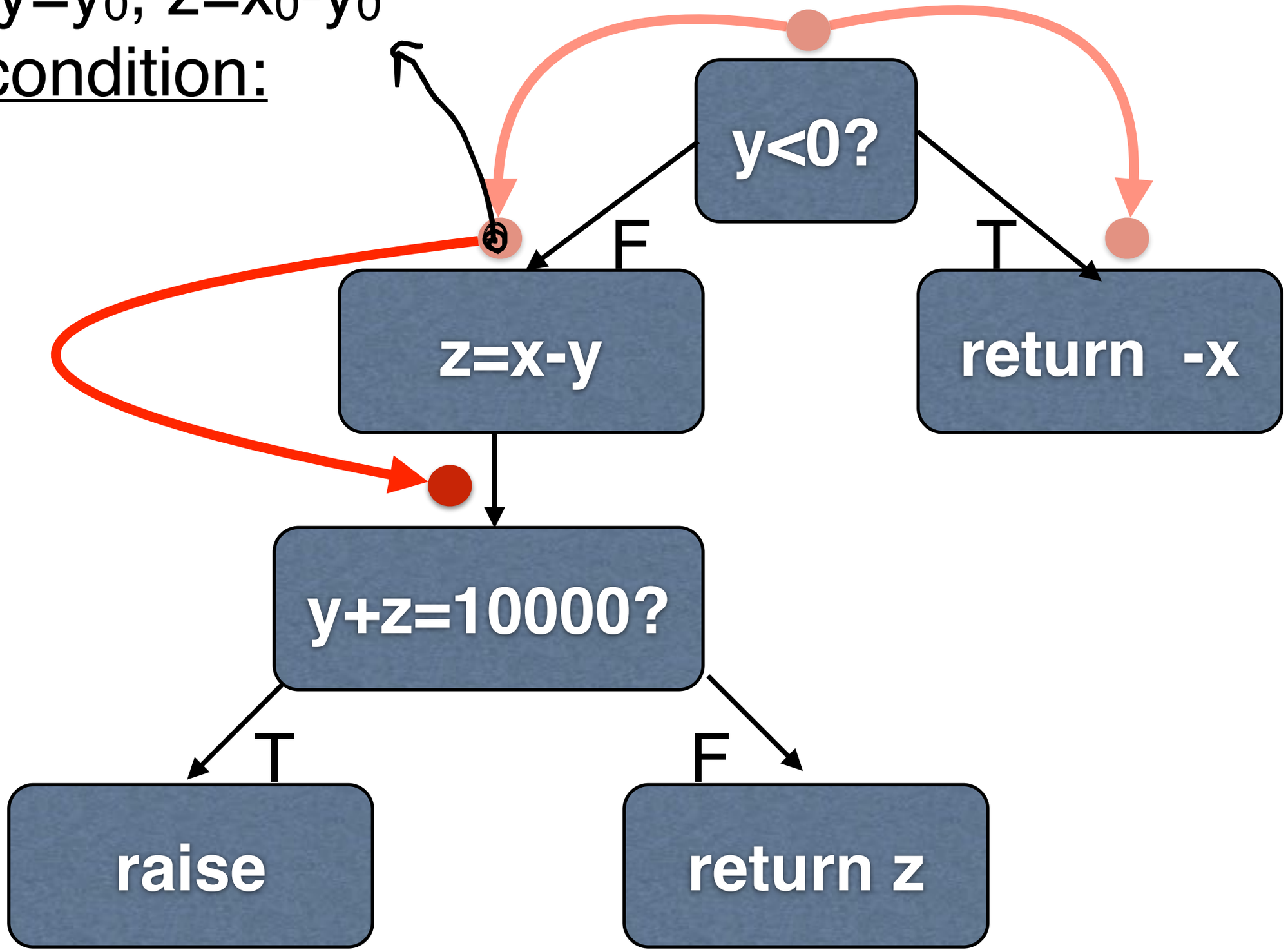


<u>symbolic state:</u>

$x=x_0$, $y=y_0$, $z=x_0-y_0$

<u>path condition:</u>

$y_0>=0$



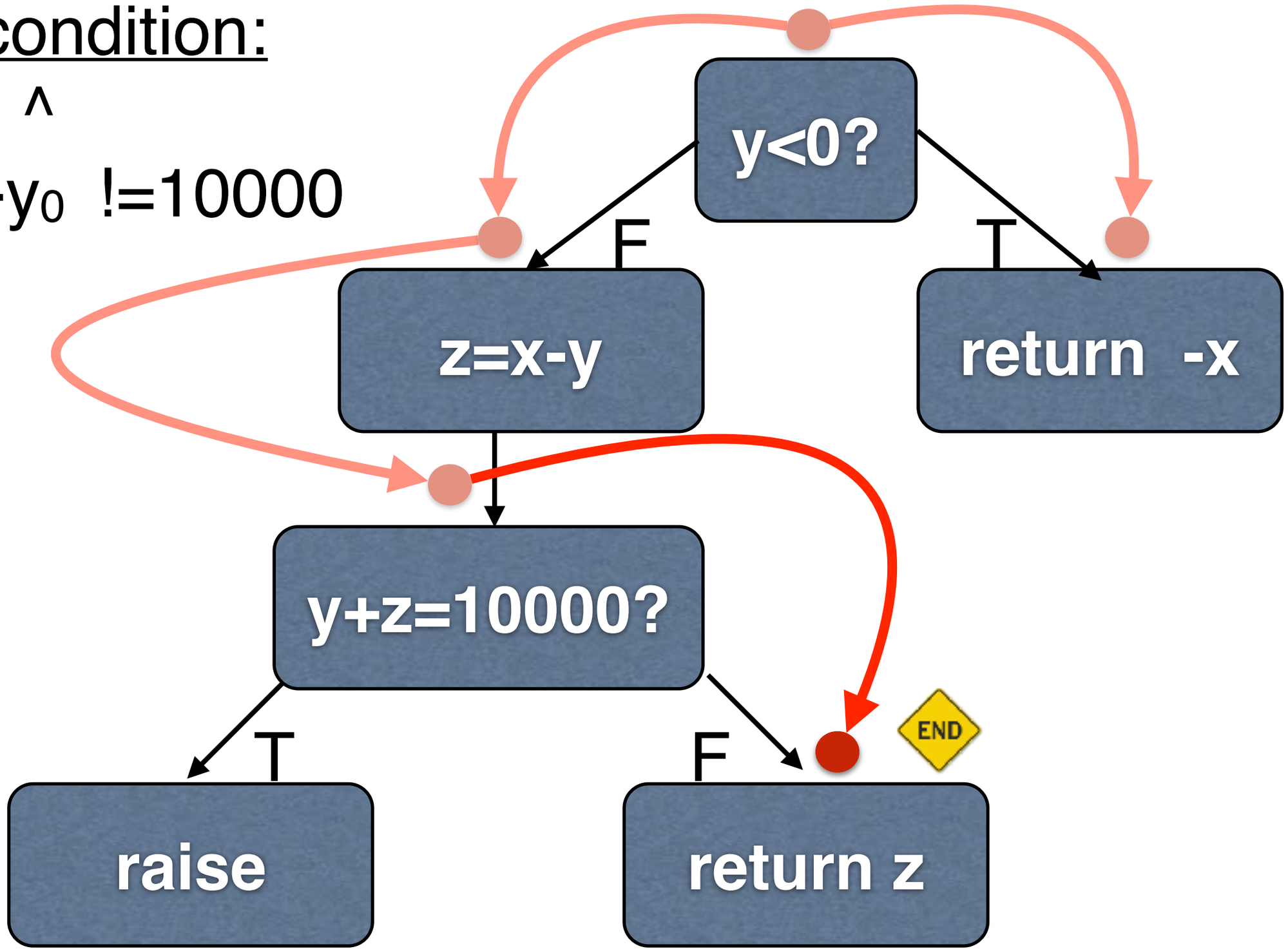
<u>symbolic state:</u>

$x=x_0$, $y=y_0$, $z=x_0-y_0$

<u>path condition:</u>

$y_0>=0$ ^

$y_0+x_0-y_0$!=10000



conjunción de condiciones

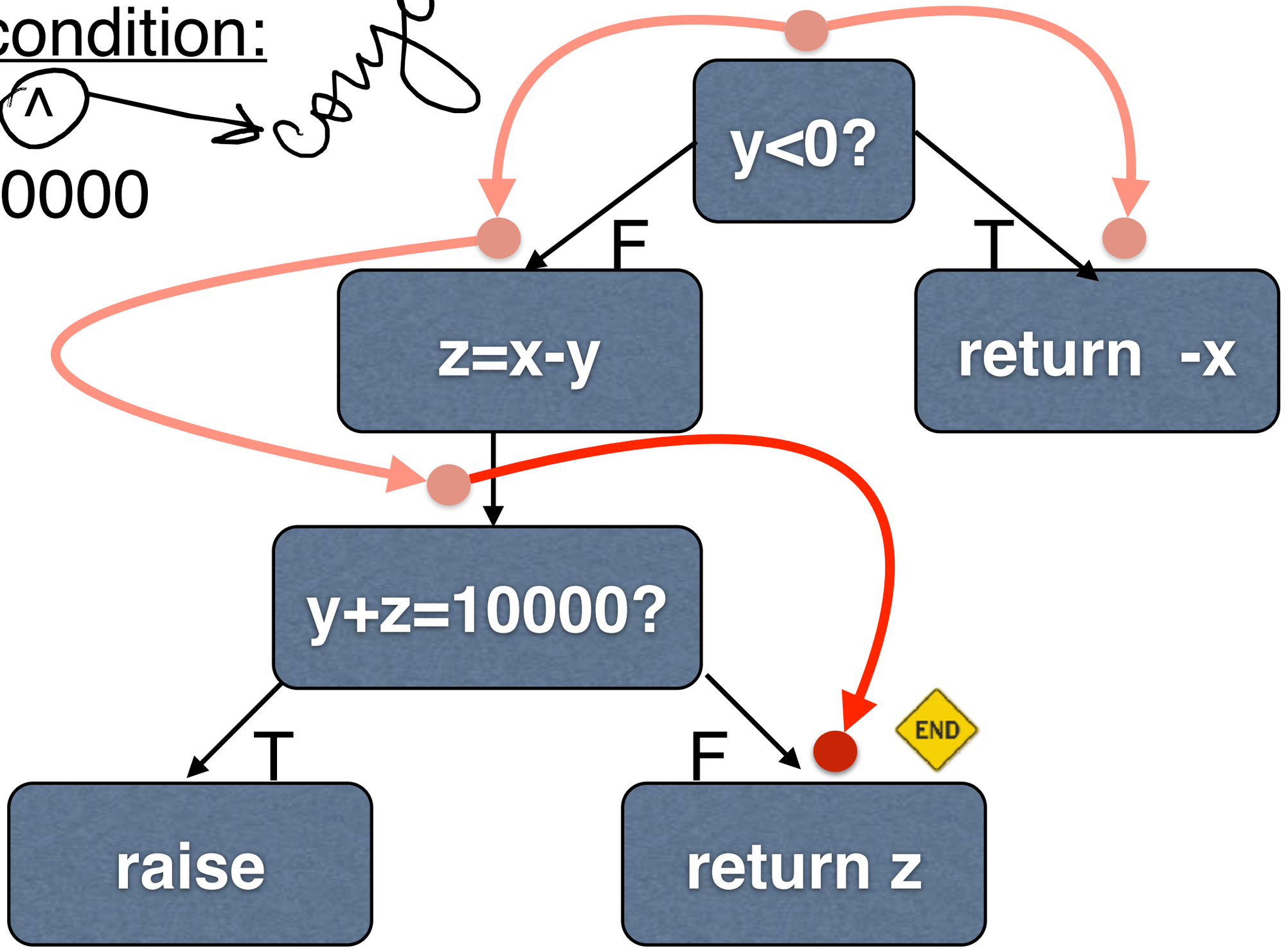
<u>symbolic state:</u>

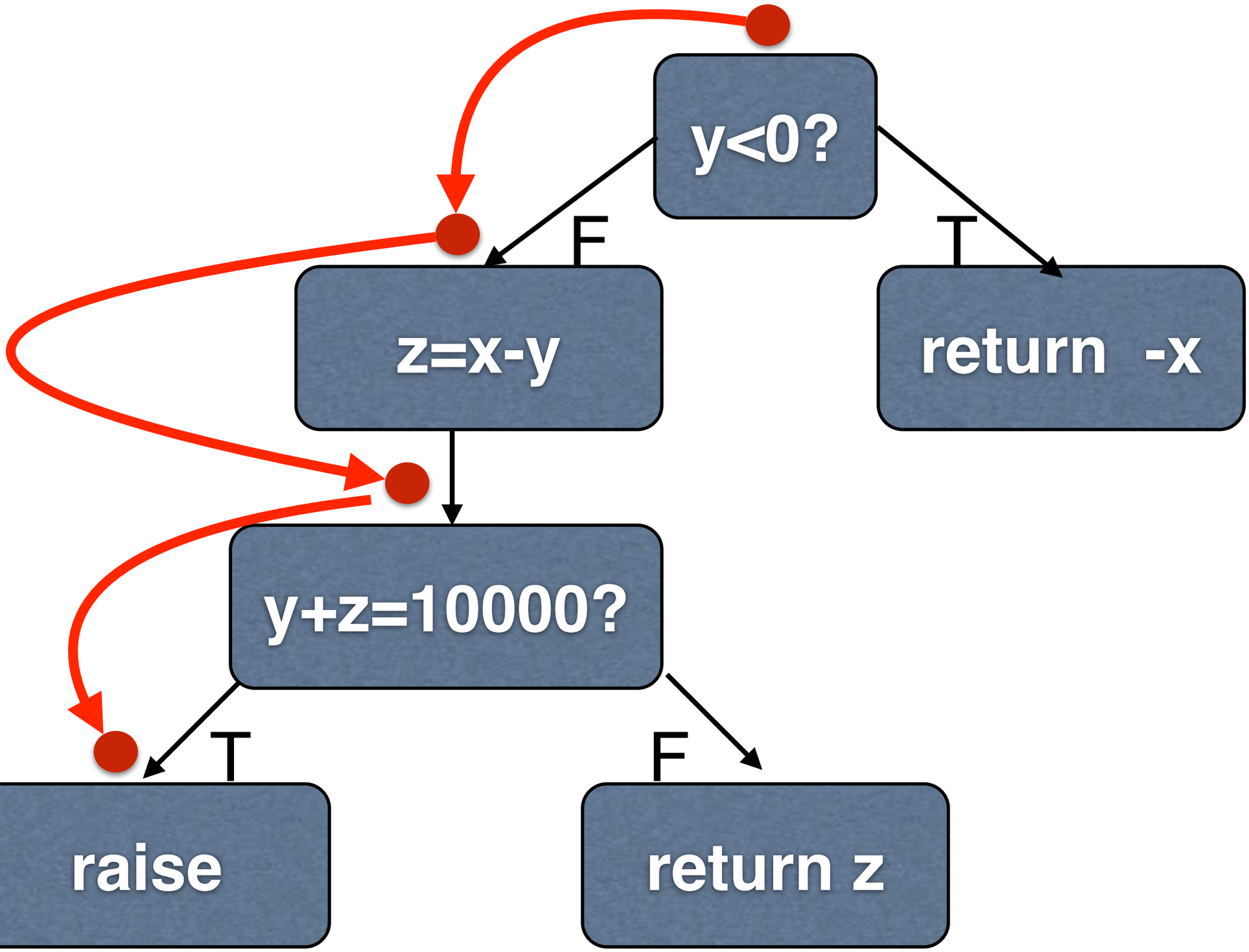
$x=x_0$, $y=y_0$, $z=x_0-y_0$

<u>path condition:</u>

$y_0>=0$ ^

x_0 !=10000



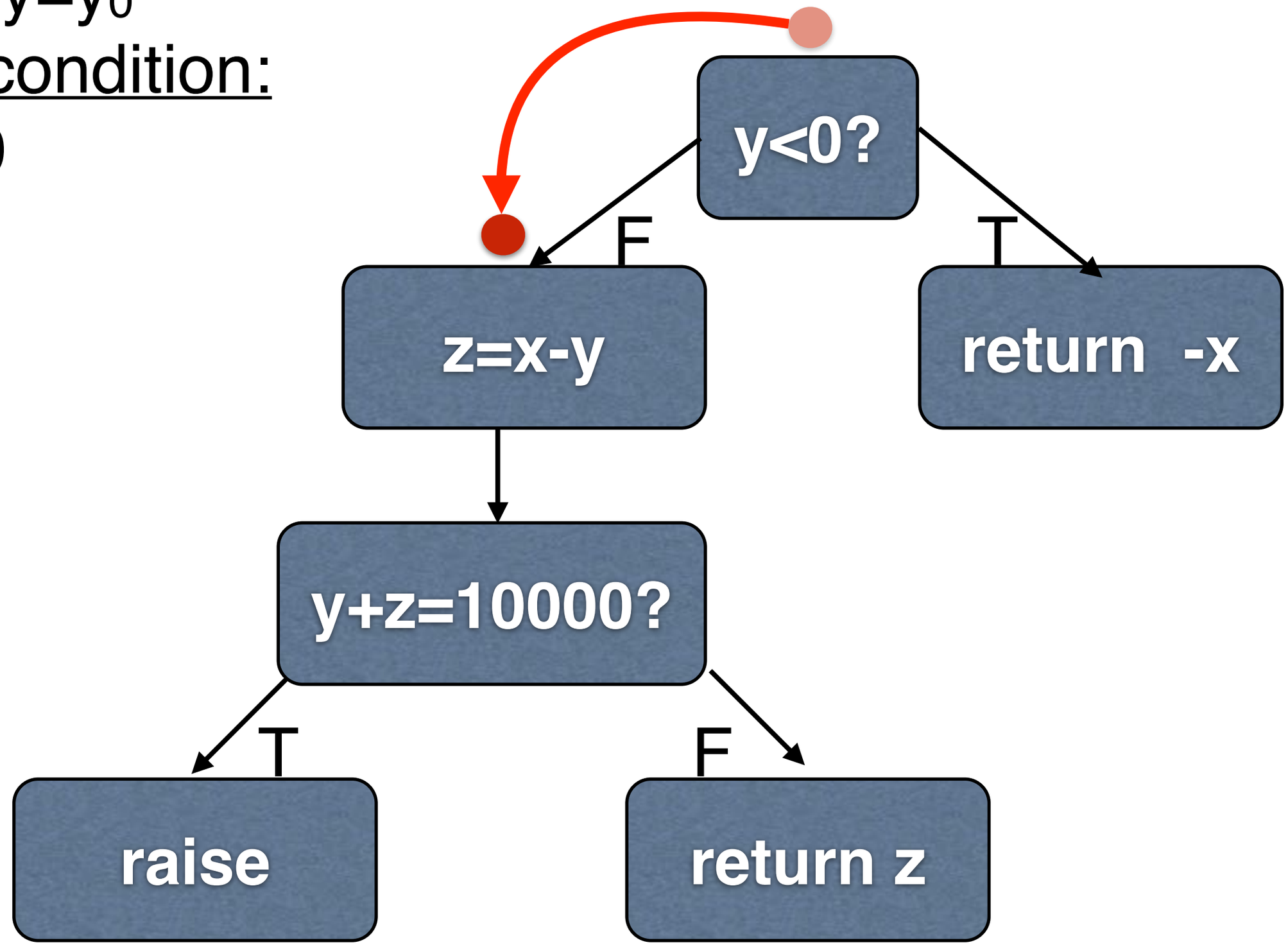

y<0?
F
T
z=x-y
return -x
y+z=10000?
T
F
raise
return z

<u>symbolic state:</u>

$x=x_0$, $y=y_0$

<u>path condition:</u>

$y_0>=0$

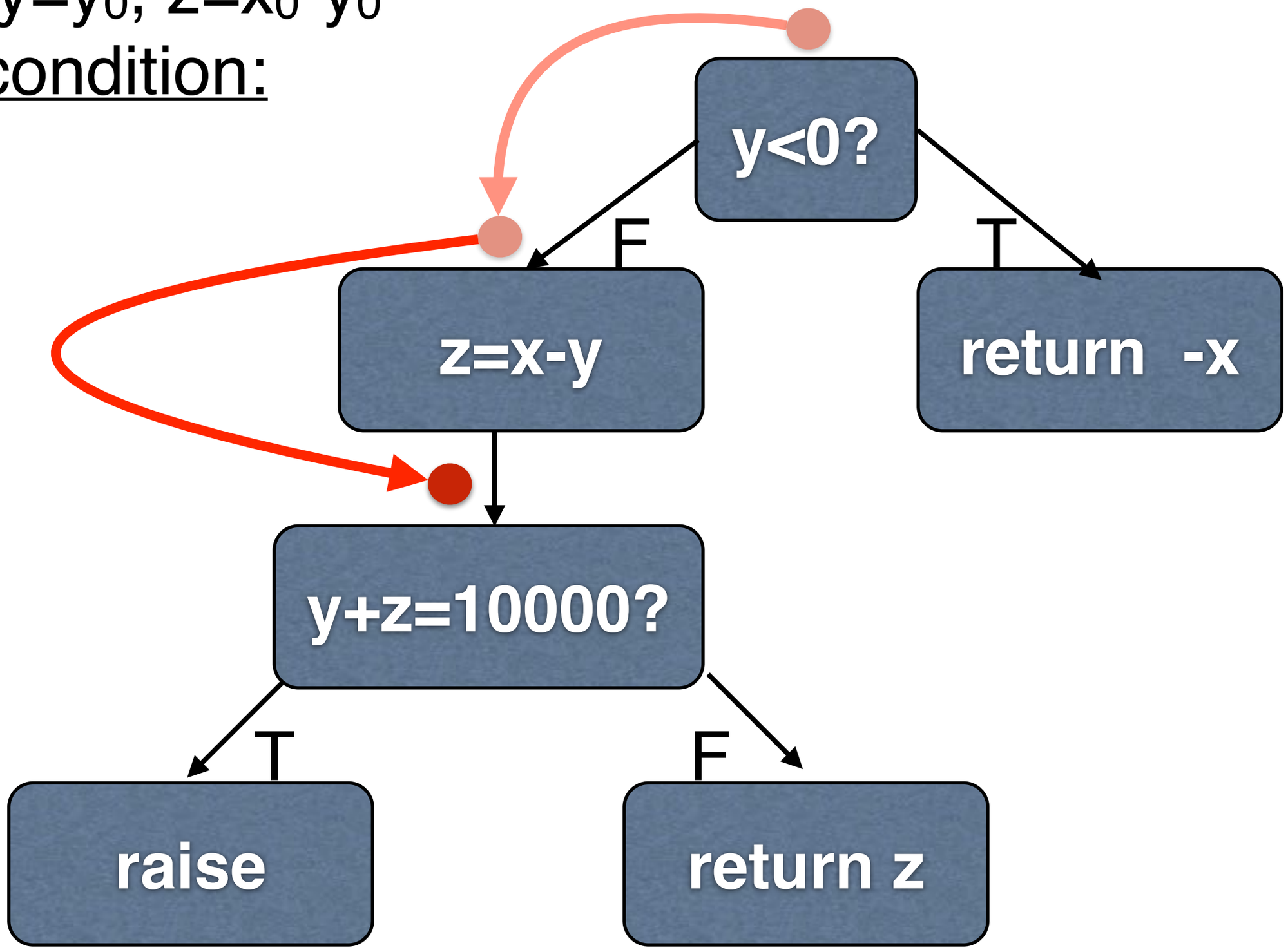


<u>symbolic state:</u>

$x=x_0$, $y=y_0$, $z=x_0-y_0$

<u>path condition:</u>

$y_0>=0$



<u>symbolic state:</u>

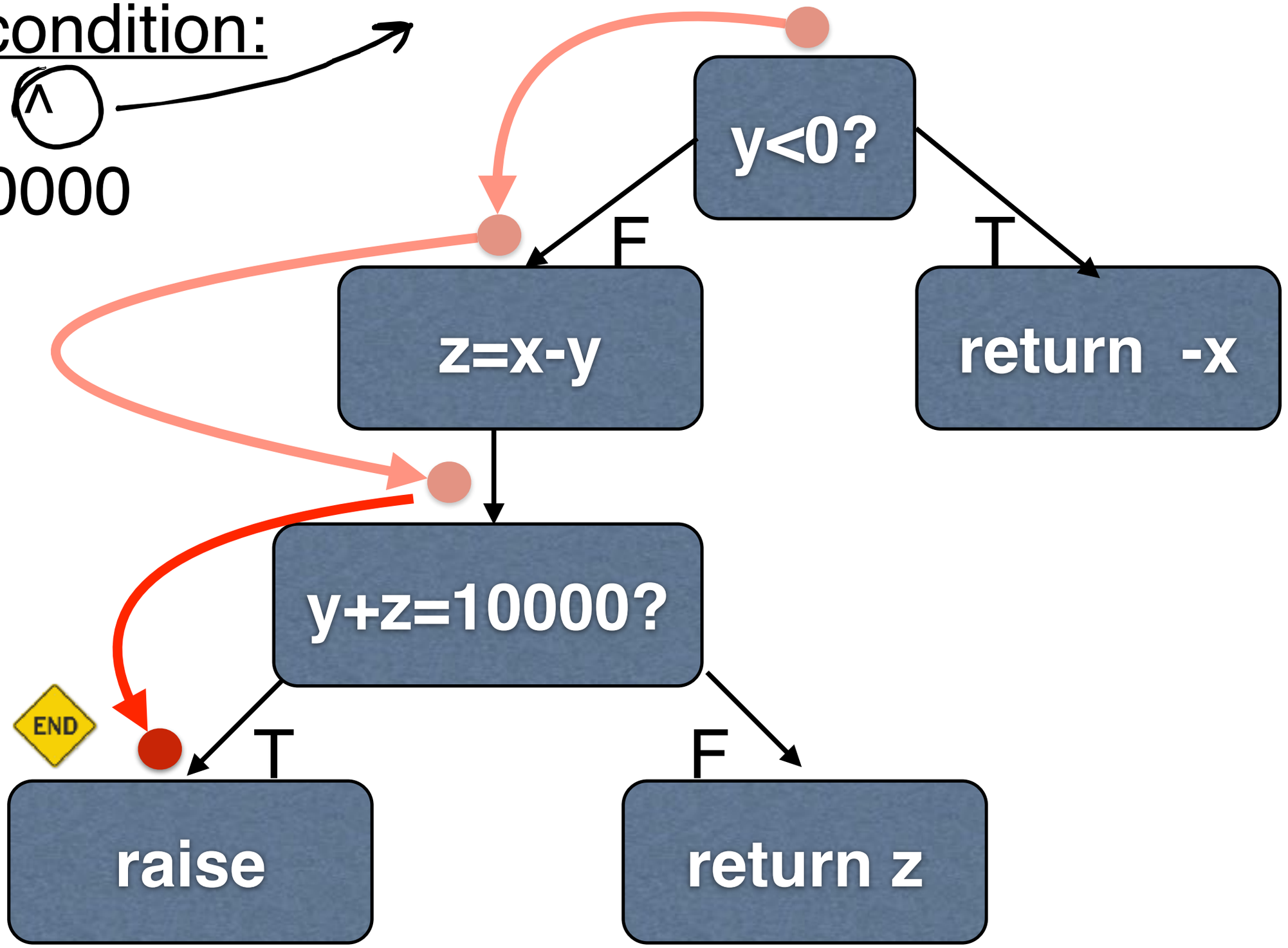
$x=x_0$, $y=y_0$, $z=x_0-y_0$

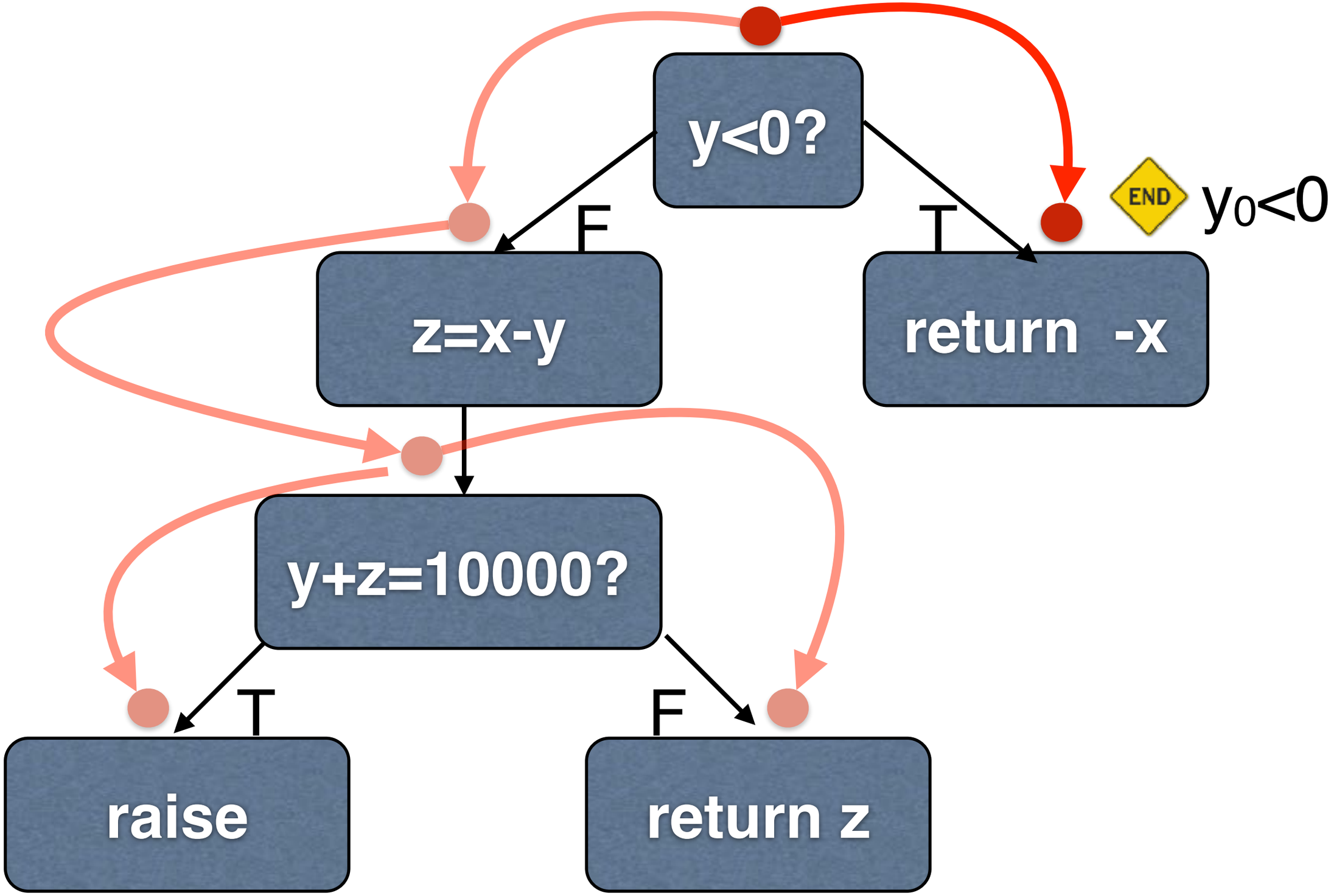
<u>path condition:</u>

$y_0>=0 \wedge$

$x_0 =10000$

simple conjunction!

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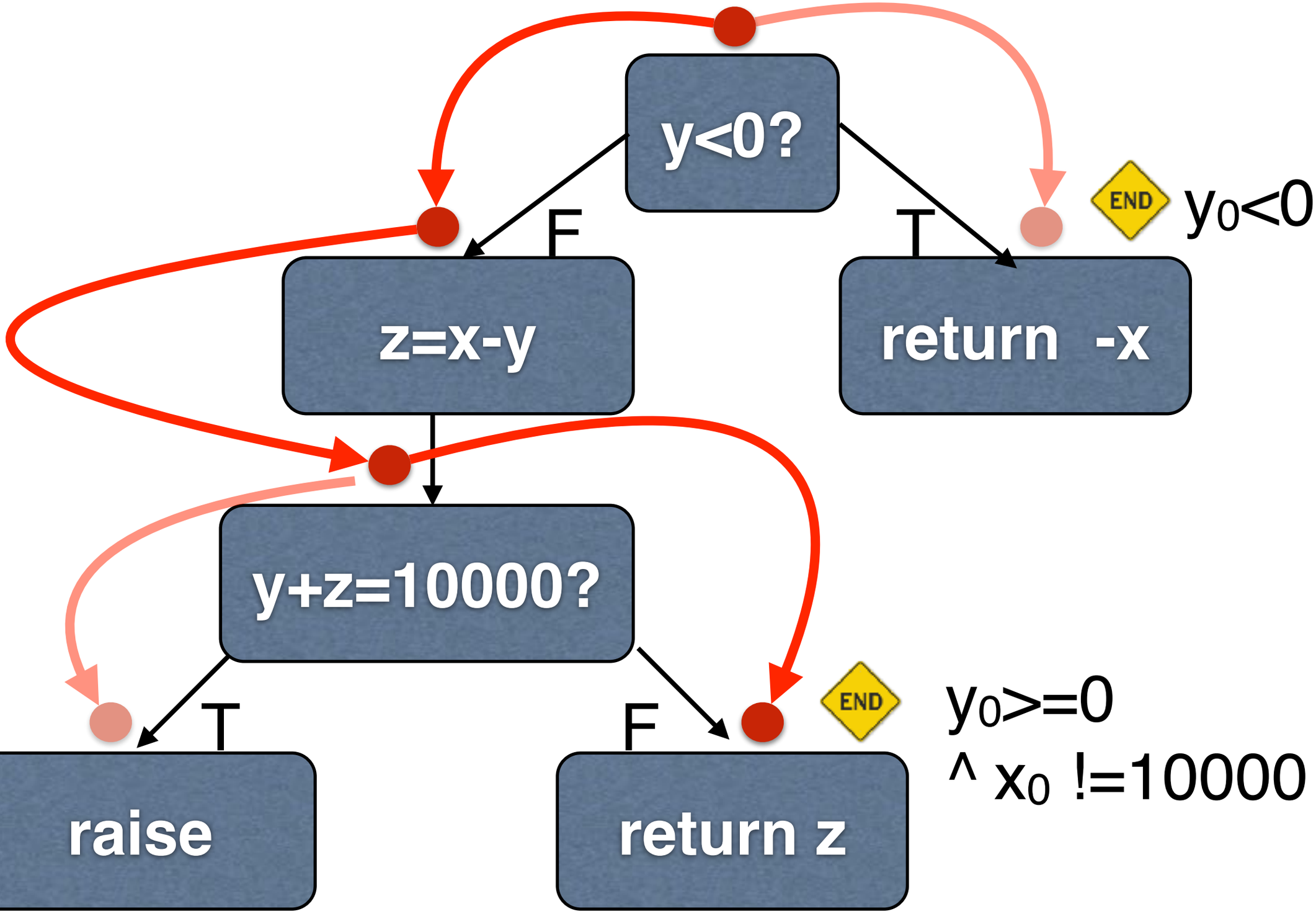
F
T
END
y0<0
z=x-y
return -x
y+z=10000?
T
F
raise
return z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F
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y0<0
z=x-y
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y+z=10000?
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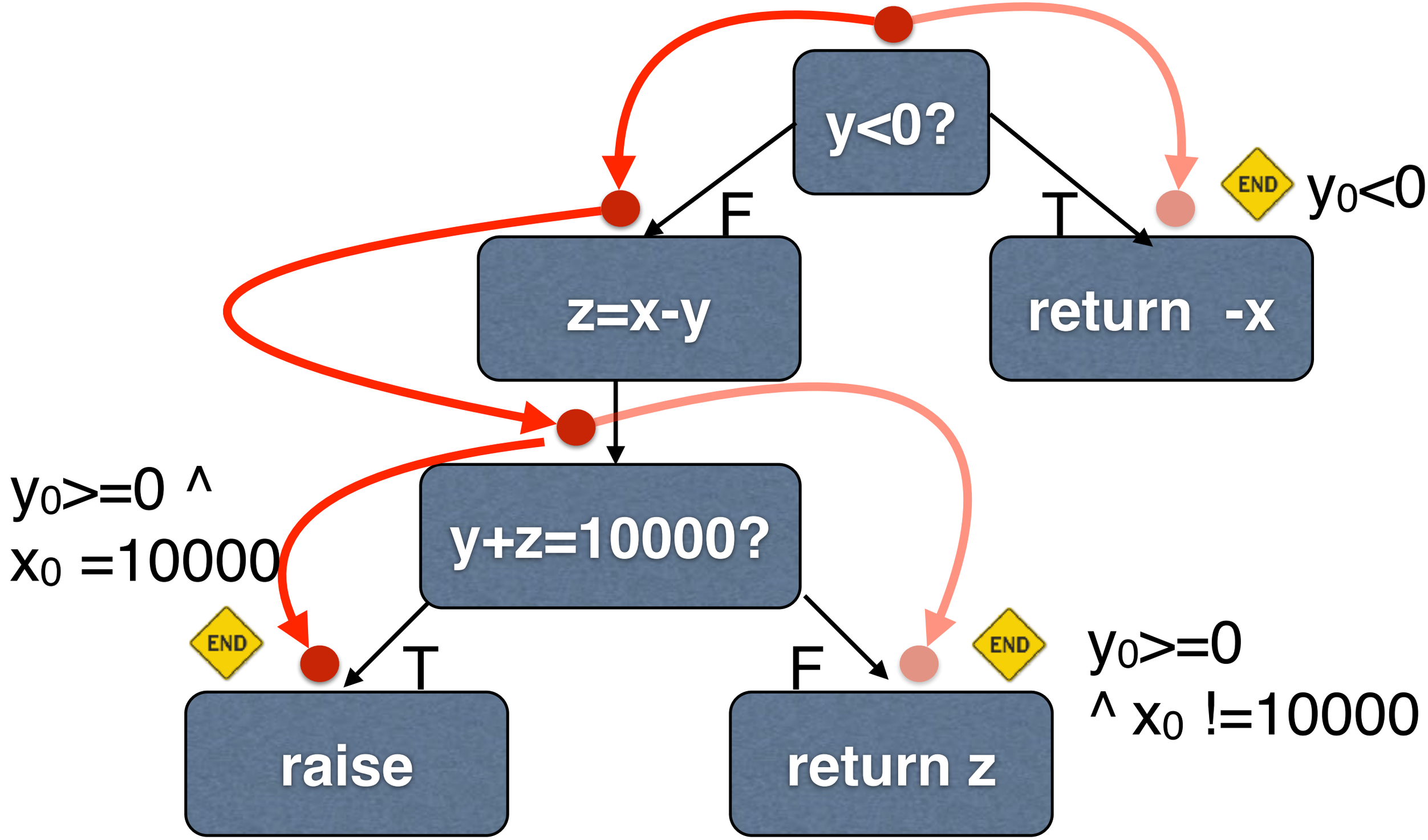
F
END
raise
return z
y0>=0
^ x0 !=10000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y0<0
z=x-y
return -x
y+z=10000?
y0>=0 ^
x0 =10000
END
T
F
END
y0>=0
^ x0 !=10000
raise
return z

Constraint Solving

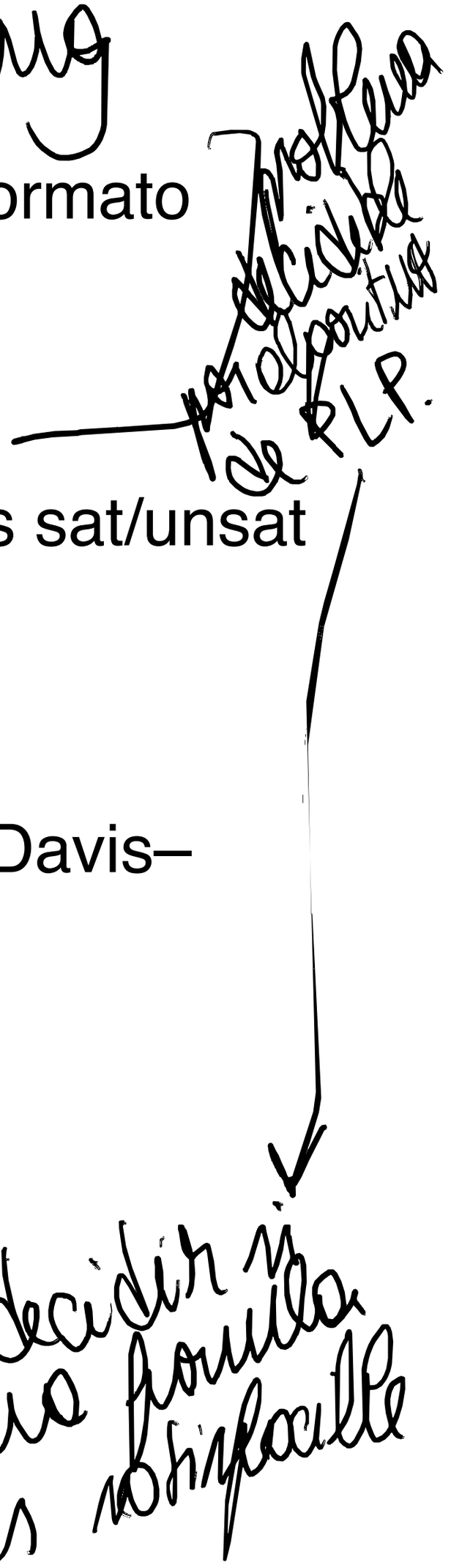
- Es un programa que resuelve fórmulas lógicas descriptas en un lenguaje
  - SAT
  - UNSAT
  - UNKNOWN/TIMEOUT
- Si es SAT, da un valor para cada variable

Determina si una fórmula lógica es válida/satisfacible o no.

SAT-Solvers

∈ Constraint Solving

- Input: Una fórmula proposicional (en formato CNF)
- Output: SAT/UNSAT
- Decidir si una fórmula proposicional es sat/unsat es decidible
- Tarda peor caso O(2^n)
- SAT-Solvers usualmente usan DPLL (Davis–Putnam–Logemann–Loveland)



DPLL

```
Algorithm DPLL
  Input: A set of clauses Φ.
  Output: A Truth Value.
```

```
function DPLL(Φ)
   if Φ is a consistent set of literals
       then return true;
   if Φ contains an empty clause
       then return false;
   for every unit clause {l} in Φ
      Φ ← unit-propagate(l, Φ);
   for every literal l that occurs pure in Φ
      Φ ← pure-literal-assign(l, Φ);
   l ← choose-literal(Φ);
   return DPLL(Φ ∧ {l}) or DPLL(Φ ∧ {not(l)});
```

- "←" denotes assignment. For instance, "*largest* ← *item*" means that the value of *largest* changes to the value of *item*.
- "**return**" terminates the algorithm and outputs the following value.

DPLL

- DPLL (Davis–Putnam–Logemann–Loveland)
  Output: SAT/UNSAT
  - Elijo un literal cuyo valor no ha sido fijado
  - Propago el valor del literal hasta no poder eliminar mas literales
  - Si hay conflicto, hago backtrack
  - Si no lo hay, elijo una nueva variable para asignar

DPLL: Ejemplo

A or B or C

and

Not A or B or C

and

Not A or Not B or Not C

DPLL: Ejemplo

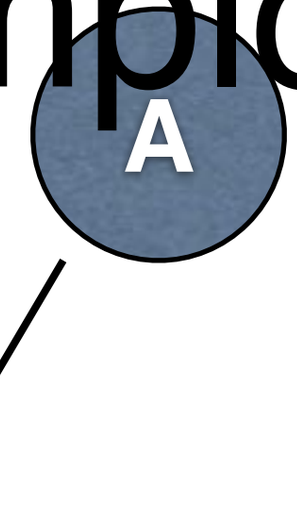
A or B or C

and

Not A or B or C

and

Not A or Not B or Not C



DPLL: Ejemplo

True

True

and

B or C

and

Not B or Not C

DPLL: Ejemplo

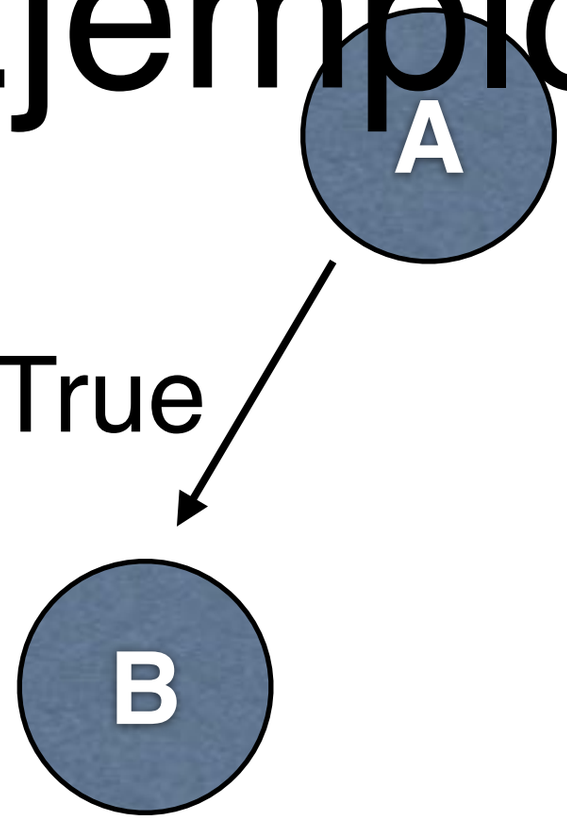
True

and

B or C

and

Not B or Not C



DPLL: Ejemplo

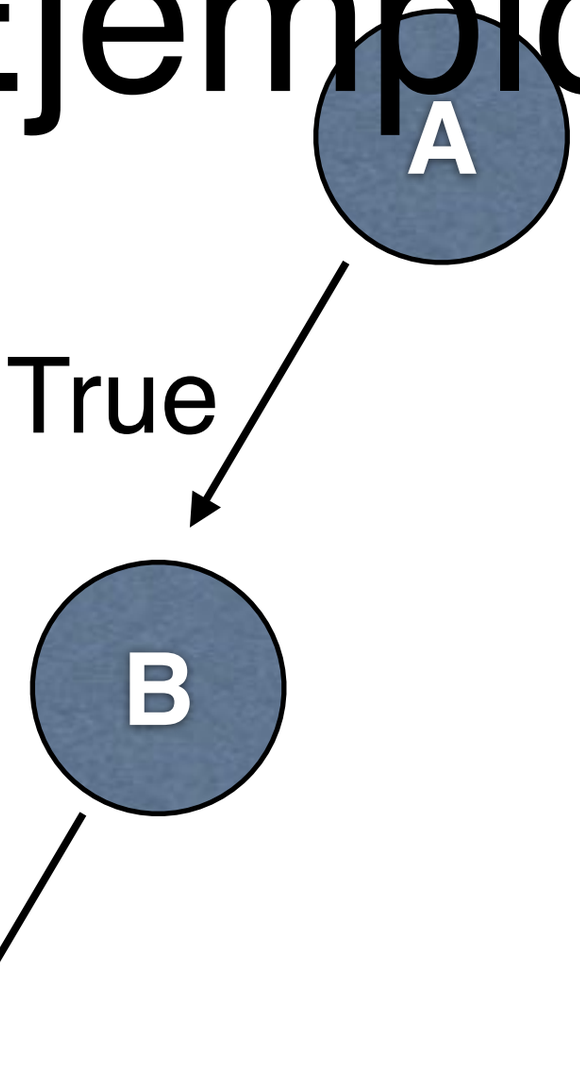
True

and

B or C

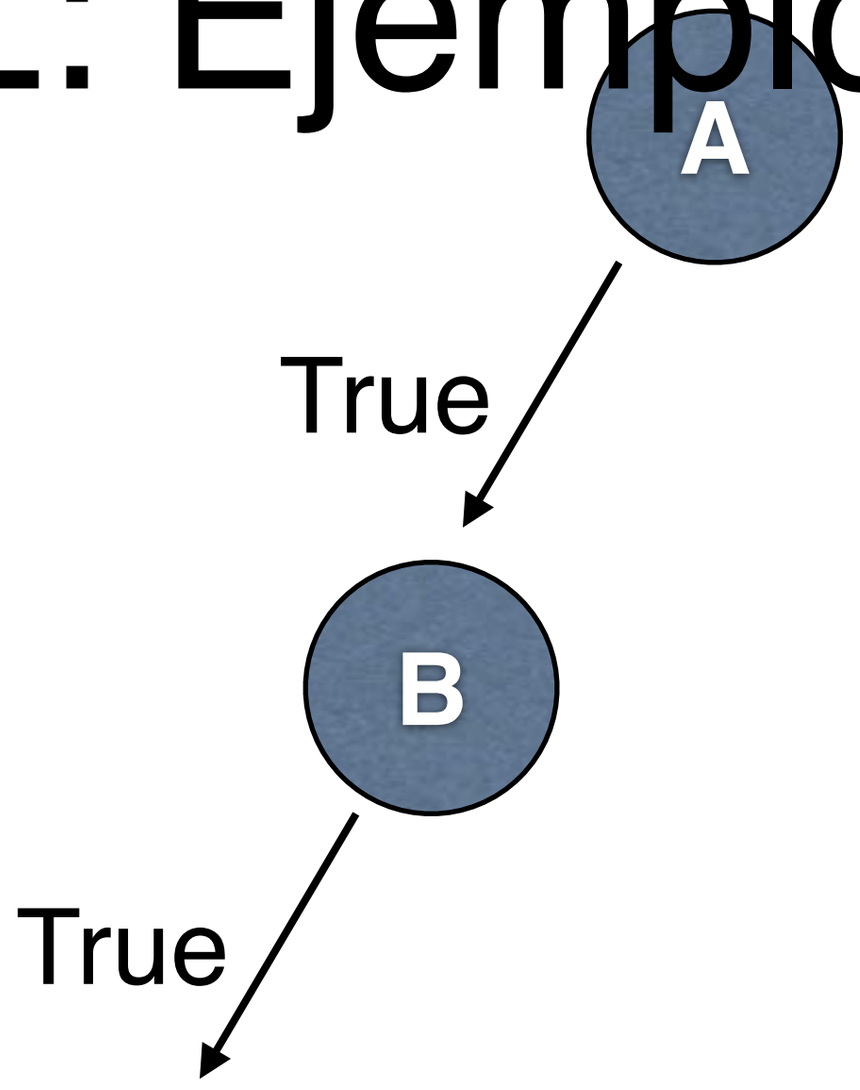
and

Not B or Not C



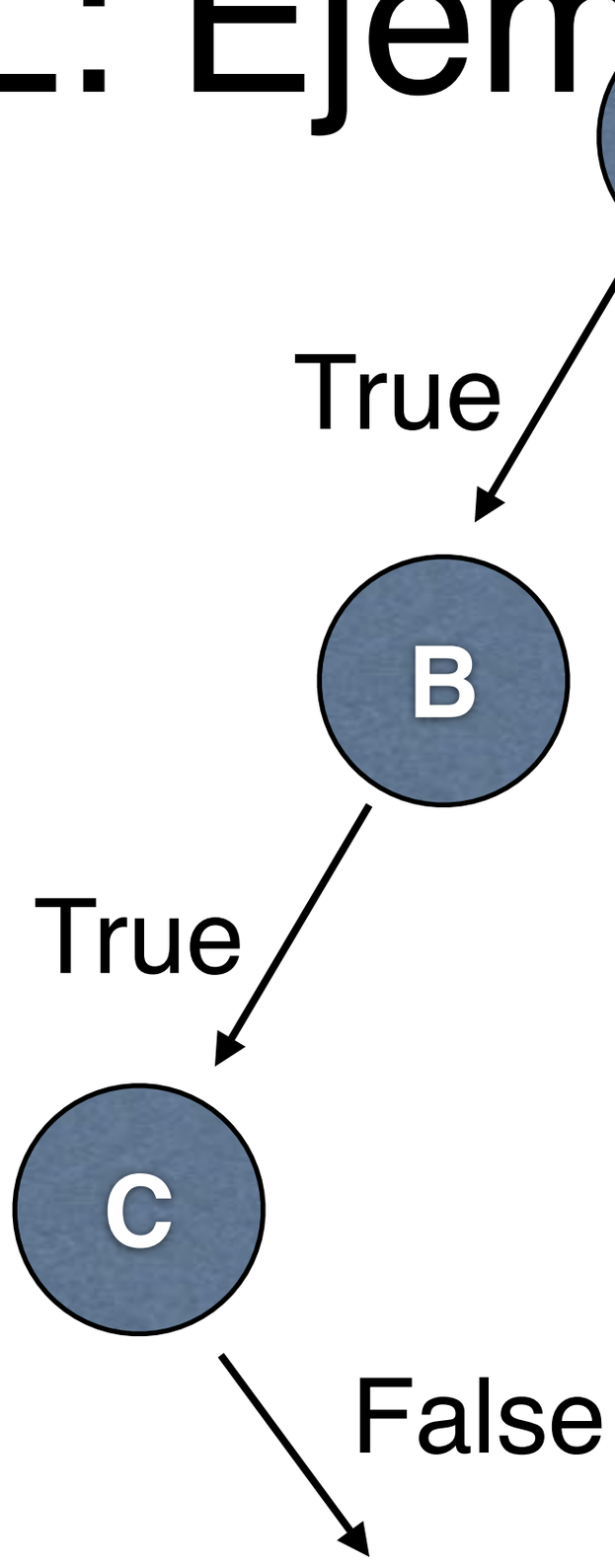
DPLL: Ejemplo

True
and
True
and
Not C

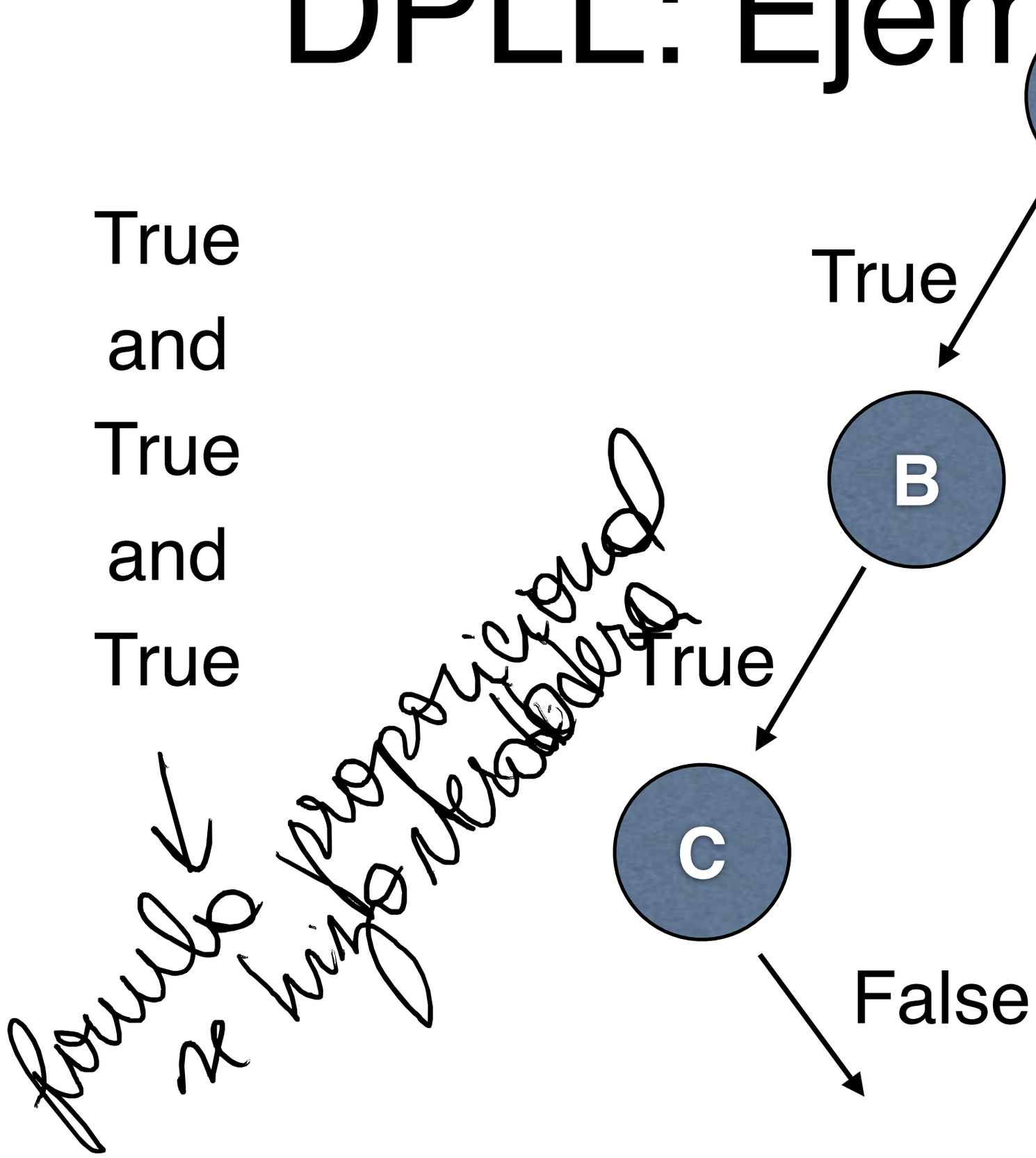


DPLL: Ejemplo

True
and
True
and
Not C



DPLL: Ejemplo



DPLL: Ejemplo

A or B or C

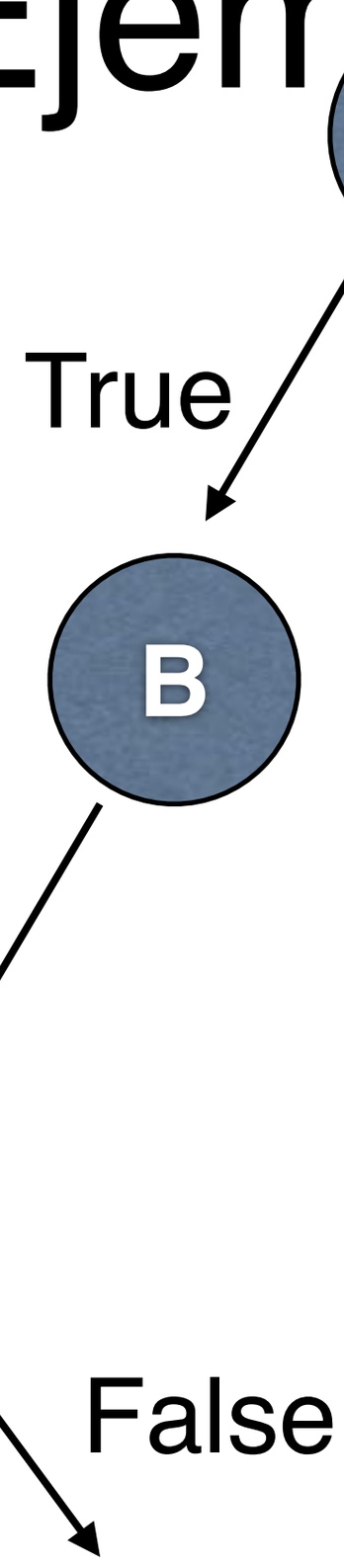
and

Not A or B or C

and

Not A or Not B or Not C

La fórmula
Es satisfacible
(A=true, B=True, C=False)



given a conflict → learn to create clauses

Conflict-Driven Clause Learning

SAT-Solving

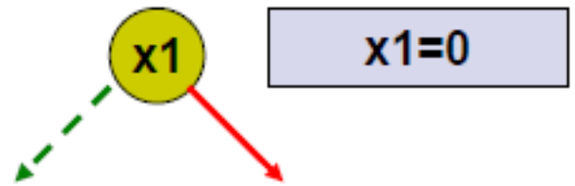
- Mejorar DPLL usando “learning de cláusulas”
- Cuando hay un conflicto, lo “aprendo” como una fórmula nueva que agrego a lo que tengo que cumplir
- Permite encontrar mas rápidamente “contradicciones” dentro de la fórmula

clause captures conflict
& try to solve conflict first
& avoid further issues down the line

CDCL: Ejemplo

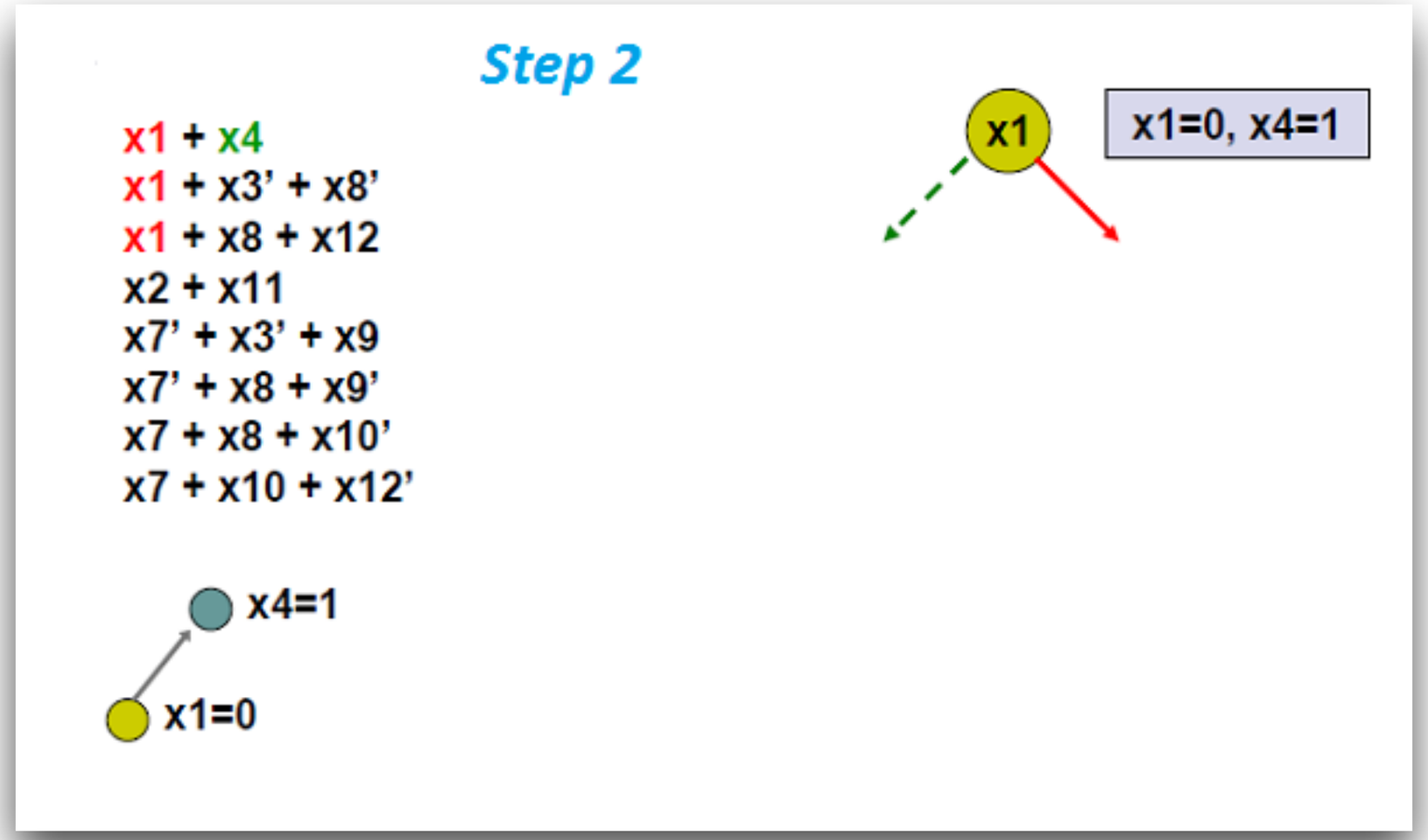
Step 1

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

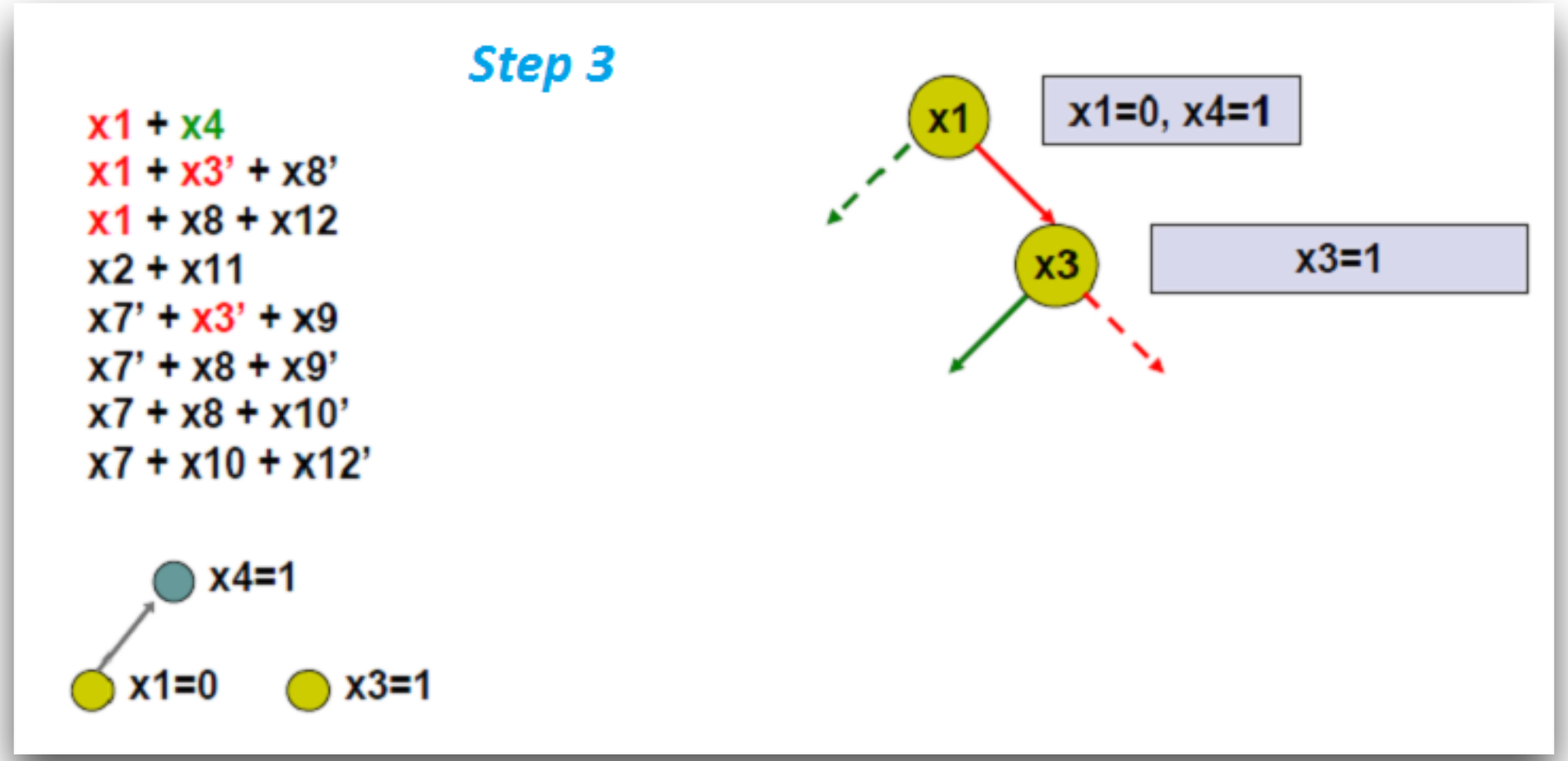


x1=0

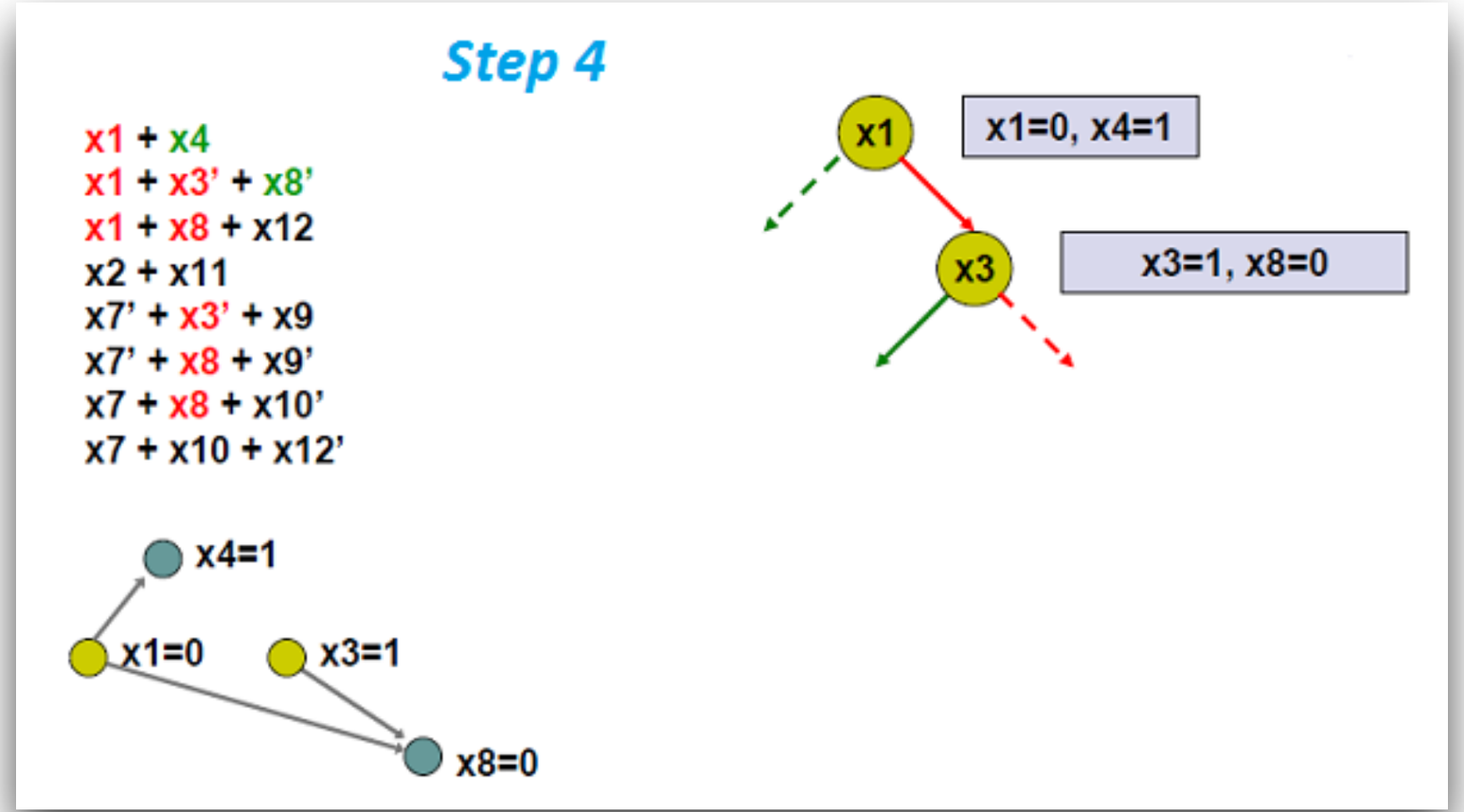
CDCL: Ejemplo



CDCL: Ejemplo



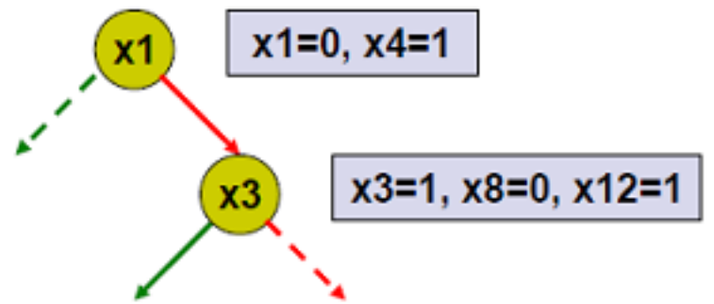
CDCL: Ejemplo

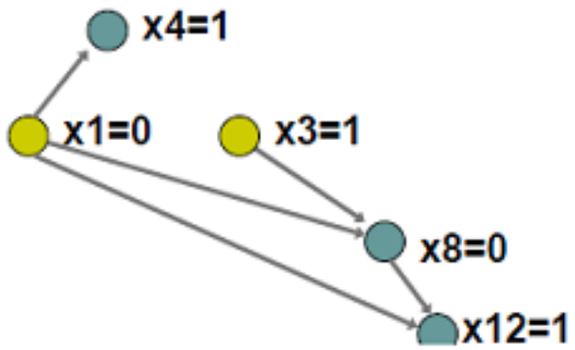


CDCL: Ejemplo

Step 5

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

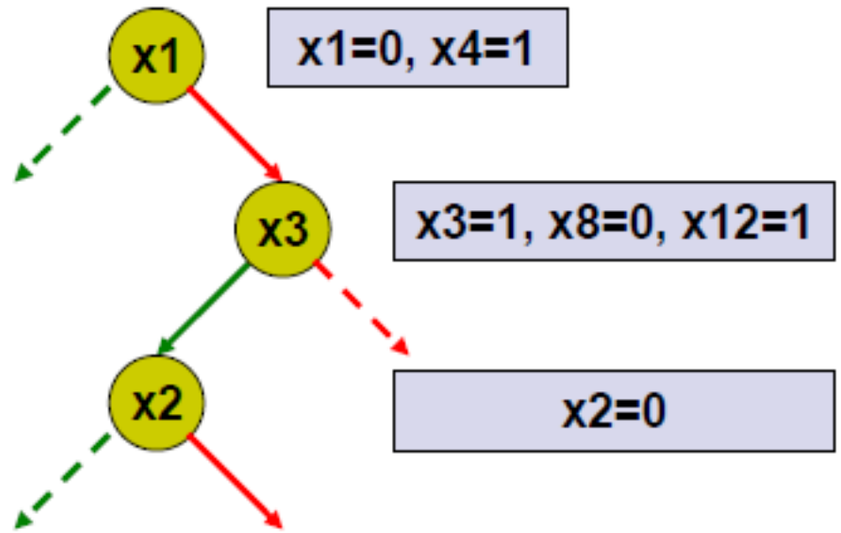


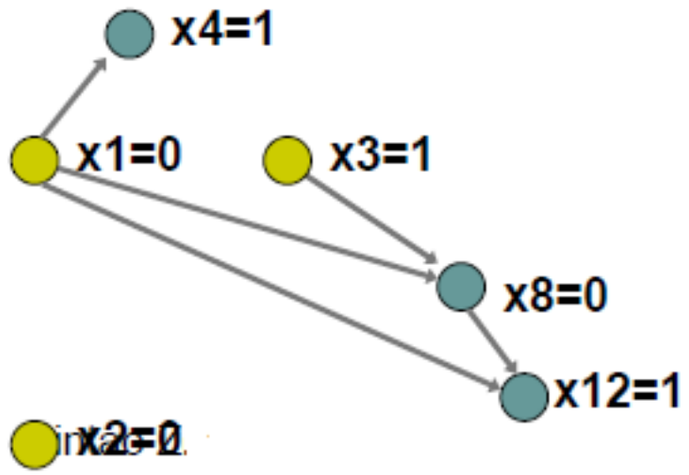


CDCL: Ejemplo

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

Step 6

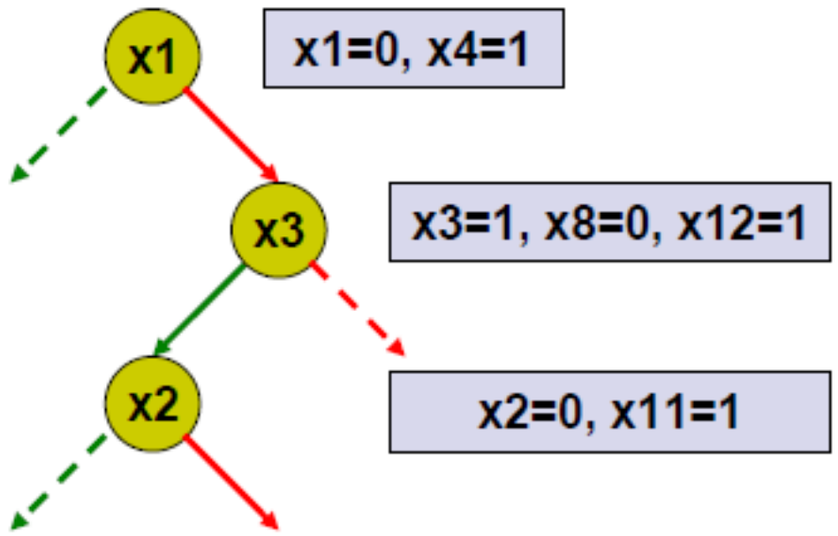


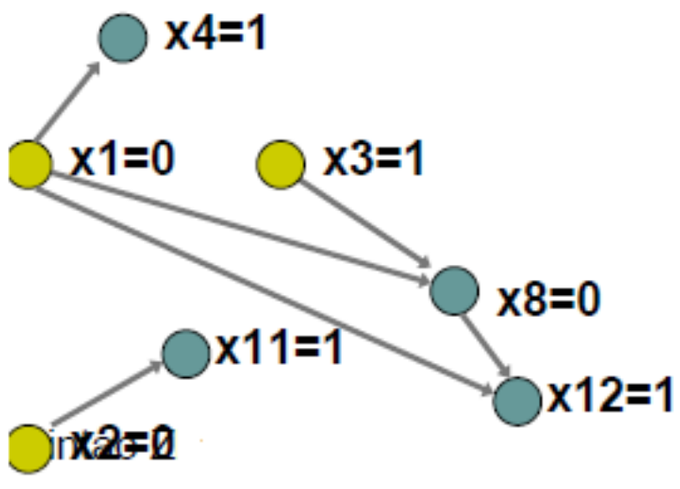


CDCL: Ejemplo

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

Step 7

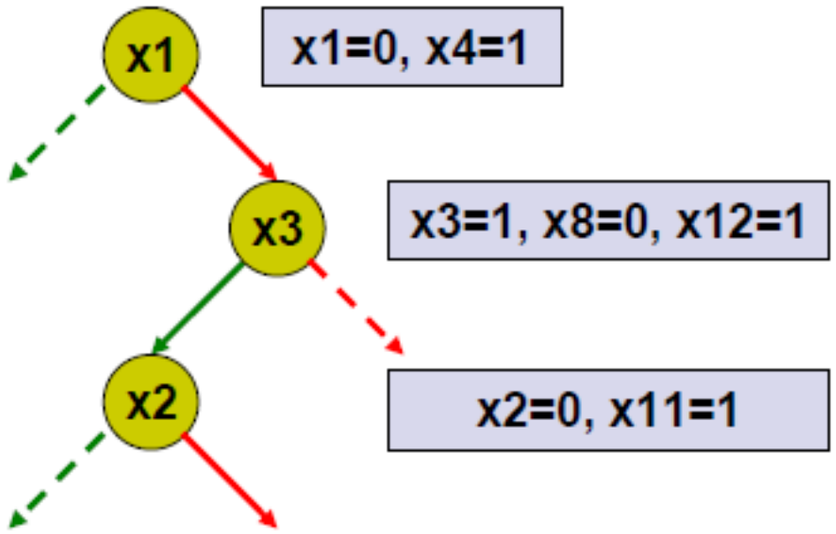


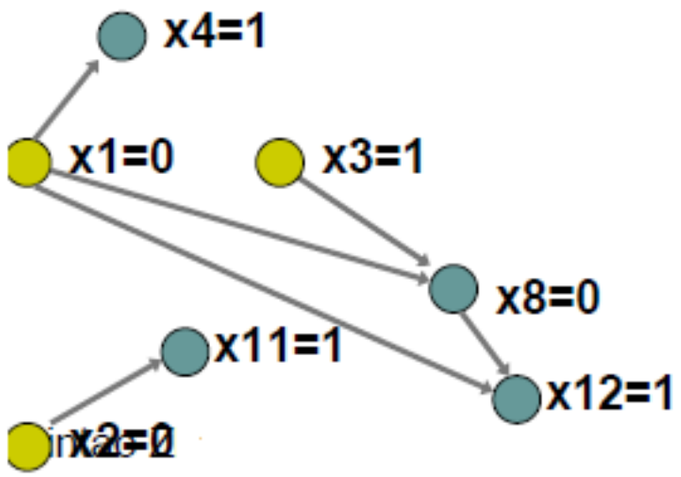


CDCL: Ejemplo

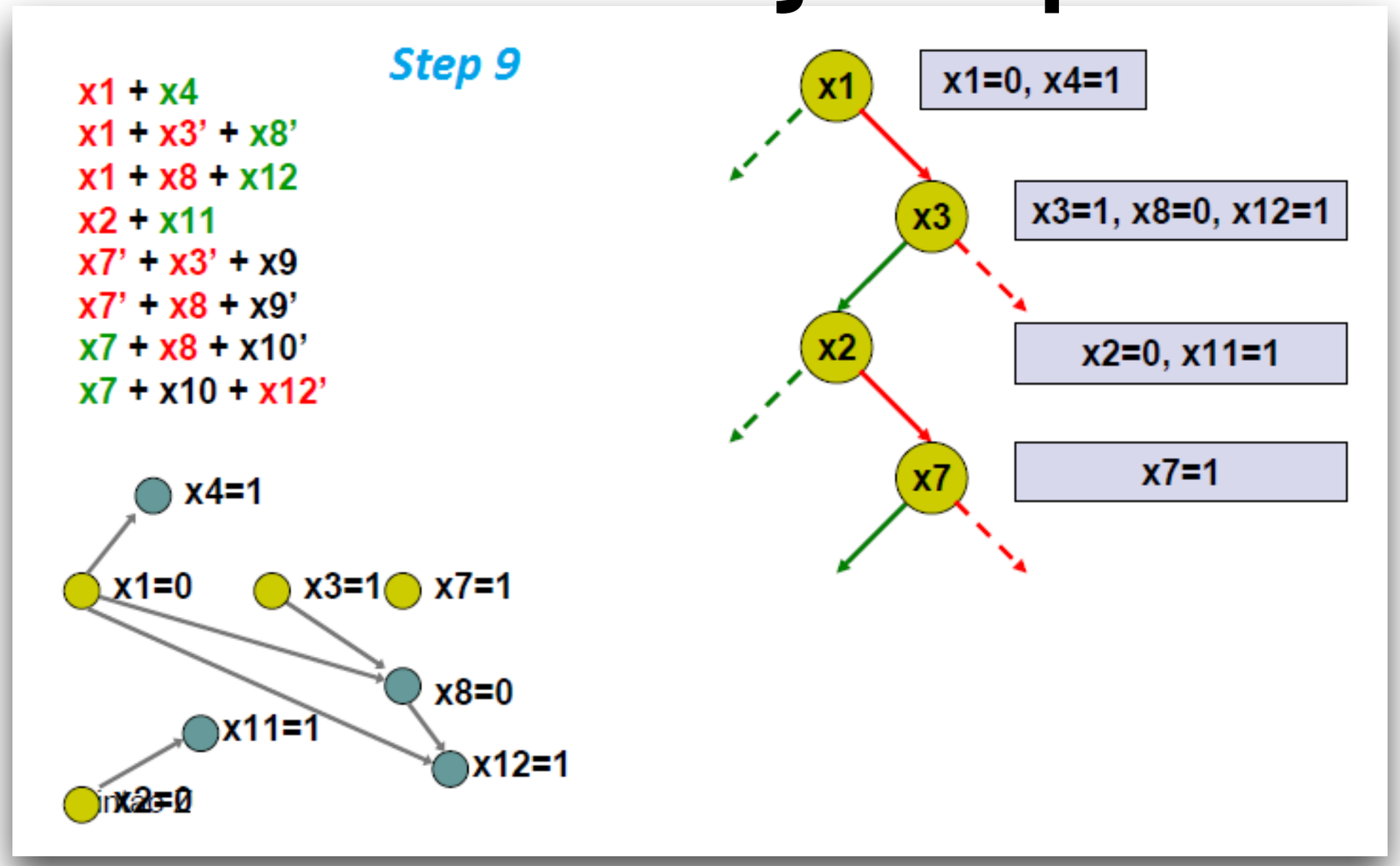
x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

Step 8





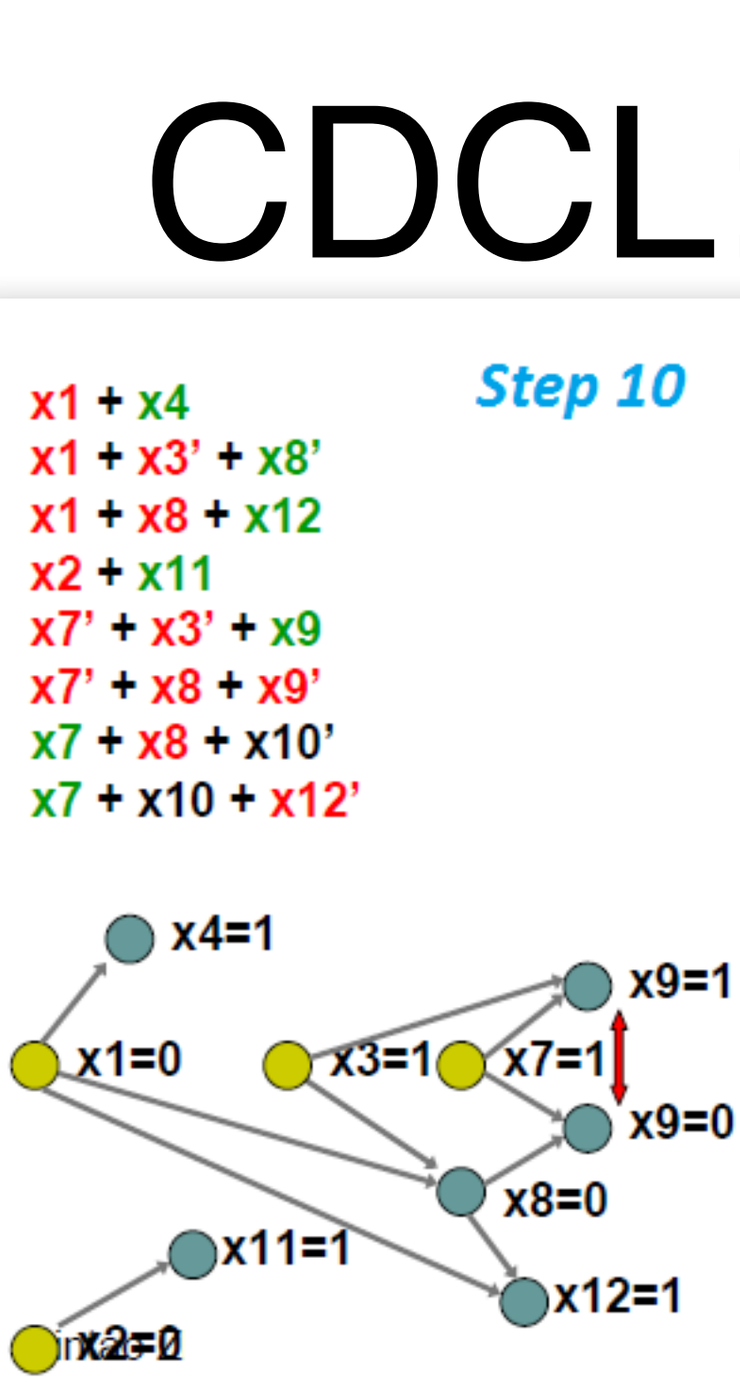
CDCL: Ejemplo

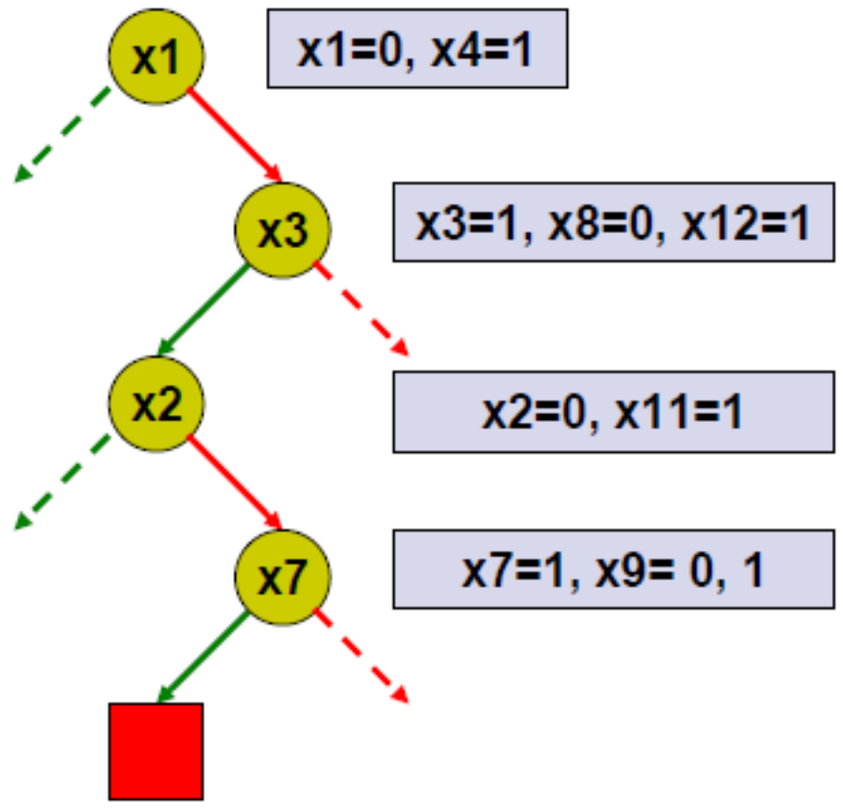


CDCL: Ejemplo

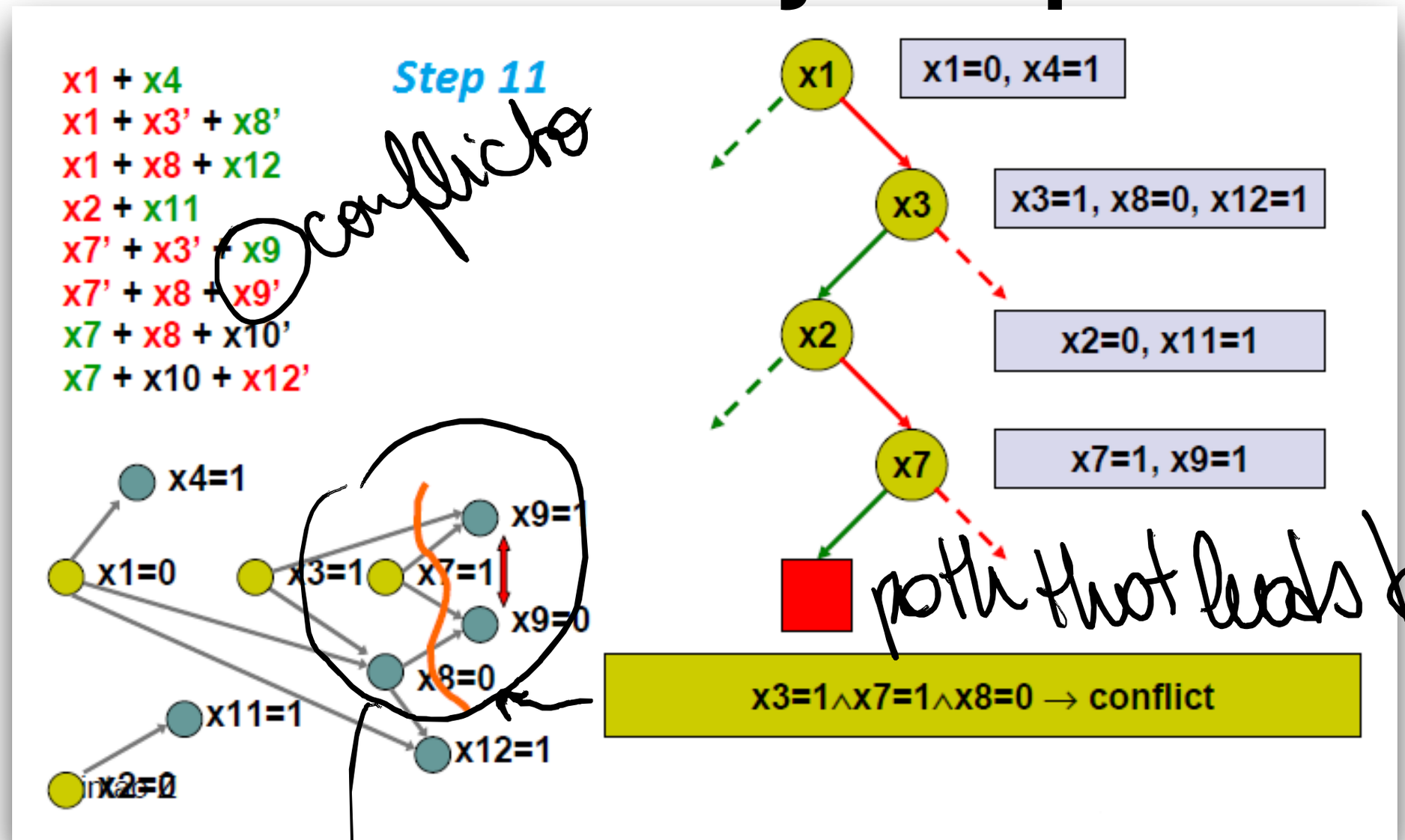
x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

Step 10





CDCL: Ejemplo



CDCL: Ejemplo

If a implies b, then b' implies a'

Step 12

$x3=1 \wedge x7=1 \wedge x8=0 \rightarrow$ conflict

Not conflict $\rightarrow (x3=1 \wedge x7=1 \wedge x8=0)'$

true $\rightarrow (x3=1 \wedge x7=1 \wedge x8=0)'$

$(x3=1 \wedge x7=1 \wedge x8=0)'$

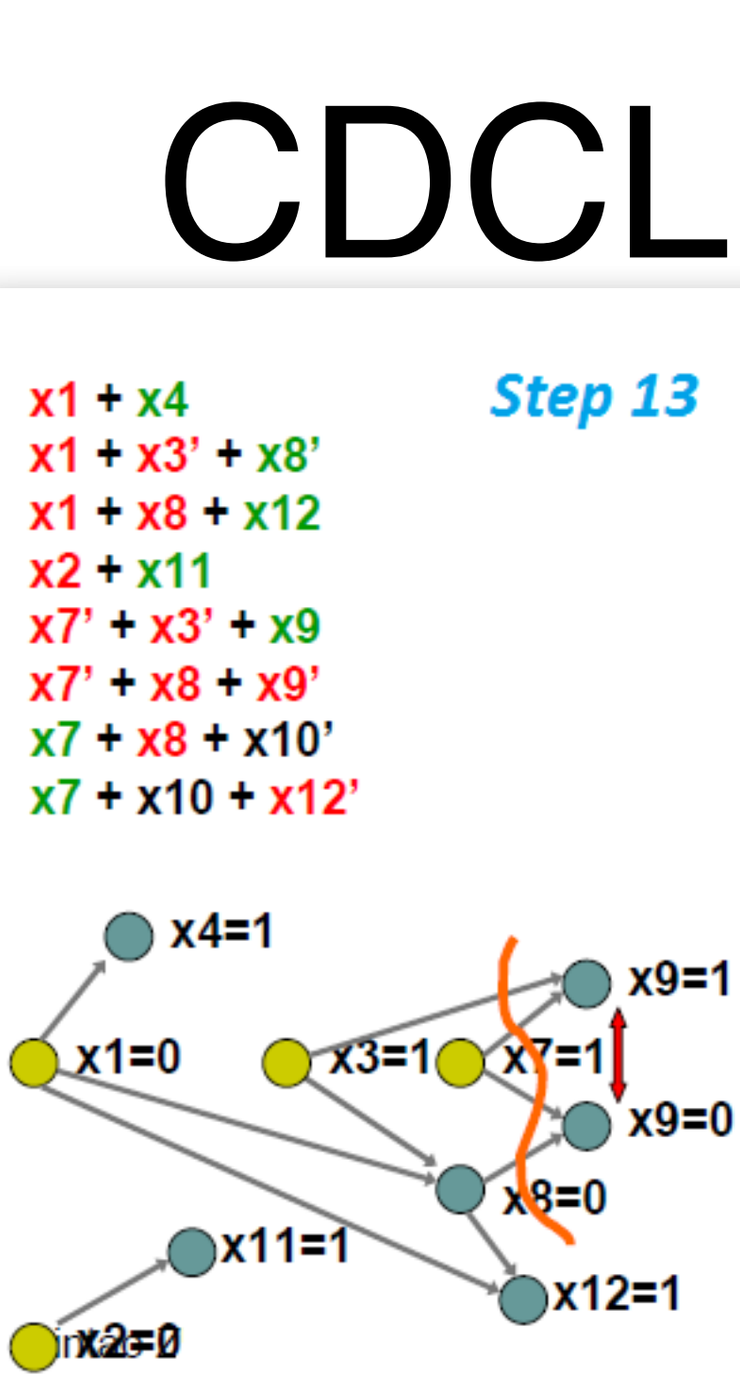
$(x3' + x7' + x8)$

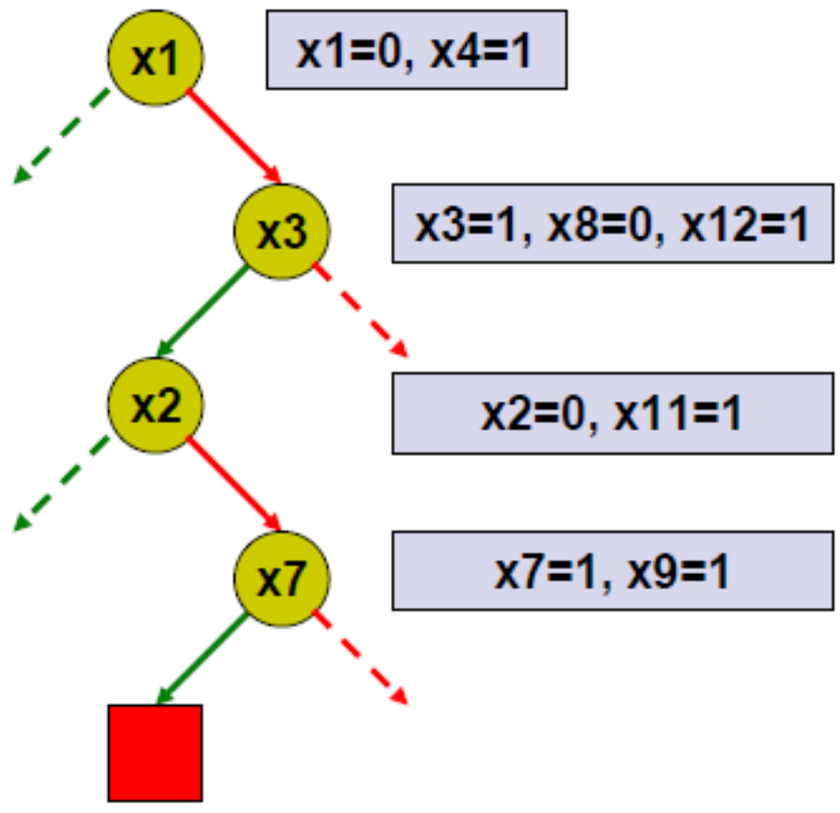
new created clause to prevent conflict from being reached

CDCL: Ejemplo

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'

Step 13





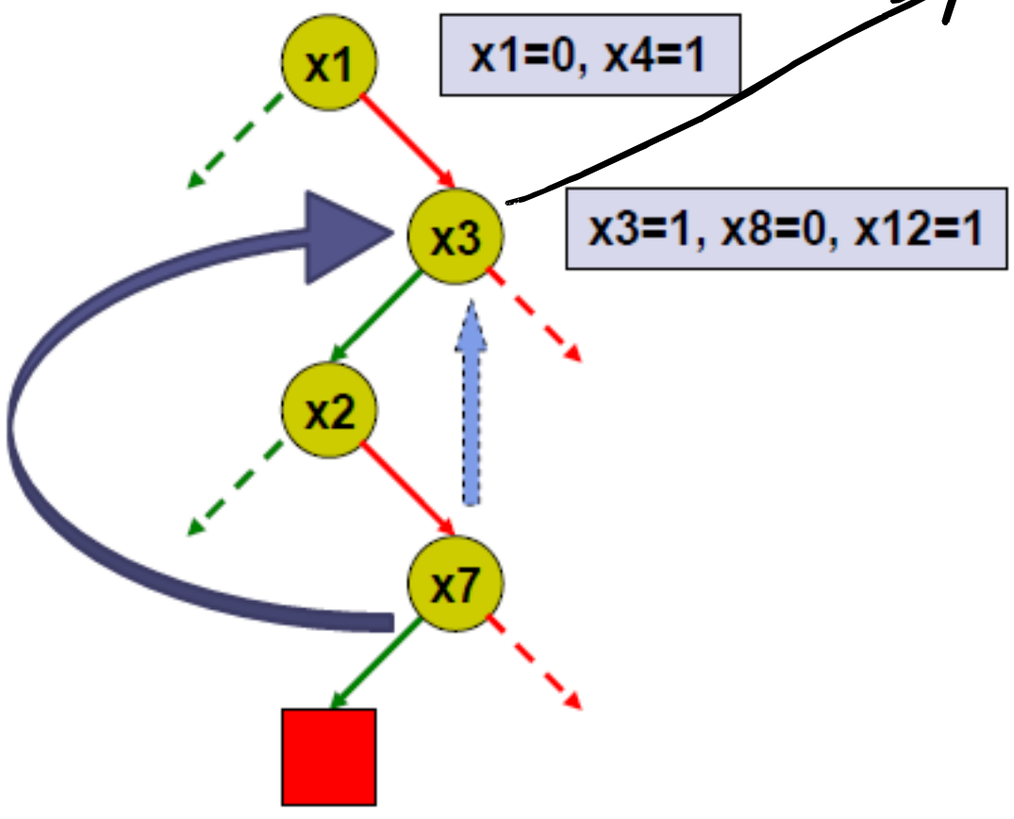
x3=1∧x7=1∧x8=0 → conflict

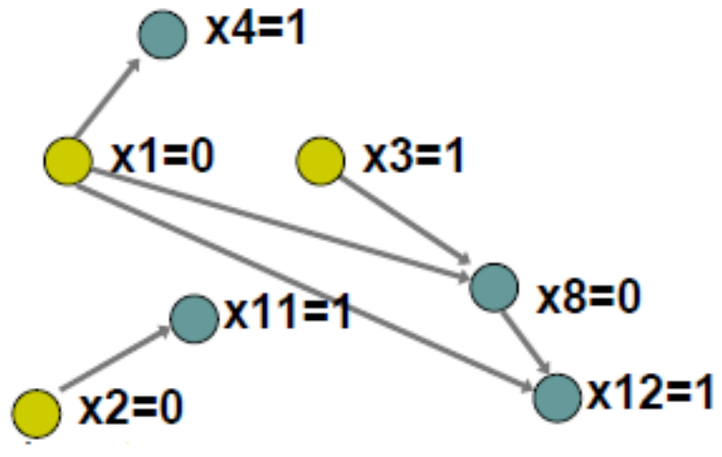
Add conflict clause: x3'+x7'+x8

CDCL: Ejemplo

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'
x3' + x8 + x7'

Step 14





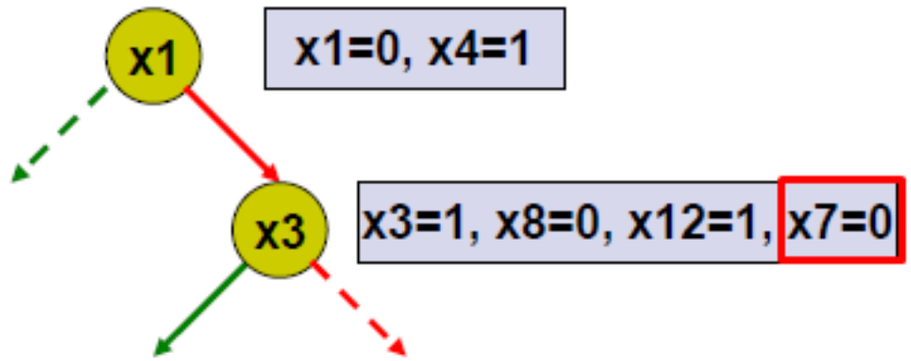
Backtrack to the decision level of x3=1:
x7 = 0

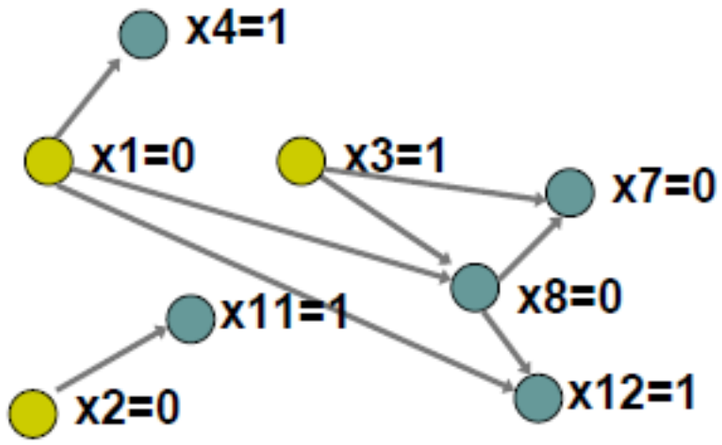
backtrack to earliest of direct decisions

CDCL: Ejemplo

x1 + x4
x1 + x3' + x8'
x1 + x8 + x12
x2 + x11
x7' + x3' + x9
x7' + x8 + x9'
x7 + x8 + x10'
x7 + x10 + x12'
x3' + x8 + x7'

Step 15





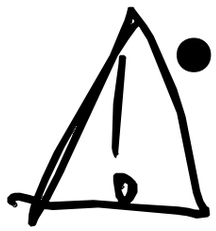
SAT-Solvers

- SAT4J (https://www.sat4j.org)
- MiniSAT (http://minisat.se)
- Lingeling (http://fmv.jku.at/lingeling/)
- MaxSAT (http://sat.inesc-id.pt/open-wbo/)

SMT-Solvers

- El SAT-Solver únicamente resuelve fórmulas proposicionales
- Un SMT-Solver permite resolver fórmulas
  - Con cuantificadores (para todo, existe)
  - Con “teorías” (ej: enteros, arreglos, bitvectors, números reales, strings, gramáticas, etc)

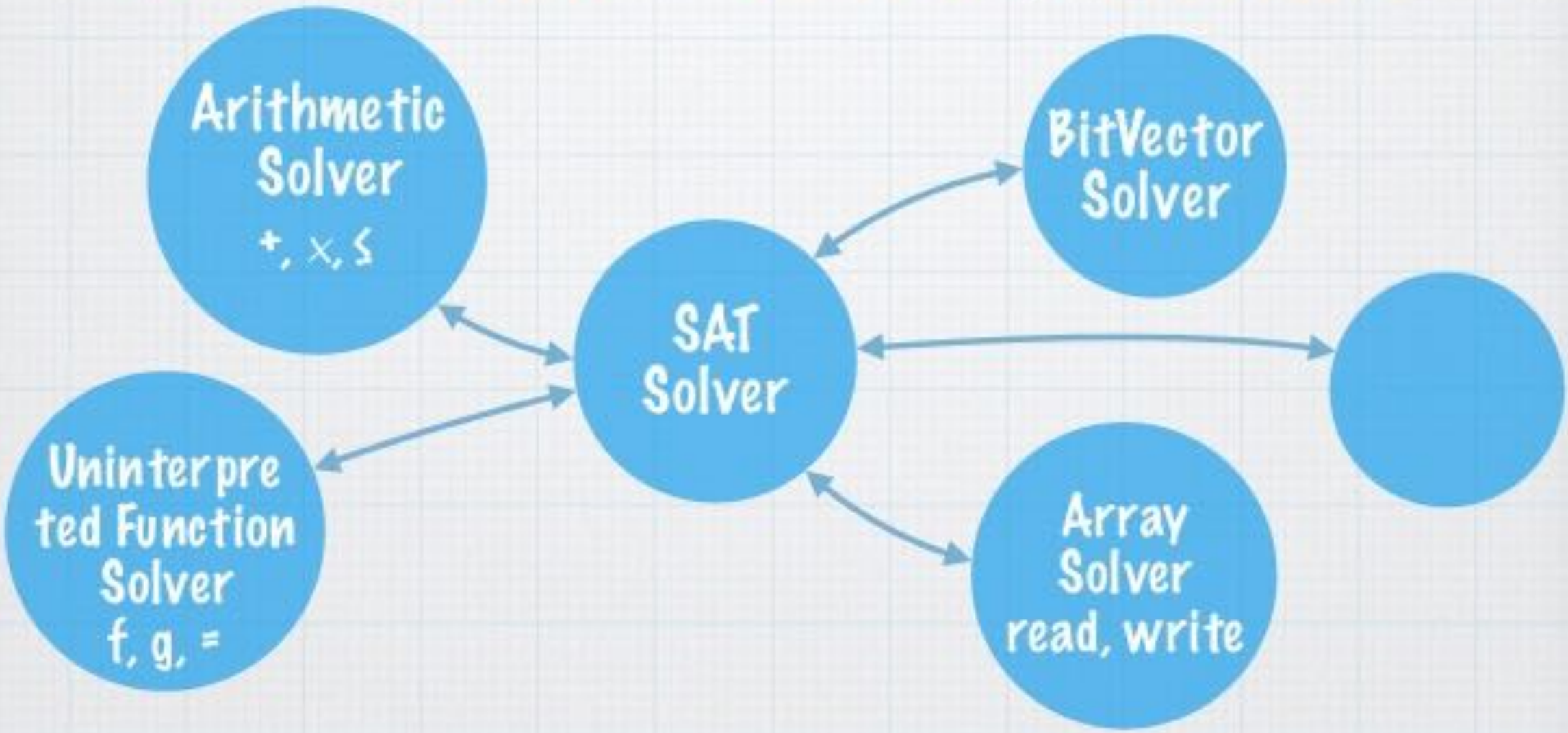
SMT-Solvers



- Pero decidir si una fórmula FOL es sat/unsat **NO** es decidible

- Input: Una fórmula FOL con teorías (arrays, enteros, números reales, funciones no interpretadas, etc.)
- Output: SAT/UNSAT/UNKNOWN (timeout)
- Usa DPLL + solventes específicos para otros problemas

SMT Solver Impl.
SAT Solver + Theory solvers



* SAT solver is responsible for Boolean reasoning
* Theory solvers are responsible for handling specific functions/relations etc.

↳ SMT solver asigna a variables proposicionales del SAT, predicados sobre el dominio de cuerdas.

SMT-Solvers

https://github.com/Z3Prover/z3

https://cvc4.github.io

https://yices.csl.sri.com

SMT-Lib

- Es un lenguaje stándard para escribir fórmulas para un SMT-Solver (lenguaje p/ cualquier SMT-Solver)
- Casi todos los SMT-Solvers poseen un lenguaje nativo + un módulo para traducir de SMT-Lib
- http://smtlib.cs.uiowa.edu
- Existe una especificación del comportamiento esperado de cada función
- Es un lenguaje para máquinas, no para humanos (simil XML)

SMT-Lib: Ejemplo

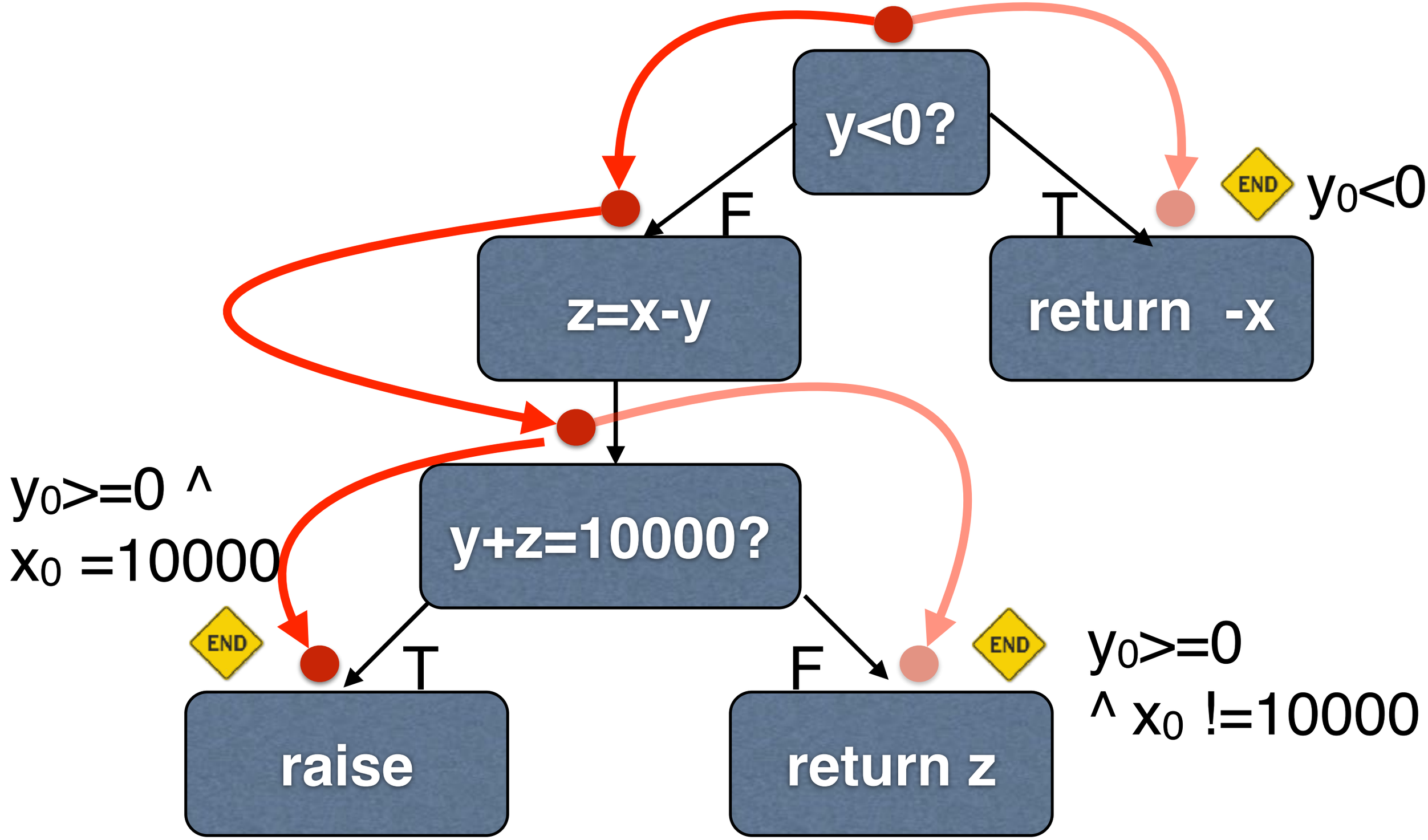
```
(declare-const p Bool)
(assert (and p (not p)))
(check-sat) ; returns 'unsat'
(exit)
```

SMT-Lib: Ejemplo

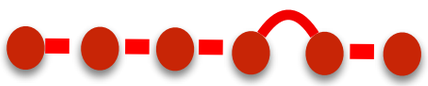
```
(declare-const x Int)
(declare-const y Int)
(assert (= (- x y) (+ x (- y 1))))
(check-sat)
; unsat
(exit)
```

```
(declare-const x_0 (_ BitVec 32))
(declare-const x_1 (_ BitVec 32))
(declare-const x_2 (_ BitVec 32))
(declare-const y_0 (_ BitVec 32))
(declare-const y_1 (_ BitVec 32))
(assert (= x_1 (bvadd x_0 y_0)))
(assert (= y_1 (bvsub x_1 y_0)))
(assert (= x_2 (bvsub x_1 y_1)))

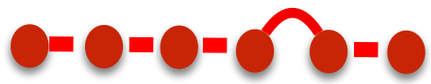
(assert (not
  (and (= x_2 y_0)
       (= y_1 x_0))))
(check-sat)
```


y<0?
F
T
END
y0<0
z=x-y
return -x
y+z=10000?
y0>=0 ^
x0 =10000
END
T
F
END
y0>=0
^ x0 !=10000
raise
return z

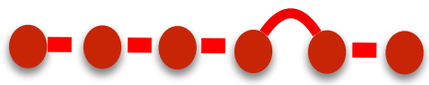
Constraint Solving



$y_0<0$

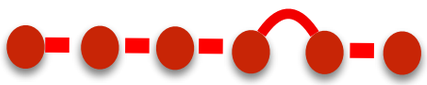


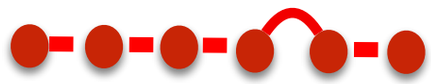
$y_0>=0 \wedge x_0 != 10000$



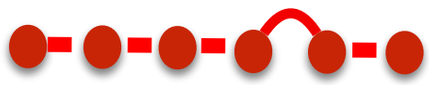
$y_0>=0 \wedge x_0 = 10000$

Constraint Solving



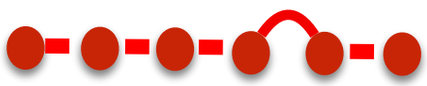


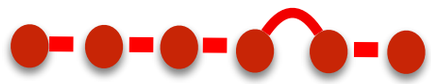
$y_0 >= 0 \wedge x_0 \neq 10000$



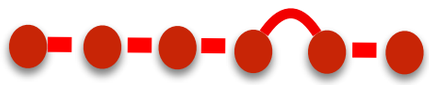
$y_0 >= 0 \wedge x_0 = 10000$

Constraint Solving





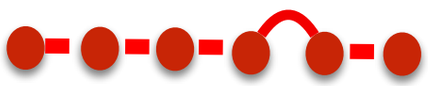
$y_0 >= 0 \wedge x_0 != 10000$



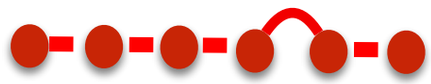
$y_0 >= 0 \wedge x_0 = 10000$

$y_0 = -1$

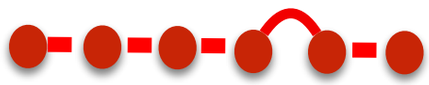
Constraint Solving



y_0=-1

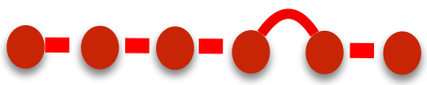


y_0>=0 ^ x_0 !=10000

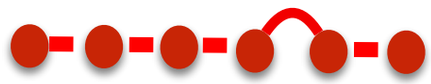


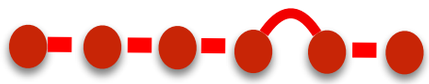
y_0>=0 ^ x_0 =10000

Constraint Solving



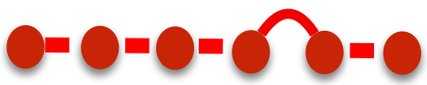
y_0=-1



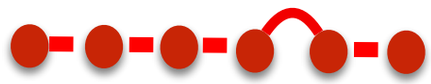


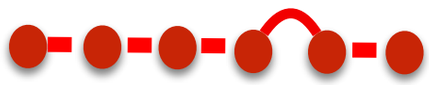
y_0>=0 ^ x_0 =10000

Constraint Solving



y_0=-1

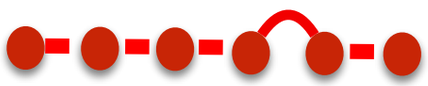




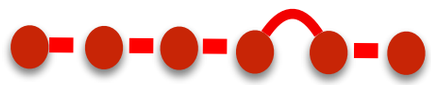
y_0>=0 ^ x_0 =10000

y_0=0, x_0 =0

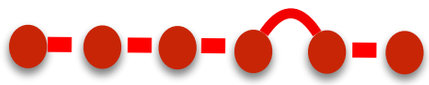
Constraint Solving



y_0=-1

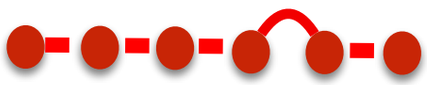


y_0=0, x_0 =0

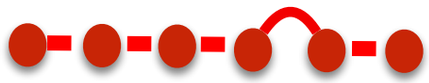


y_0>=0 ^ x_0 =10000

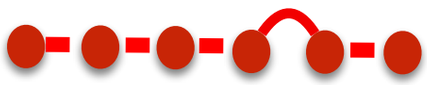
Constraint Solving



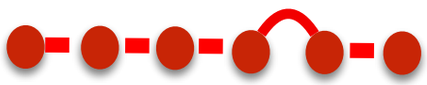
y_0=-1



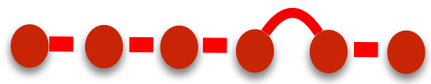
y_0=0, x_0 =0



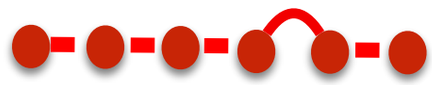
Constraint Solving



y_0=-1

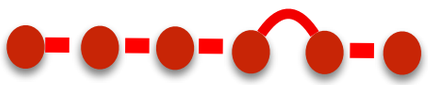


y_0=0, x_0 =0

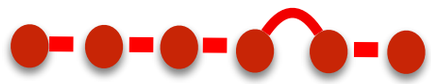


y_0=0, x_0 =10000

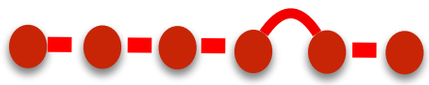
Constraint Solving



y_0=-1



y_0=0, x_0 =0



y_0=0, x_0 =10000

testme(0,-1)
testme(0,0)
testme(10000,0)

] generated 3 testcases from solver from SMT-solver

```
1. def testme(x, y):
2.   if (y<0):
3.       return -x
4.   else:
5.       z = x - y
6.       if (y+z=10000):
7.           raise Exception(“error”)
8.       else:
9.           return z
```

pseudocódigo pl generadores con

Ejecución Simbólica

```
execution_paths = compute_paths(cfg, limit).iterator()
Para cfg_path En execution_paths
  Si budget es no vacío
    path_condition = exec_symbolic(cfg_path)

    solution = solve(path_condition)

    Si solution is SAT:
      new_test = create_test(entry_f, solution)
      Agregar new_test a testSuite

retornar testSuite
```

```
@Test
public void testIsOdd0(int ) {
  boolean isOdd = isOdd(1);
  assertTrue(isOdd);
}
@Test
public void testIsOdd1() {
  boolean isOdd = isOdd(3);
  assertTrue(isOdd);
}
@Test
public void testIsOdd2() {
  boolean isOdd = isOdd(5);
  assertTrue(isOdd);
}
@Test
public void testIsOdd3() {
  boolean isOdd = isOdd(15);
  assertTrue(isOdd);
}
```

```
@Test
public void testIsOdd0(int ) {
  boolean isOdd = isOdd(1);
  assertTrue(isOdd);
}
@Test
public void testIsOdd1() {
  boolean isOdd = isOdd(3);
  assertTrue(isOdd);
}
@Test
public void testIsOdd2() {
  boolean isOdd = isOdd(5);
  assertTrue(isOdd);
}
@Test
public void testIsOdd3() {
  boolean isOdd = isOdd(15);
  assertTrue(isOdd);
}
```

Test Scenario

Test Data

Test Assertions

Parameterized Unit Tests (PUTs)

```
@ParameterizedTest
@ValueSource(ints = {1,3,5,15})
public void testIsOdd(int x) {
  boolean isOdd = isOdd(x);
  assertTrue(isOdd);
}
```

1 test code multiple data

searched via symbolic execution & SMT test generation constraint solver

SYMBOLIC EXEC → allows to create paths that are used by constraint solver to assign test data values.

Parameterized Unit Tests (PUTs)

```
@ParameterizedTest
@ValueSource(ints = {1,3,5,15})
public void testIsOdd(int x) {
  boolean isOdd = isOdd(x);
  assertTrue(isOdd);
}
```

- Los PUTs separan 2 dimensiones:

Parameterized Unit Tests (PUTs)

```
@ParameterizedTest
@ValueSource(ints = {1,3,5,15})
public void testIsOdd(int x) {
  boolean isOdd = isOdd(x);
  assertTrue(isOdd);
}
```

- Los PUTs separan 2 dimensiones:
  - Especificación del comportamiento esperado (assertions)

Parameterized Unit Tests (PUTs)

```
@ParameterizedTest
@ValueSource(ints = {1,3,5,15})
public void testIsOdd(int x) {
  boolean isOdd = isOdd(x);
  assertTrue(isOdd);
}
```

- Los PUTs separan 2 dimensiones:
  - Especificación del comportamiento esperado (assertions)
  - Selección de datos de test relevantes (coverage)

Parameterized Unit Testing

- Varios test frameworks soportan Parameterised Unit Tests (PUTs):
  - .NET: Soportado por MBUnit, NUnit
  - Java: Soportado a partir de JUnit 4.X
- Existen tools para generar test inputs para PUTs:
  - .NET: Microsoft Visual Studio
  - Java: AgitarOne (http://www.agitar.com)

Parameterized Unit Tests + Ejecución Simbólica

- Podemos pensar al PUT como el entry point de la generación de tests con ejecución simbólica
- Todos los argumentos tienen que ser soportados por el constraint solver (ej: enteros, reales, strings)
- La generación de casos de tests **no crea secuencias de invocaciones a métodos** como lo hace Random Testing Orientado a Objetos

Parameterized Unit Tests

```
@ParameterizedTest
public static void p_test2(int valueX, int valueY) {
  Adder adder = new Adder();
  int rv = adder.performAction(valueX, valueY);
  int expectedValue = valueX + valueY;
  assertEquals(expectedValue, rv);
}
```

Parameterized Unit Tests

```
@ParameterizedTest
public static void p_test2(int[] array) {
  assumeTrue(array!=null); // pre
  sort(array);
  assertTrue(isSorted(array)); // post
}
```

Parameterized Unit Tests

```
@ParameterizedTest
public static void p_test1(int i0, int i1, int i2) {
  RBTree root = new RBTree();
  root.insert(i0);
  root.insert(i1);
  root.insert(i2);
  assertTrue(root.contains(i0));
  assertTrue(root.contains(i1));
  assertTrue(root.contains(i2));
}
```

PUTs: Inputs Integer

```
@ParameterizedTest
public static void p_test2(int len, int a1, int a2) {
   assumeTrue(len>1); // pre
   MiniStack s = new MiniStack(len);
   s.push(a1);
   s.push(a2);
   assertTrue(s.contains(a1);
   assertTrue(s.contains(a2));
   assertTrue(s.isNotEmpty());
}
```

determina QUÉ es lo que se puede saber del dominio con el constraint solver.

Constraint Language Expresiones Enteras

- Dado un programa que opera con enteros, ¿qué expresiones puedo llegar a tener?

```
public int add(int x, int y) {
   if (x==0) {
     Return y;
   } else {
      int temp = x+y;
      return temp;
   }
}
```

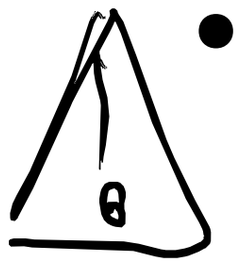
- Expresiones enteras: x+y, Condicionales: x==0

ejemplo del dominio del lenguaje.

Expresiones Enteras

- Expresiones Enteras:
  - Literales: 0,1,2,…
  - Variables Enteras: var0, var1, var
  - Operaciones: E+E, E-E, E*E, E/E, E%E
- Fórmulas:
  - E==E, E!=E, E>E,E>=E,E<E,E<=E

Expresiones Enteras



- Necesitamos un constraint solver que soporte todas las expresiones enteras (y sus fórmulas) para poder resolver constraints enteras

Constraint Language Expresiones Enteras

Var0>0
Var0<Var1
Var1<Var2
Var3==Var2

Var0: 10
Var1: 11
Var2: 12
Var3: 12

PUTs: Inputs String

```
@ParameterizedTest
public static void p_test3(String id, String
emailAddress) {
  assumeTrue(id!=null);
  assumeTrue(emailAddress!=null);
  assumeTrue(isValid(emailAddress));
  Customer s = new Customer(id);
  s.setEmailAddress(emailAddress);
  assertTrue(s.hasValidEmailAddress());
}
```

PUTs: Inputs String

- Dado un programa que opera con strings, ¿qué expresiones puedo llegar a tener?

```
public int checkId(String id) {
  If (id.startWith(“hello”)
      Return 1;
  } else if (id.endsWith(“world”) {
      Return 2;
  } else {
      String s = id.toLowerCase();
      Return s.equals(“hola mundo”);
  }
}
```

Constraint Language
Cadenas de Strings

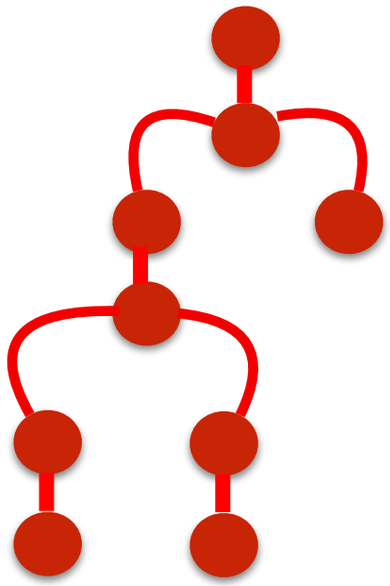
- Expresiones sobre Strings:
  - Valores literales: “”, “A”, “B”, …
  - Variables string: var0, var1, var
  - Expresiones: E+E, E.substring(int,int), etc.
- Constraints:
  - E.equals(E), !E.equals(E), E.contains(E), etc

Constraint Language
Cadenas de Strings

Var0.endsWith(“Mundo”)
Not equals(Substring(Var0,0,4),”Hola”)
EqualsIgnoreCase(Substring(Var0,0,4),”Hola”)

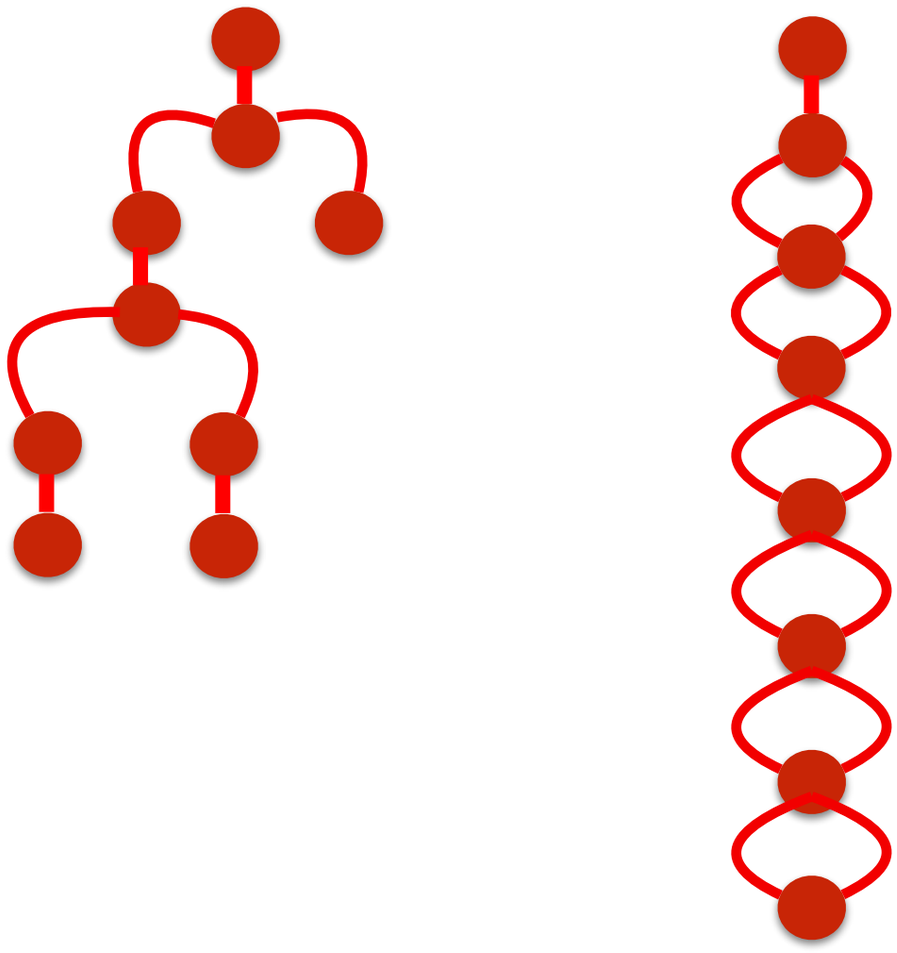
Var0: “holA Mundo”

Ejecución Simbólica: Limitaciones



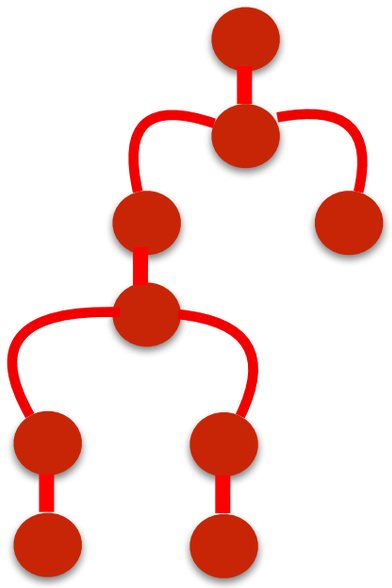
3 caminos

Ejecución Simbólica: Limitaciones

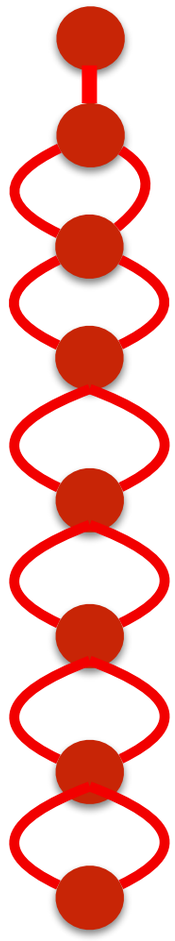


3 caminos

Ejecución Simbólica: Limitaciones

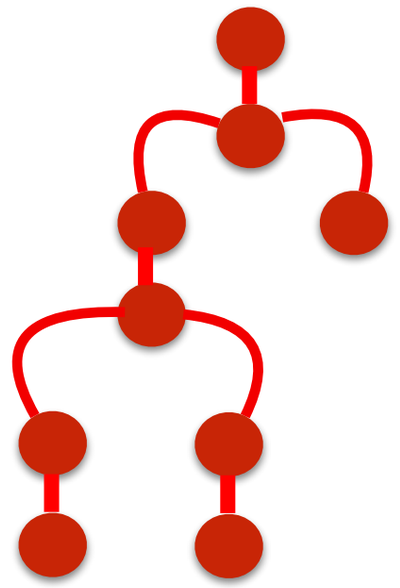


3 caminos

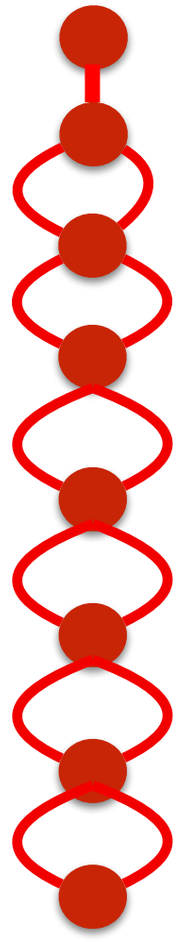


2^n caminos

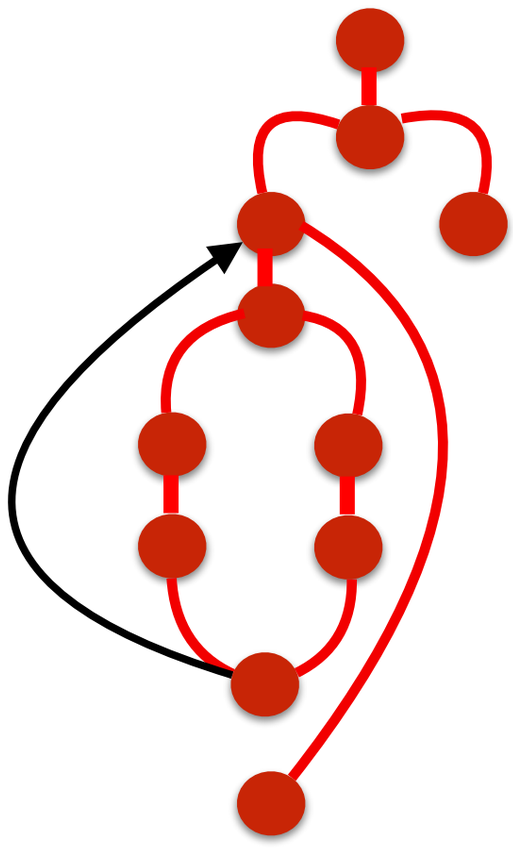
Ejecución Simbólica: Limitaciones



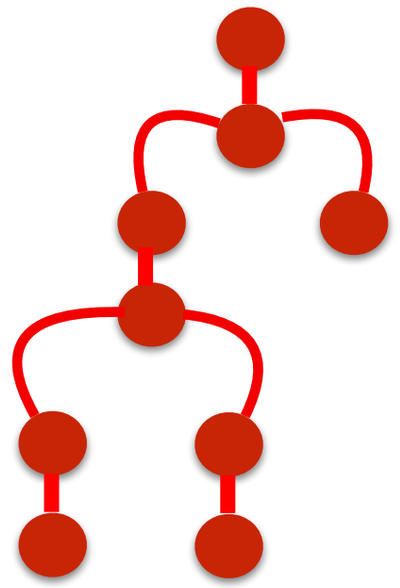
3 caminos



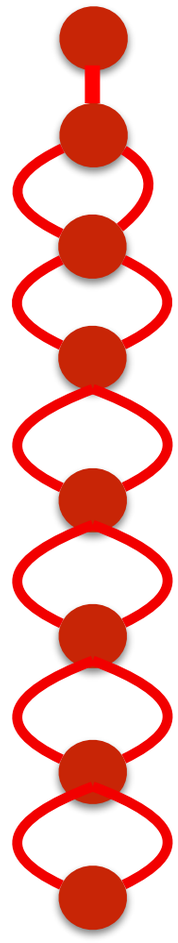
2^n caminos



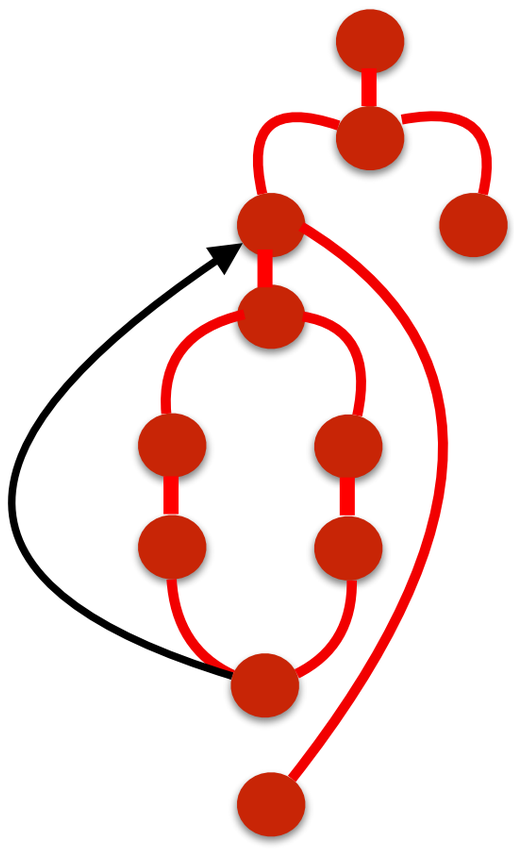
Ejecución Simbólica: Limitaciones : #cauuilon



3 caminos



2^n caminos



¡Infinitos caminos!

Ejecución Simbólica: Limitaciones

: complejidad de exploración

```
1. def nonlinear(x, y, z):
2.   if (x%y*z=42):
3.     raise Exception(“error”)
4.   else:
5.     return hash_str
```

```
1. def hashing(x, y):
2.   m = hashlib.md5()
3.   m.update(x)
4.   hash_str = m.hexdigest()
5.   if (y==hash_str):
6.     raise Exception(“error”)
7.   else:
8.     return hash_str
```

Ejecución Simbólica: Limitaciones

```
1. def nonlinear(x, y, z):
2.   if (x%y*z=42):
3.     raise Exception(“error”)
4.   else:
5.     return hash_str
```

```
1. def hashing(x, y):
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4.   hash_str = m.hexdigest()
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```

Requiere aritmética No-lineal

Ejecución Simbólica: Limitaciones

```
1. def nonlinear(x, y, z):
2.   if (x%y*z=42):
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```

Requiere aritmética No-lineal

```
1. def hashing(x, y):
2.   m = hashlib.md5()
3.   m.update(x)
4.   hash_str = m.hexdigest()
5.   if (y==hash_str):
6.     raise Exception(“error”)
7.   else:
8.     return hash_str
```

Limitaciones intrínsecas de constraint solving

Ejecución Simbólica: Limitaciones

- Explosión combinatoria (o incluso infinita) de caminos en el CFG para evaluar
- Limitaciones del Constraint Solving
  - String handling, aritmética no-lineal, aritmética de punto flotante, etc.
  - Problemas NP-completos
- Información en Runtime (files, sockets, native code, etc.)

Ejecución Simbólica: Limitaciones

- Hay una cantidad combinatoria de caminos en el CFG
- Muchos de esos caminos pueden ser irrealizables
- ¿Hay algún modo de guiar la selección de caminos para realizar la ejecución simbólica?

Caminos no satisfacibles

```
public User createUser(final String id) {
    If (id!=null && id.contains(“User”)) {
     …
    }
    doSomething();
    If (id!=null && id.contains(“User”)) {
      …
    }
    Return … //
}
```

- ¿Puede existir un camino de ejecución que entre al primer if y no entre al segundo if?

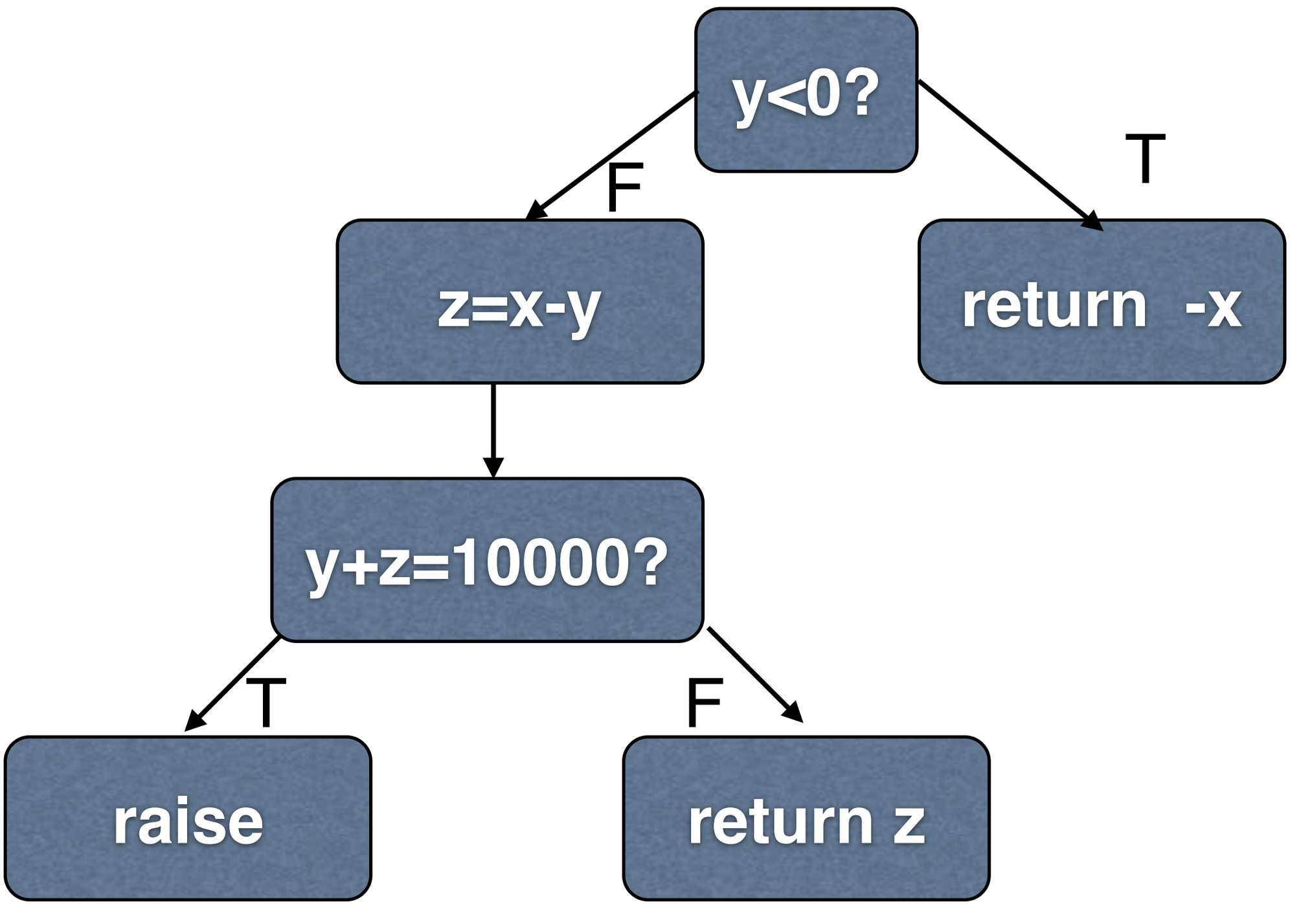
Información de Runtime

```
URL url = new URL(“http://www.something.com");
is = new InputStreamReader(url.openStream())
br = new BufferedReader(is);
line = br.readLine();
If line.equals(…) {
  // do something
} else {
  // do something else
}
```

Symbolic Exec → po over paths & pc values.

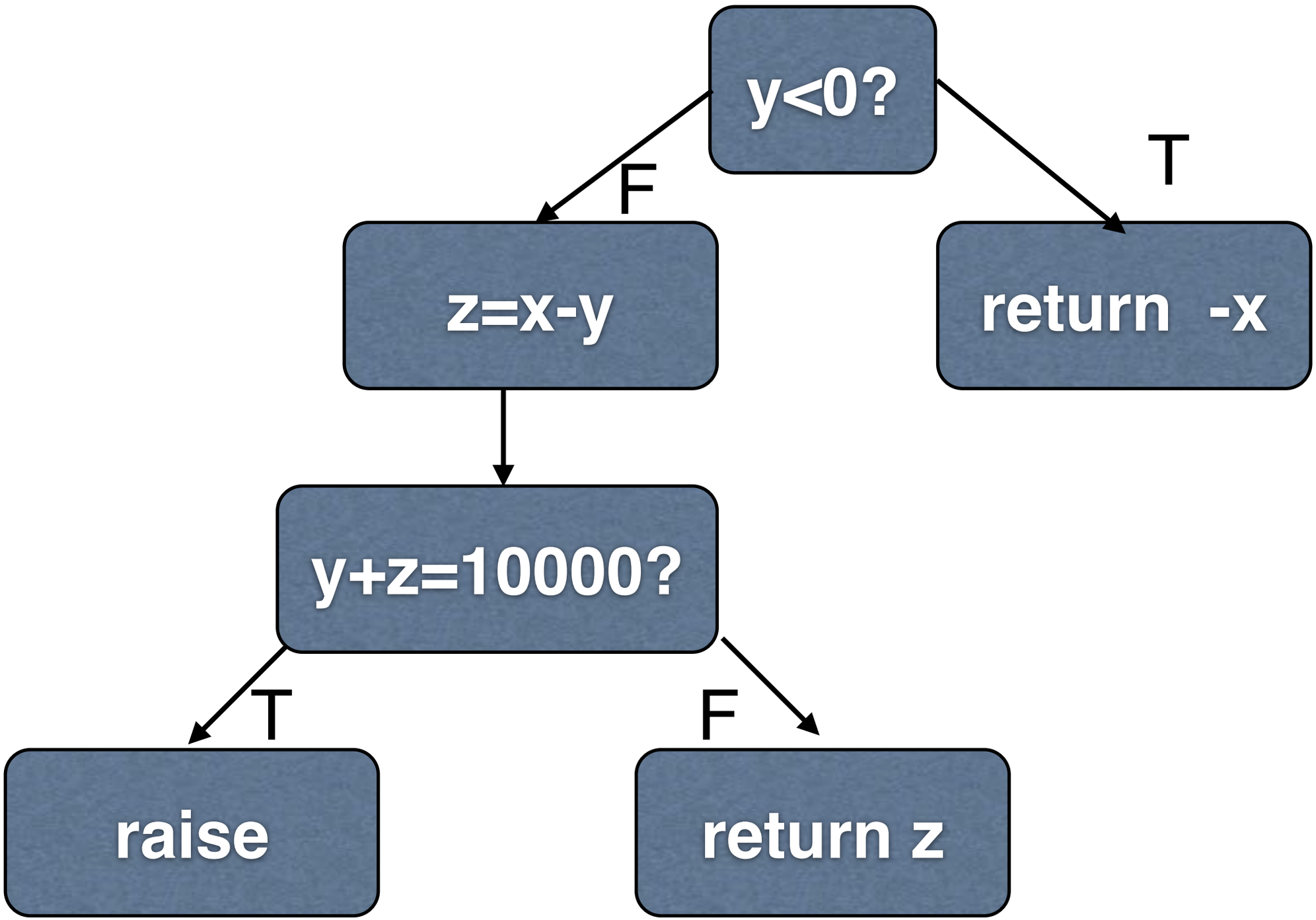
vs

Ejecución Simbólica Dinámica

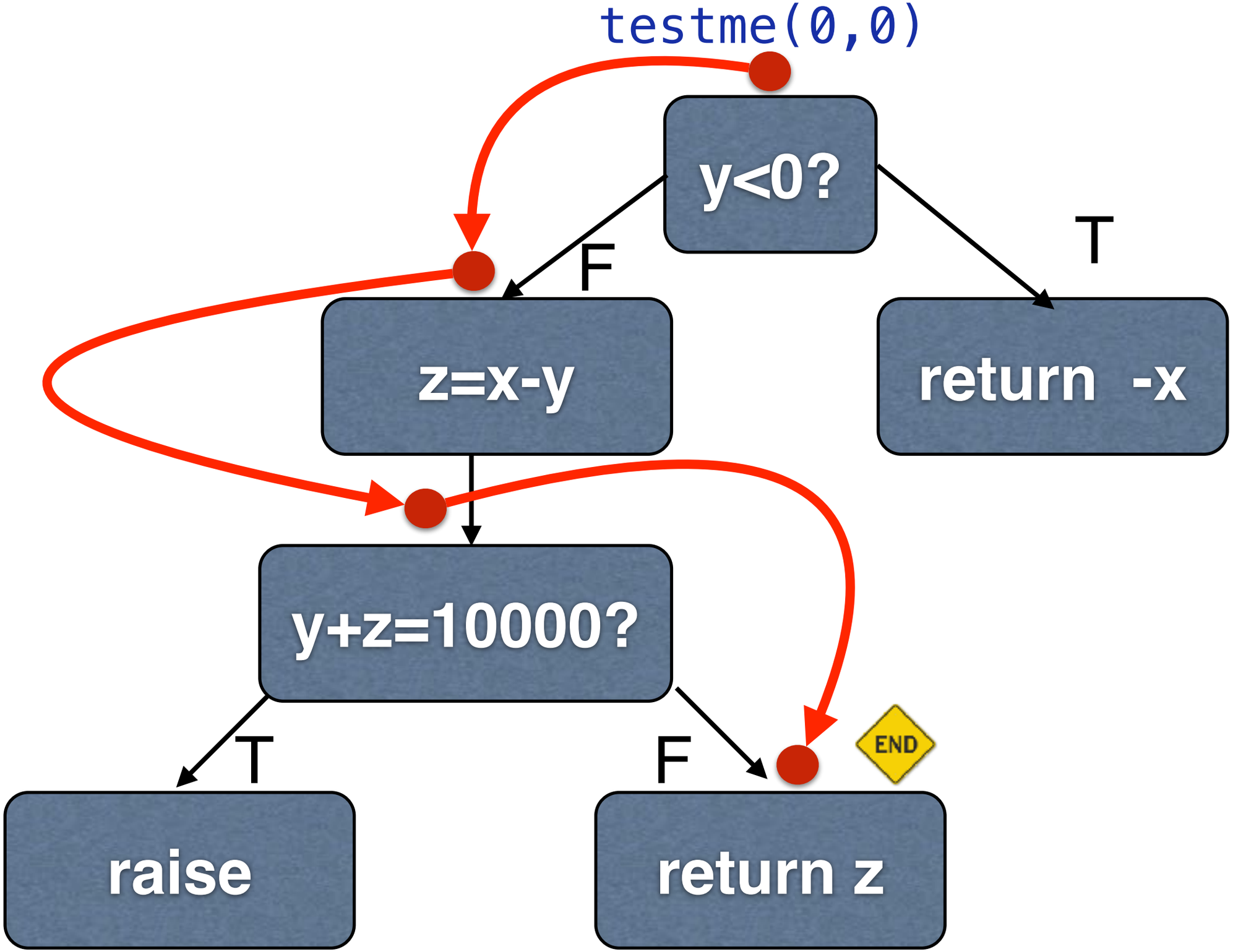


Ejecución Simbólica Dinámica

```
testme(0,0)
```

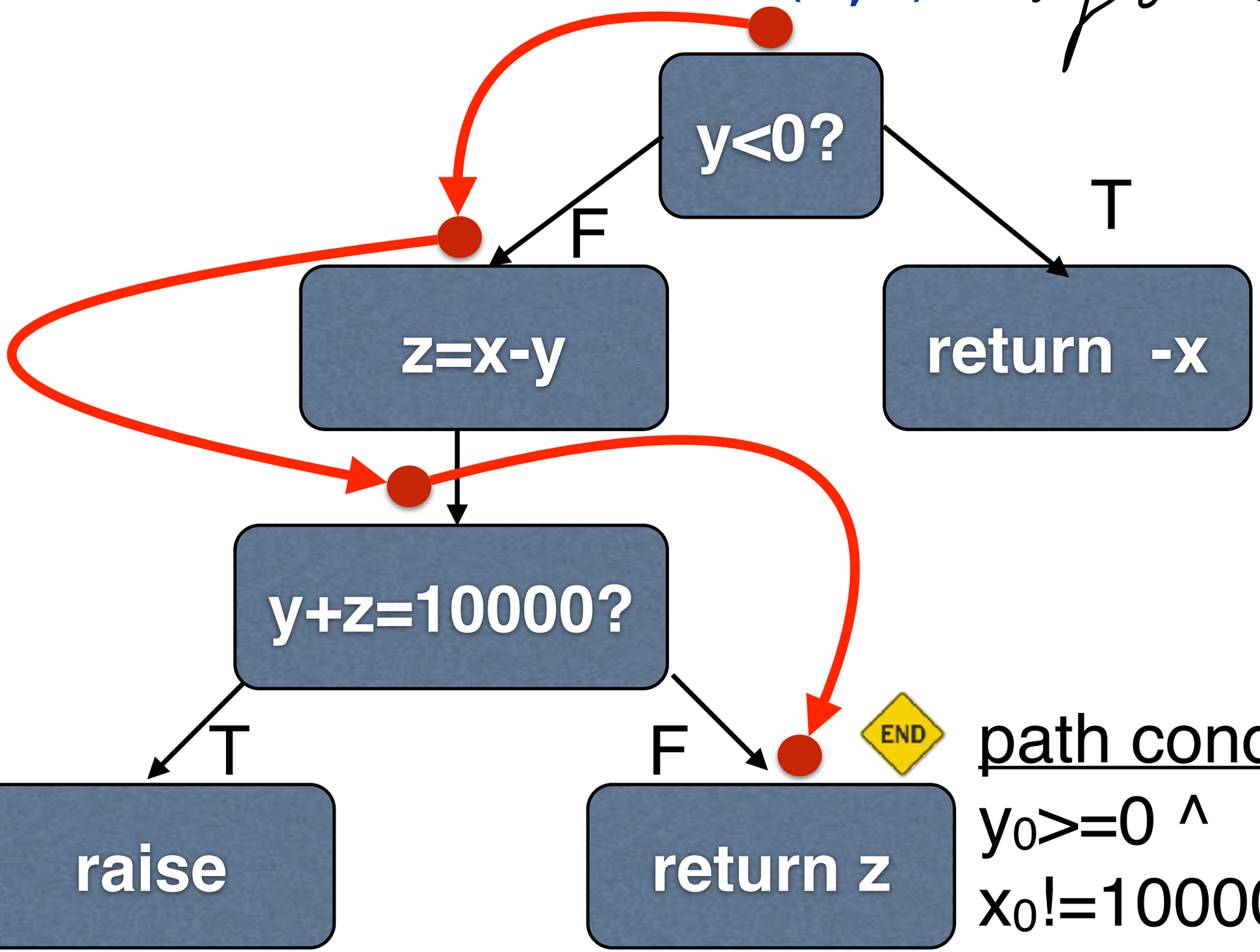


Ejecución Simbólica Dinámica



Ejecución Simbólica Dinámica

testme(0,0) → primer test

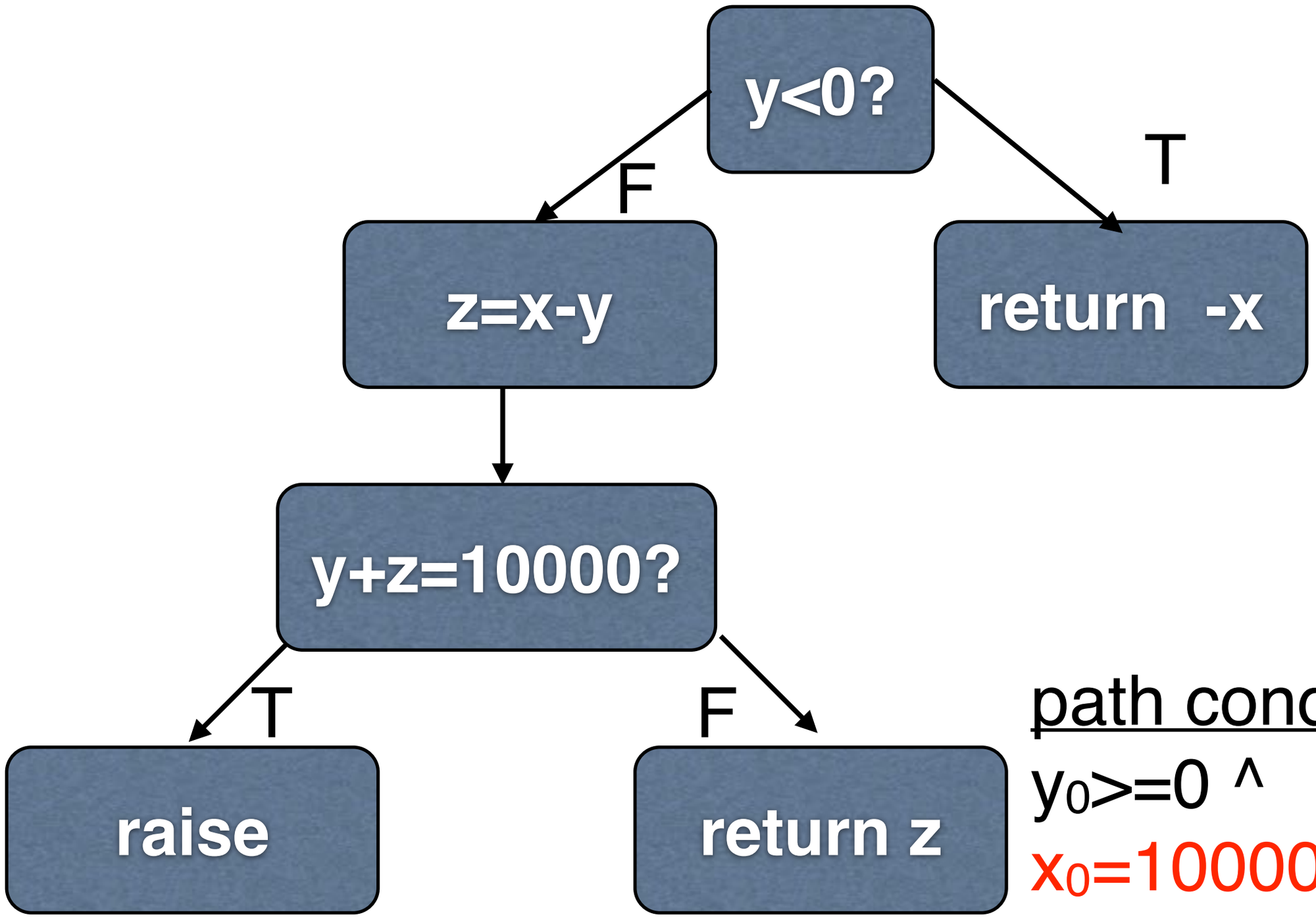


path condition:

$y_0 >= 0$ ^

$x_0 != 10000$

Ejecución Simbólica Dinámica

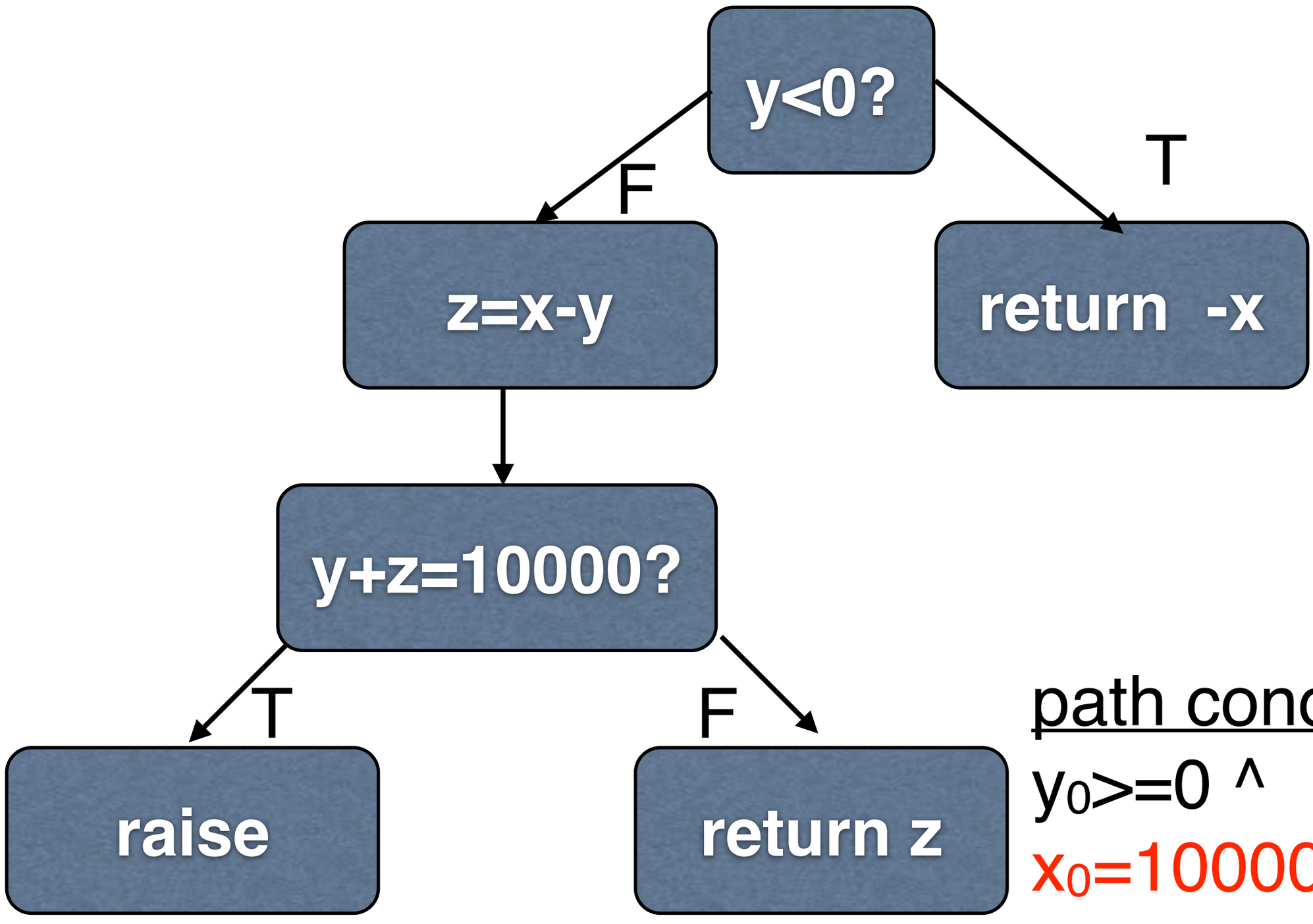


path condition:

$y_0 >= 0$ ^

$x_0 = 10000$

Ejecución Simbólica Dinámica



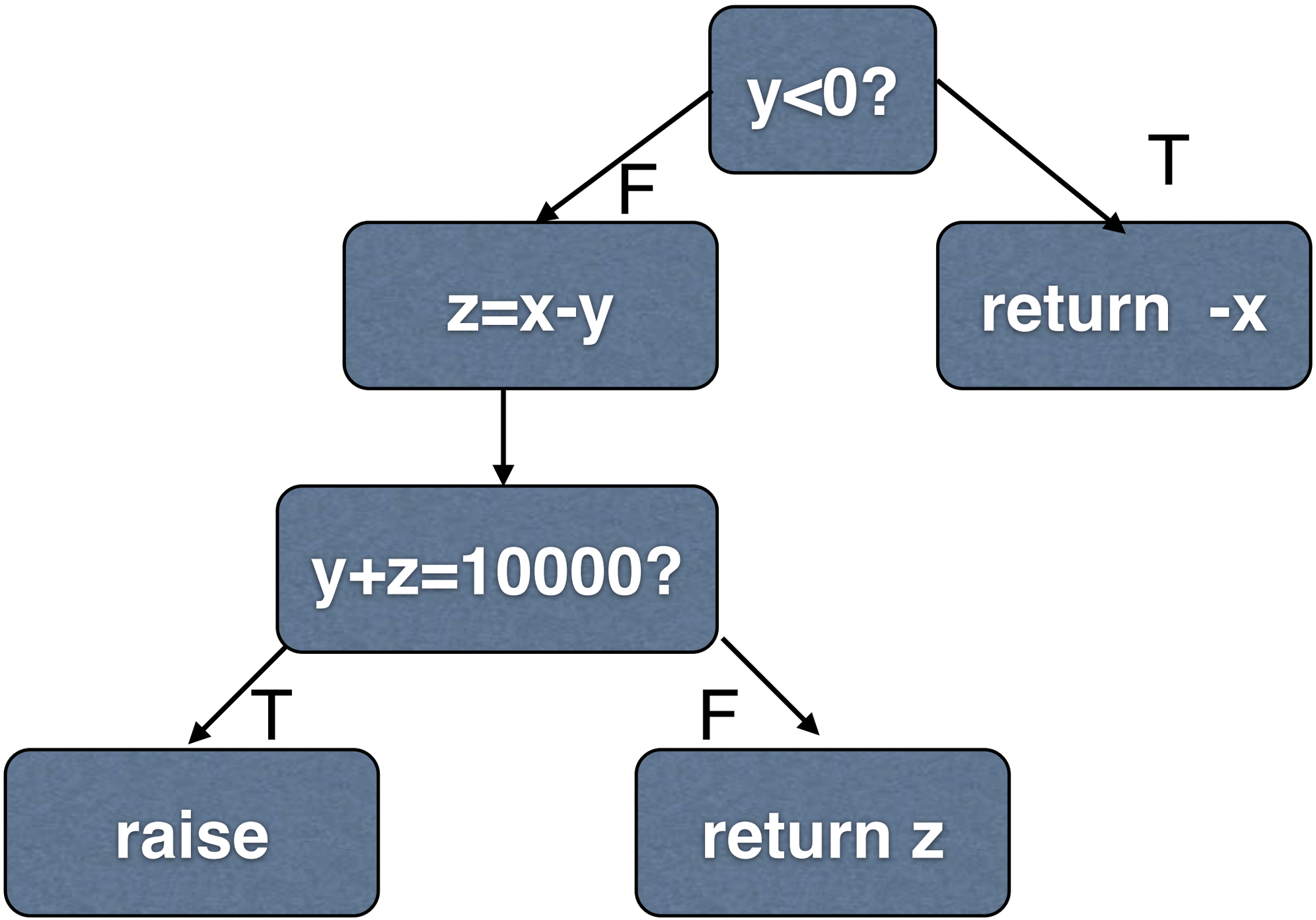
path condition:

$y_0 >= 0$ ^

$x_0 = 10000$

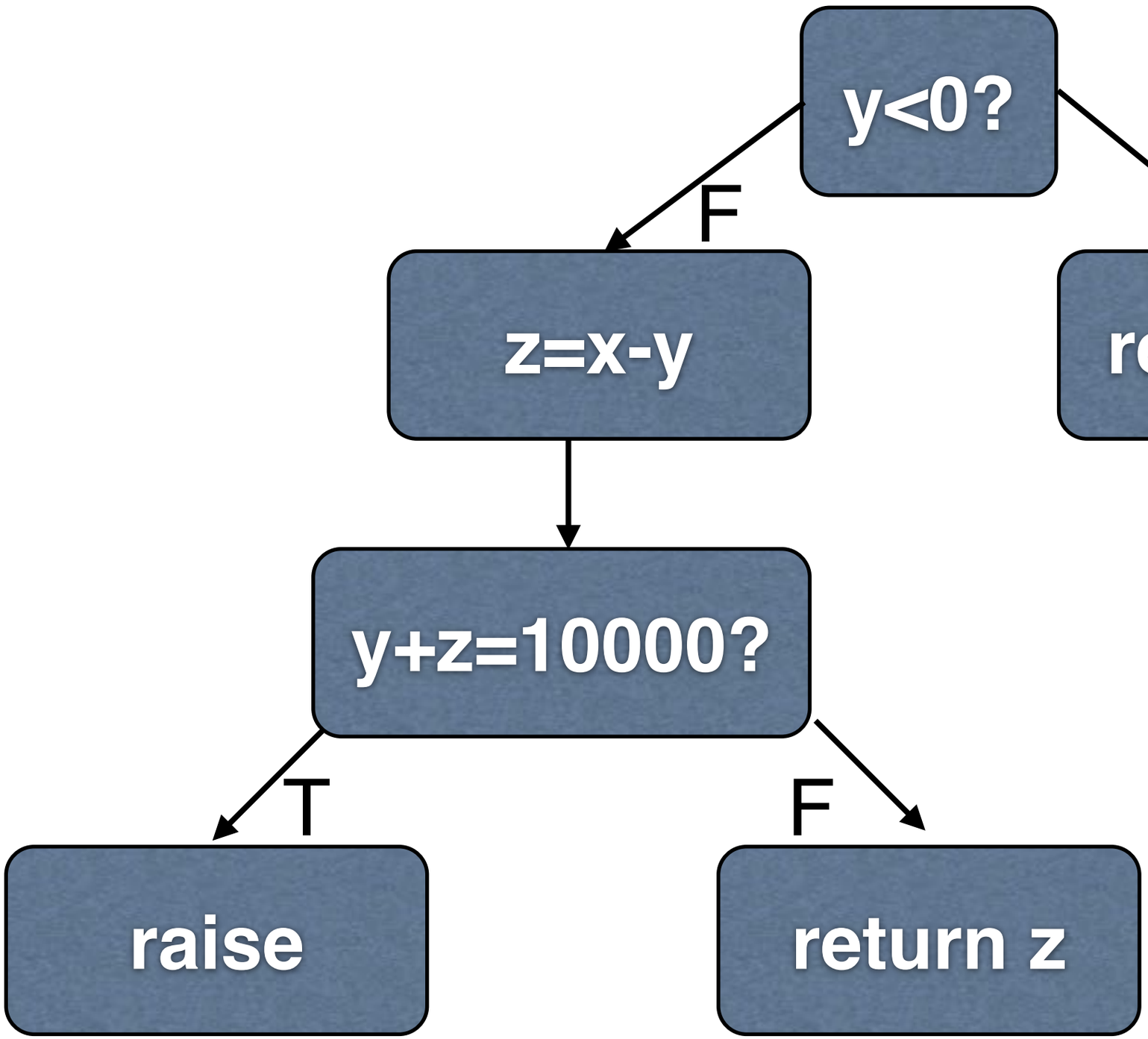
we want to go to the closest uncovered path → negate closest path condition addition

Ejecución Simbólica Dinámica

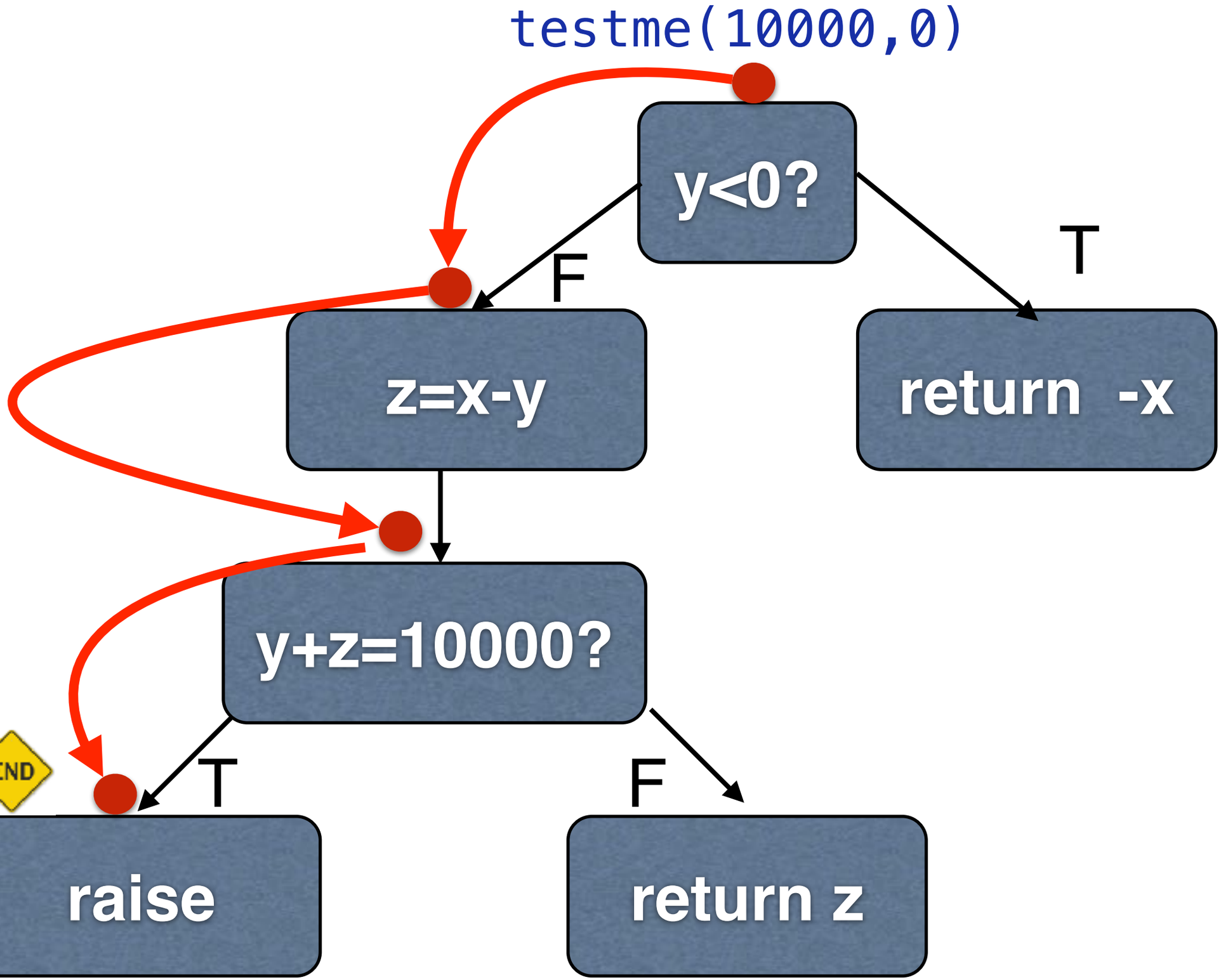


Ejecución Simbólica Dinámica

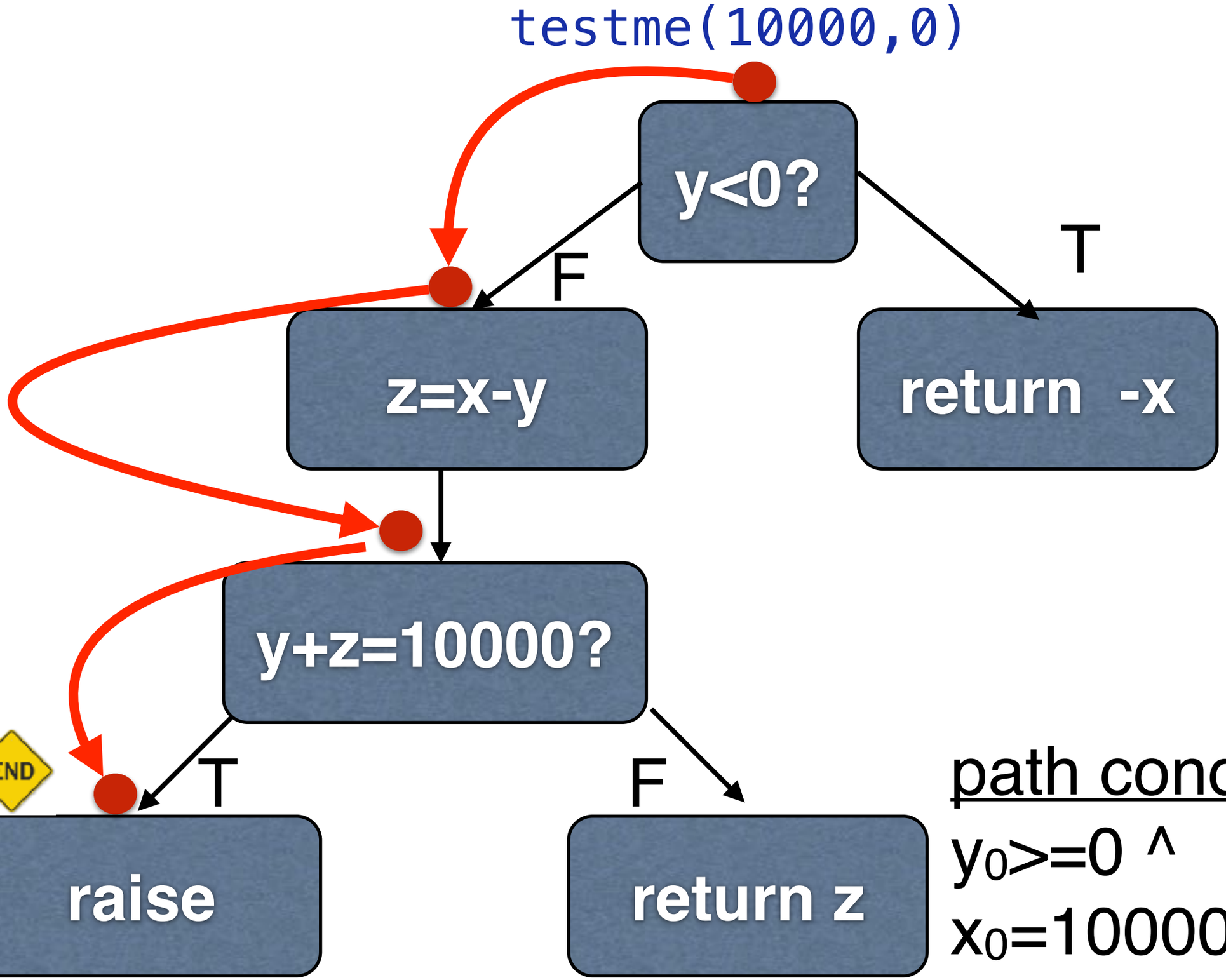
```
testme(10000,0)
```



Ejecución Simbólica Dinámica



Ejecución Simbólica Dinámica

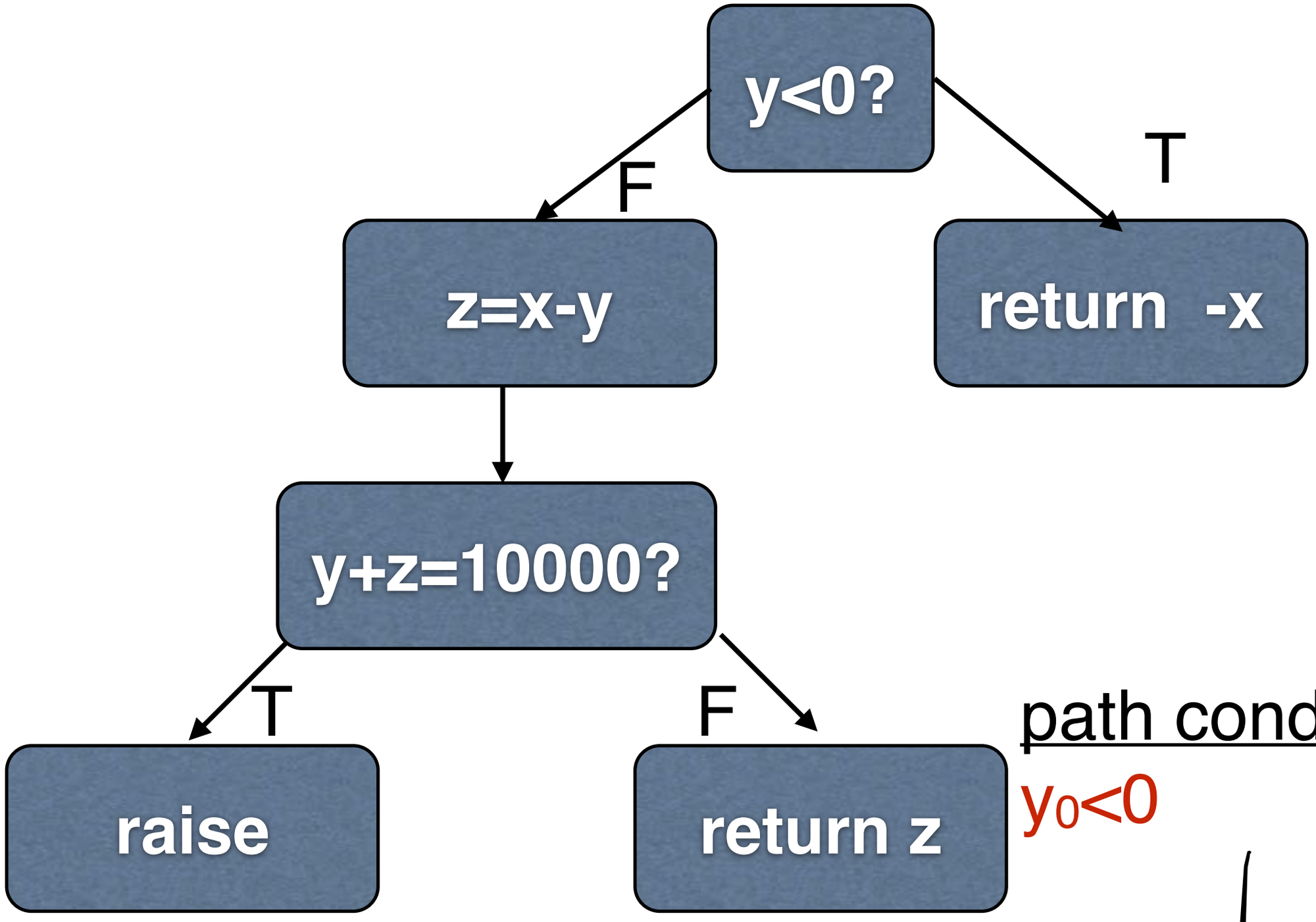


path condition:

$y_0 >= 0$ ^

$x_0 = 10000$

Ejecución Simbólica Dinámica



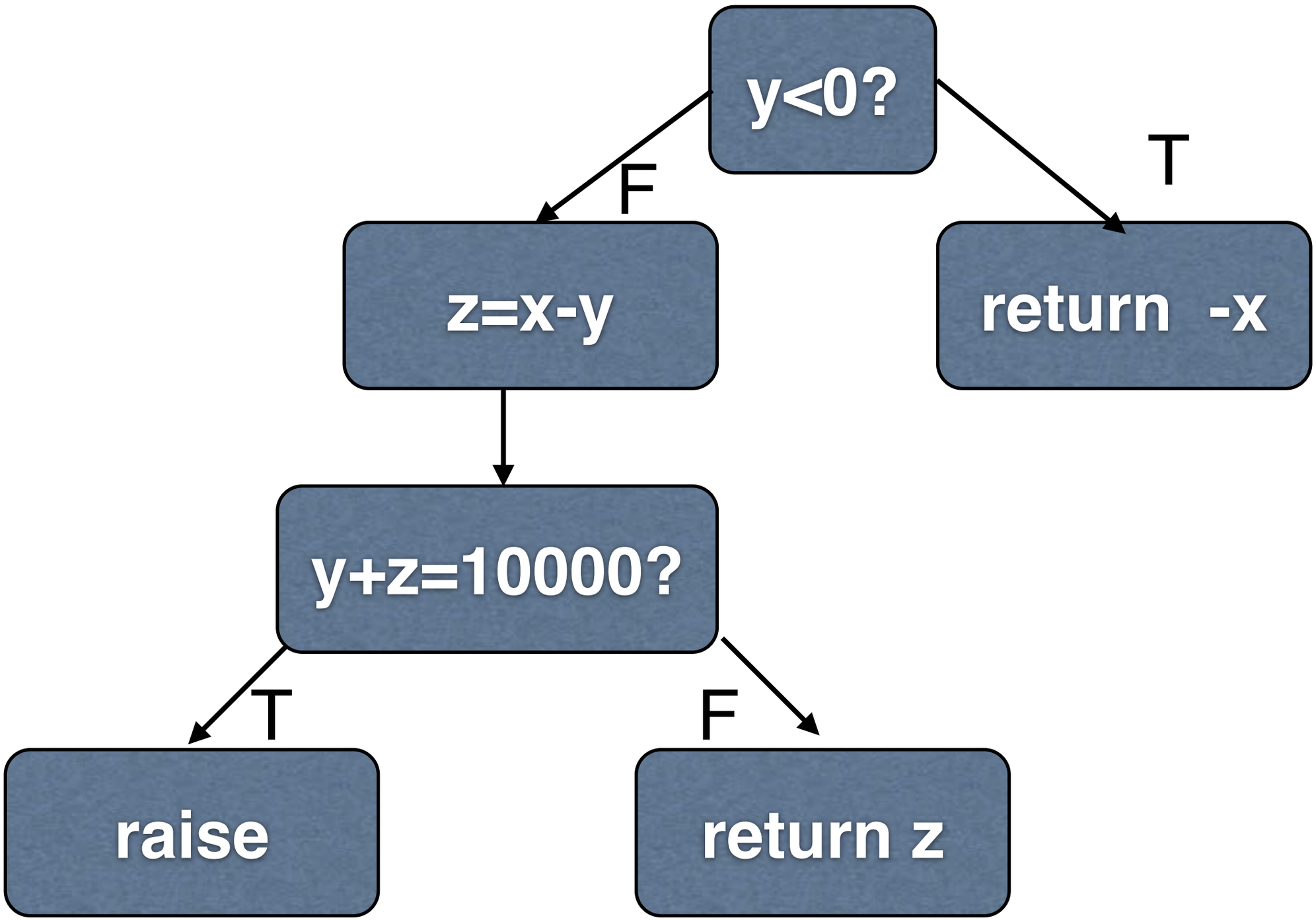
path condition:

$y_0 < 0$

removed & negated last cond

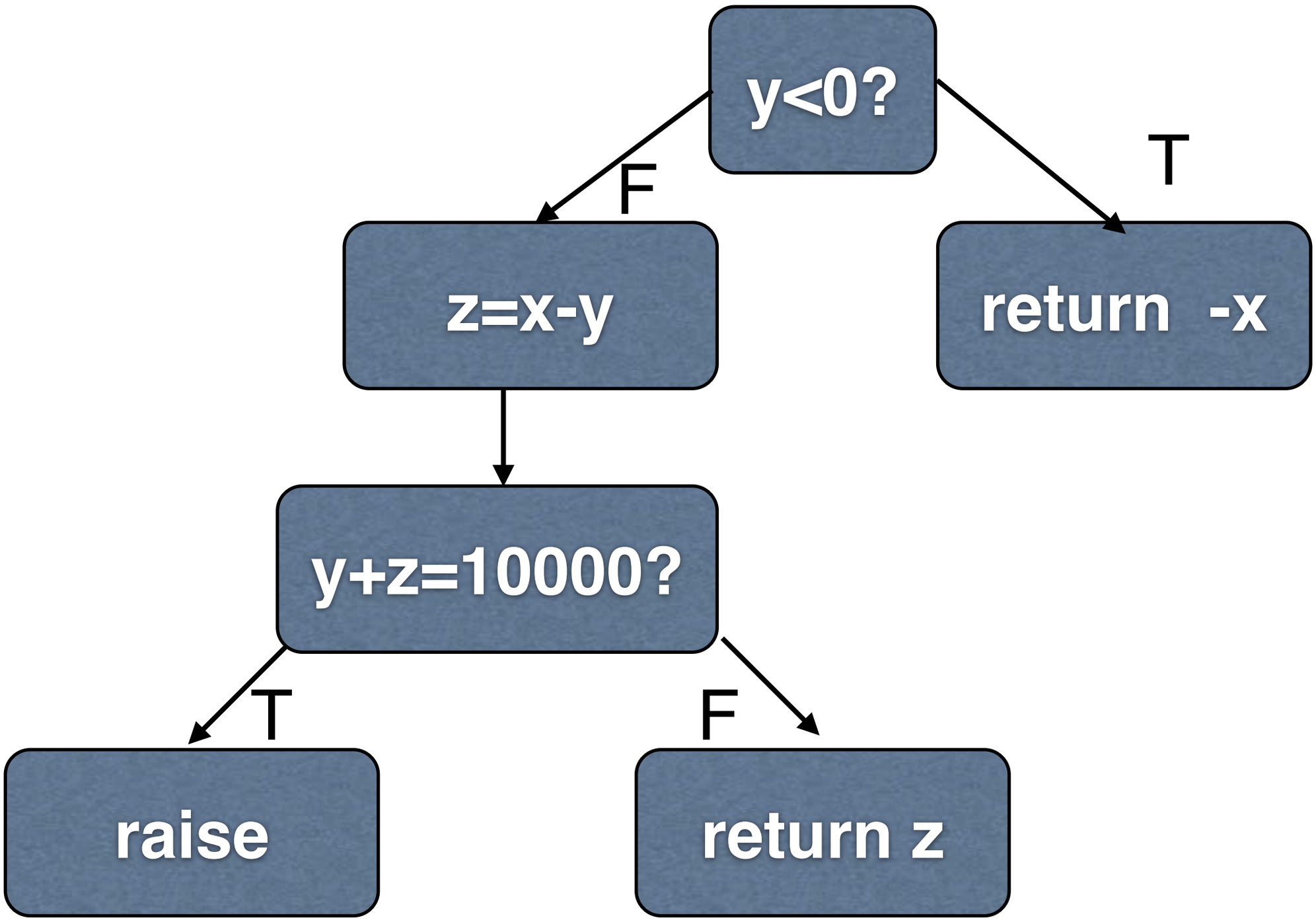
reordering condition

Ejecución Simbólica Dinámica

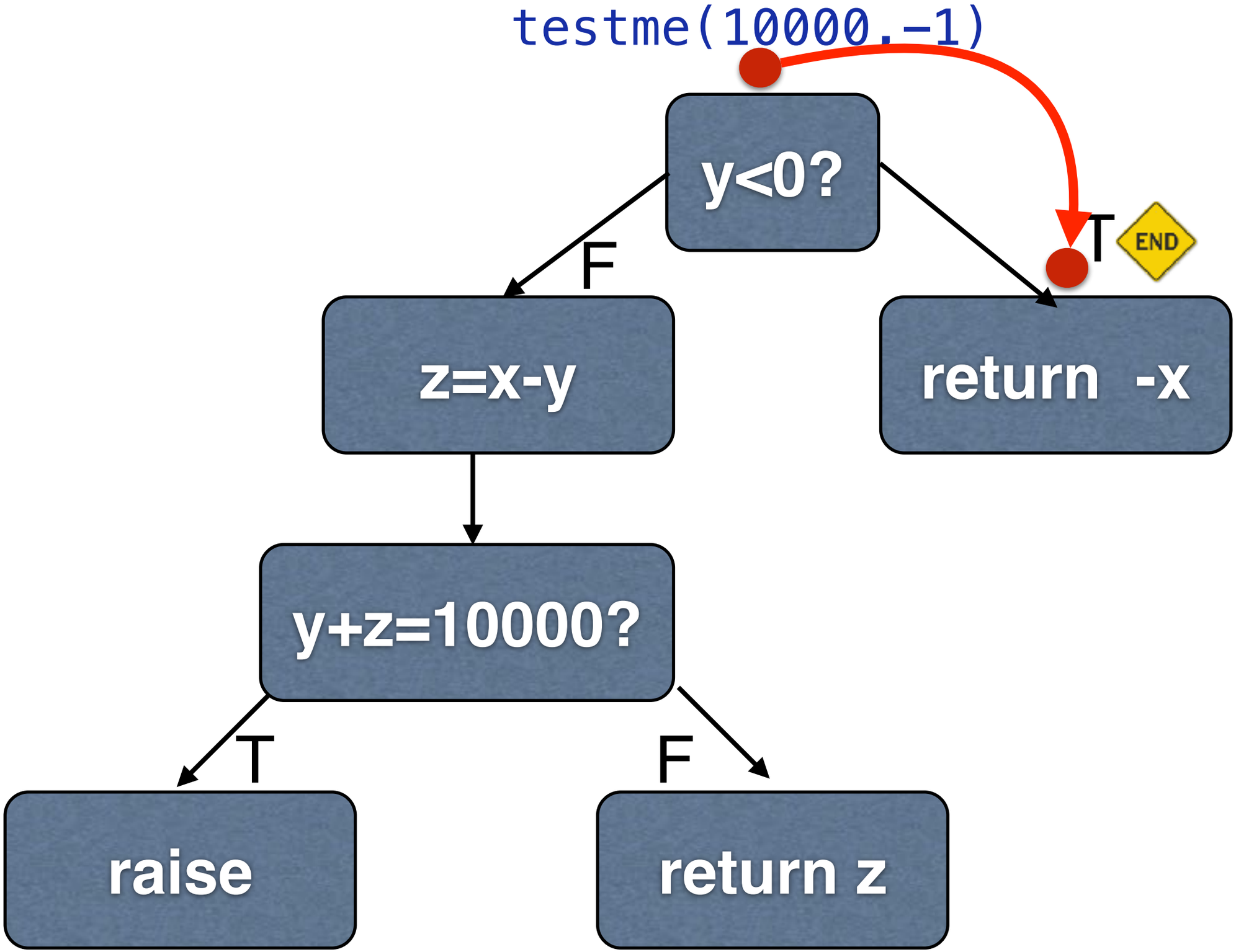


Ejecución Simbólica Dinámica

```
testme(10000,-1)
```



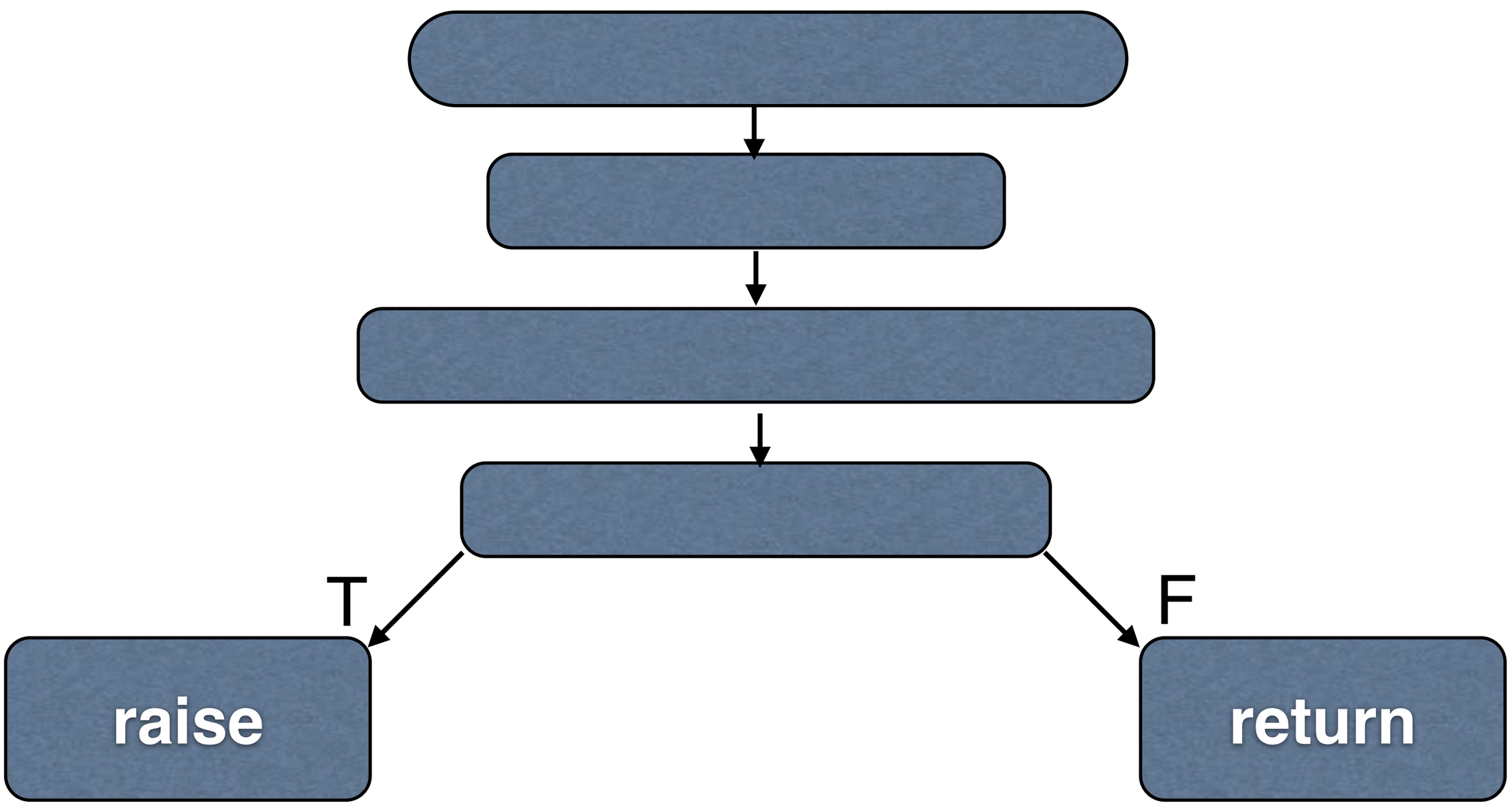
Ejecución Simbólica Dinámica



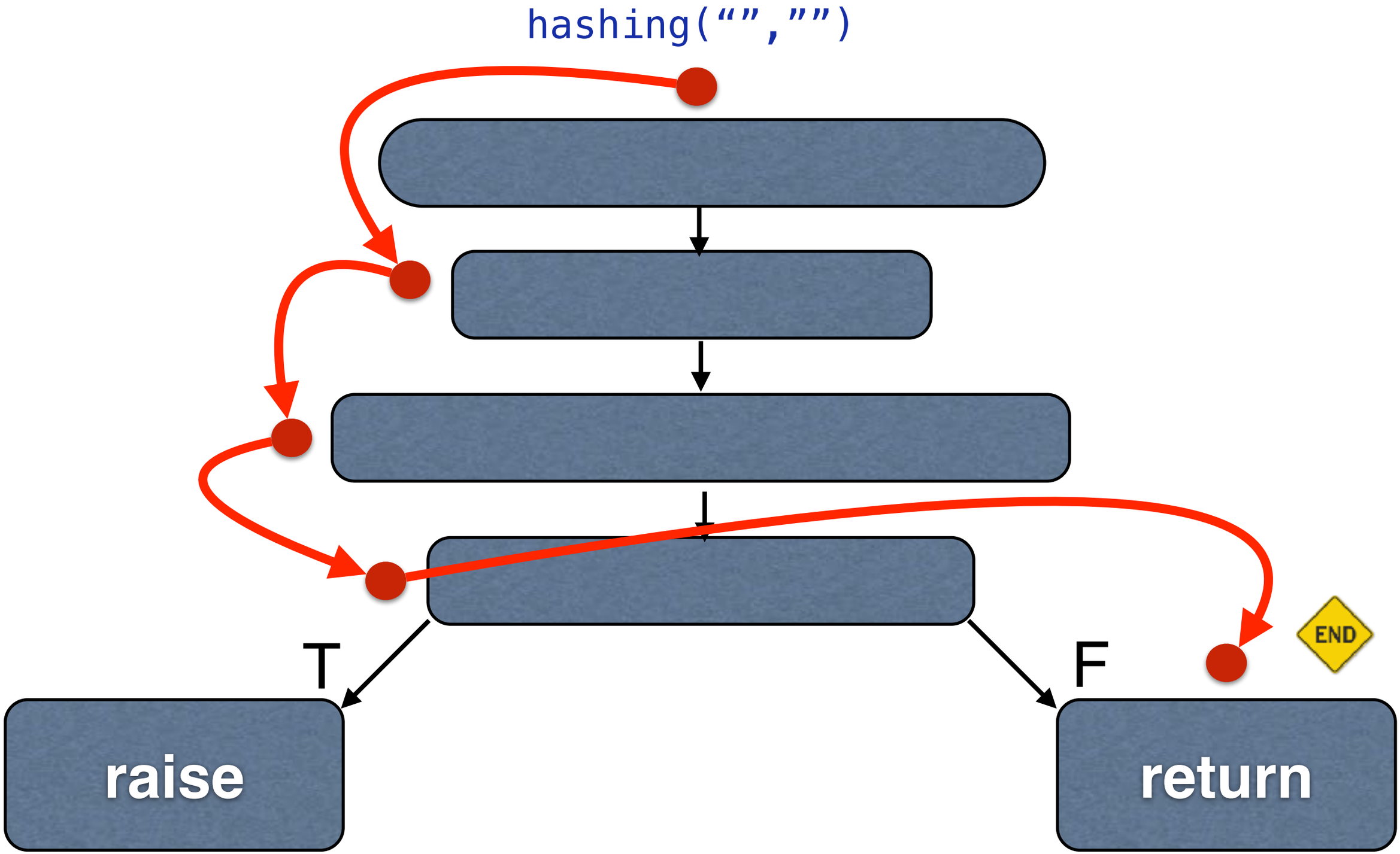
Ejecución Simbólica Dinámica

```
1. def hashing(x, y):
2.   m = hashlib.md5()
3.   m.update(x)
4.   hash_str = m.hexdigest()
5.   if (y==hash_str):
6.     raise Exception(“error”)
7.   else:
8.     return hash_str
```

Ejecución Simbólica Dinámica

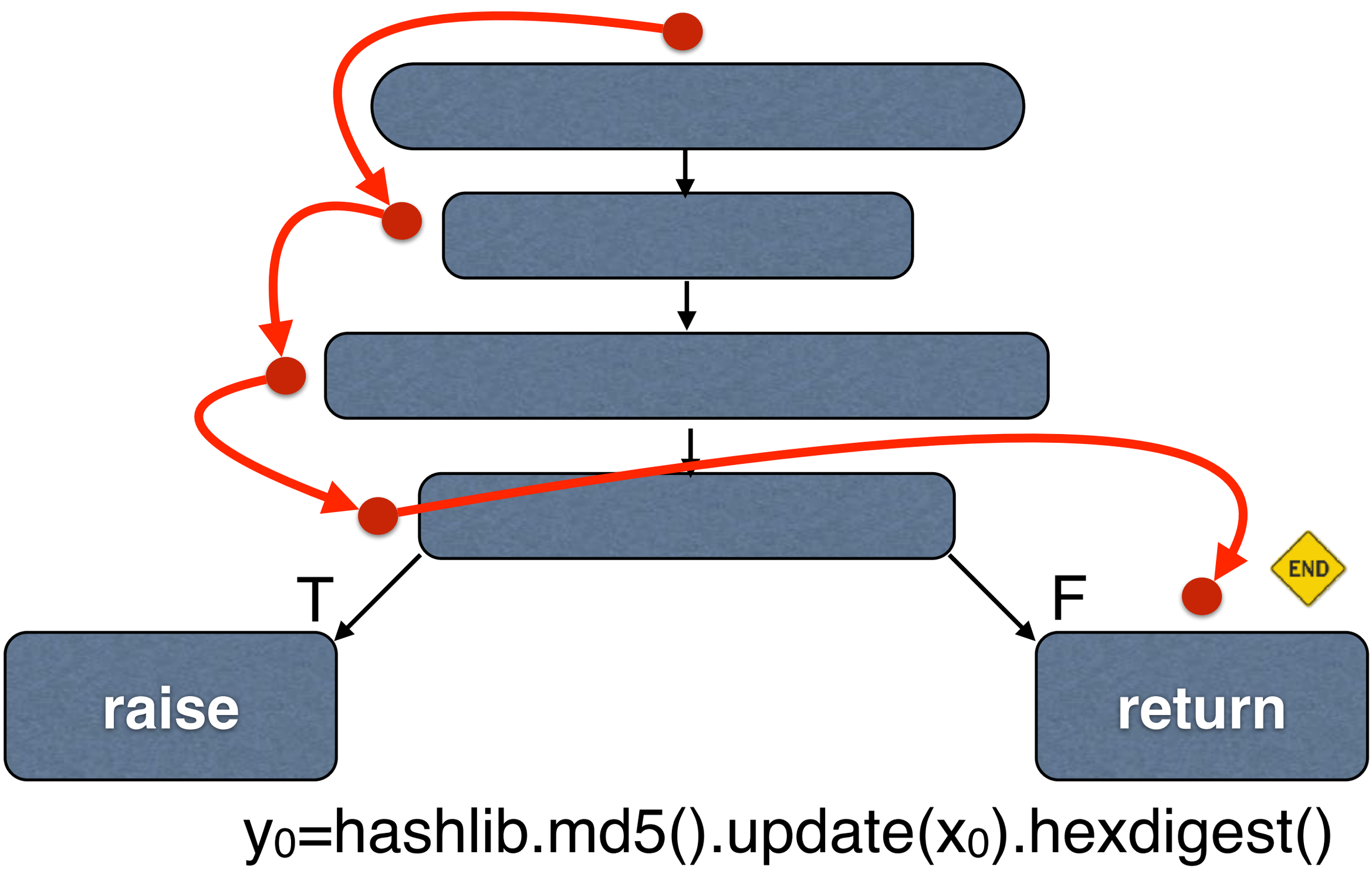


Ejecución Simbólica Dinámica



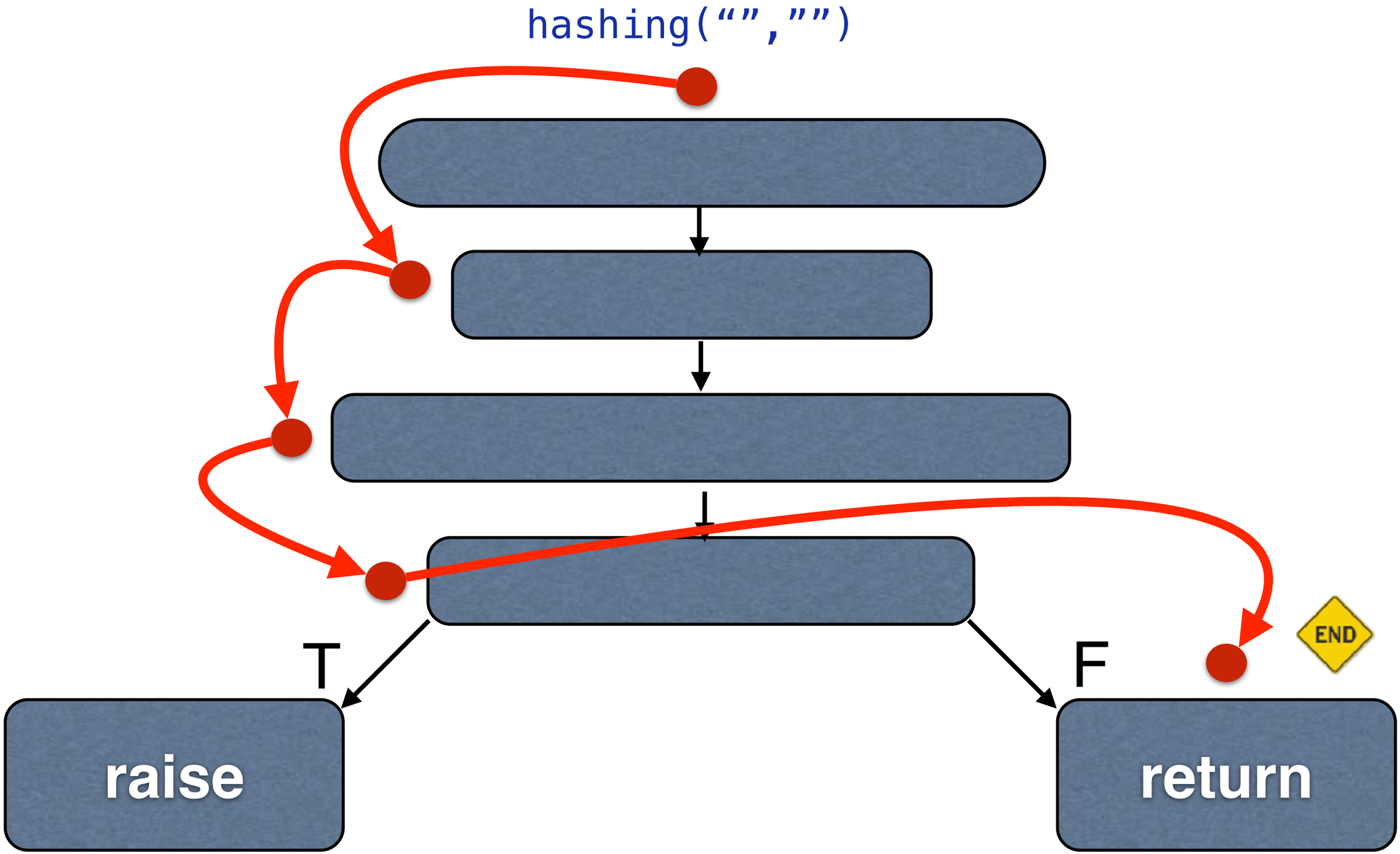
ejecución simbólica se hace al mismo tiempo que ejecución concreta. (CONCOLIC = CONcrete + SYMBOLIC)

Ejecución Simbólica Dinámica

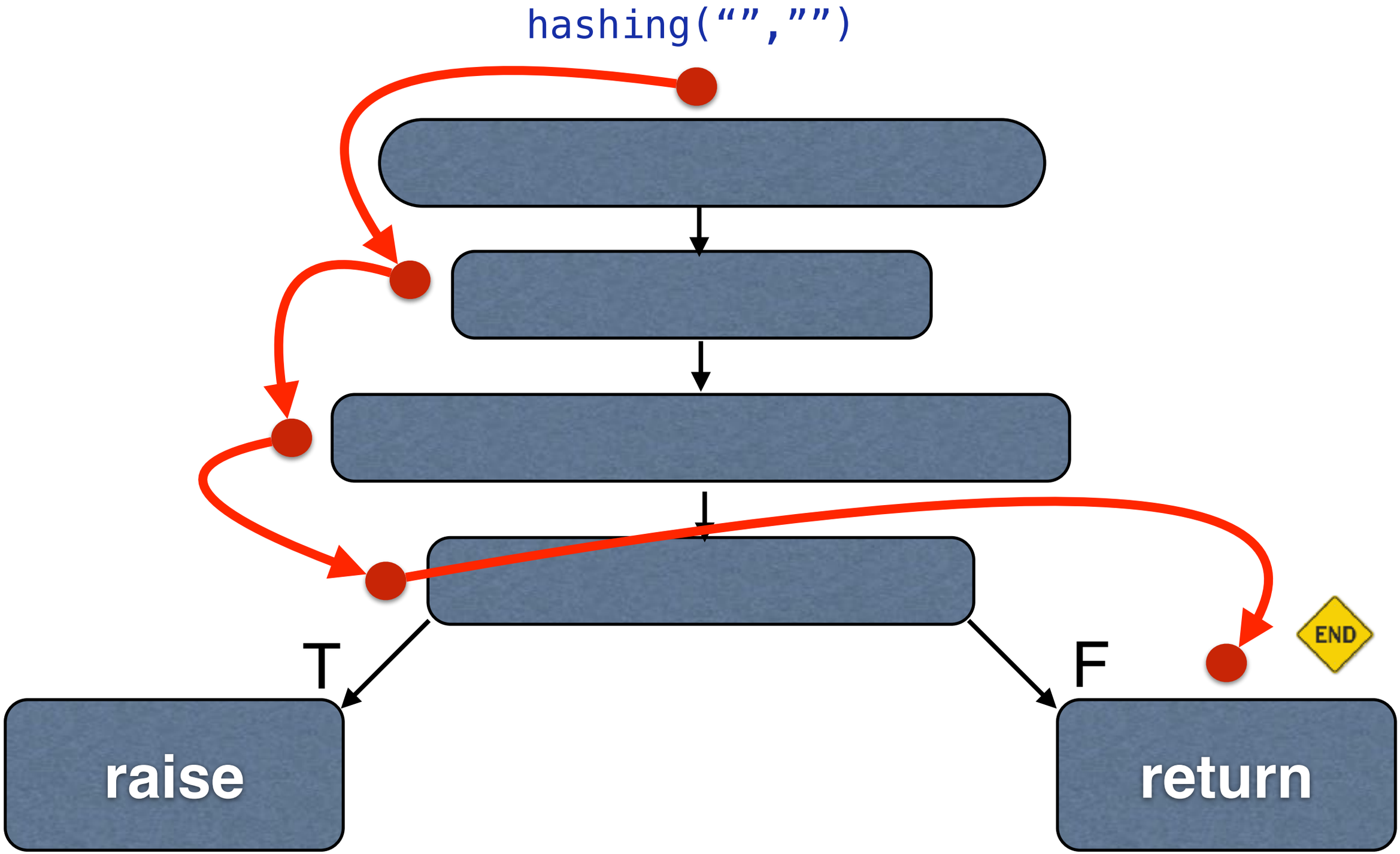


y_0=hashlib.md5().update(x_0).hexdigest()

Ejecución Simbólica Dinámica



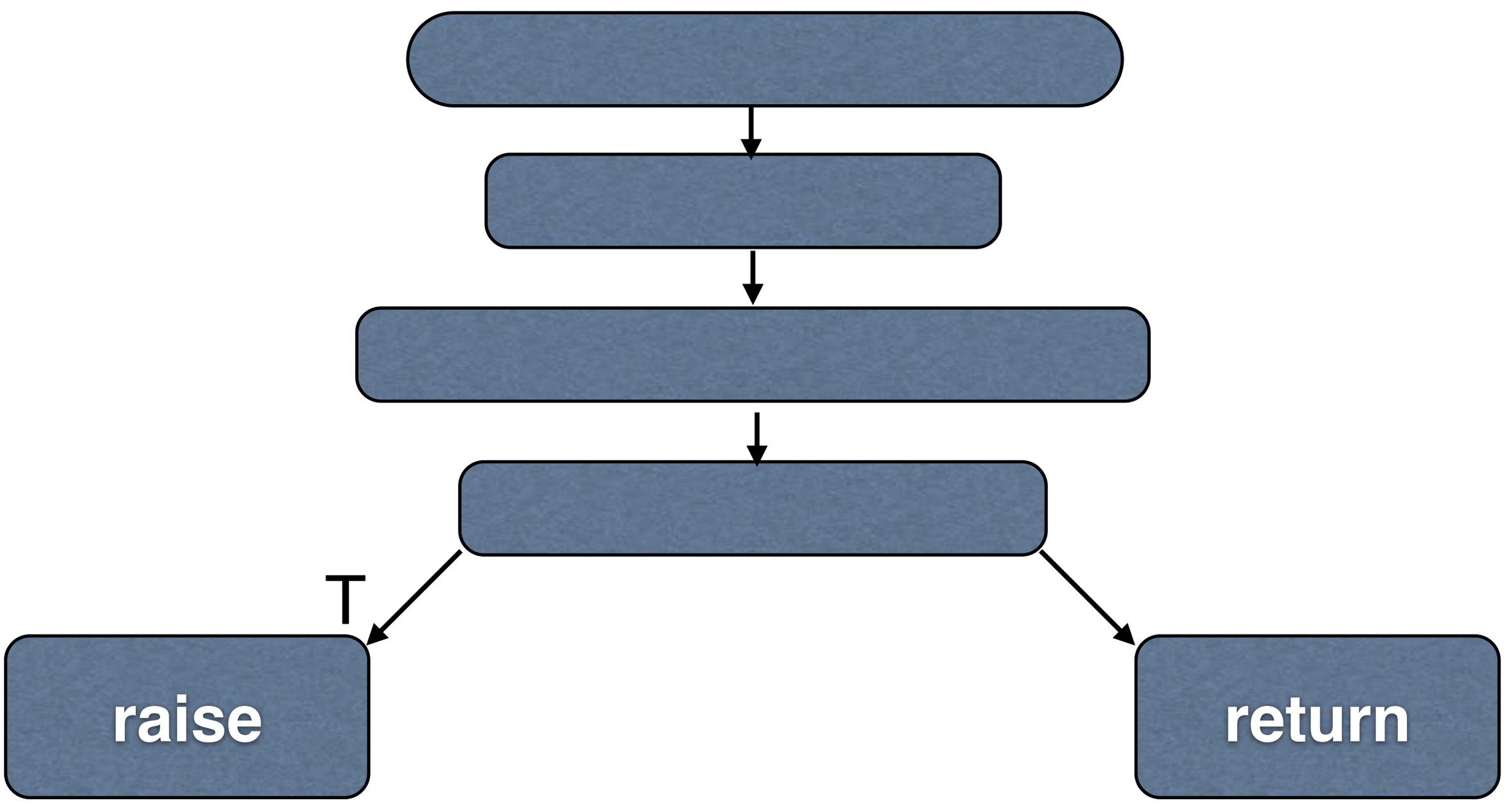
Ejecución Simbólica Dinámica



y_0=“d41d8cd98f00b204e9800998ecf8427e”

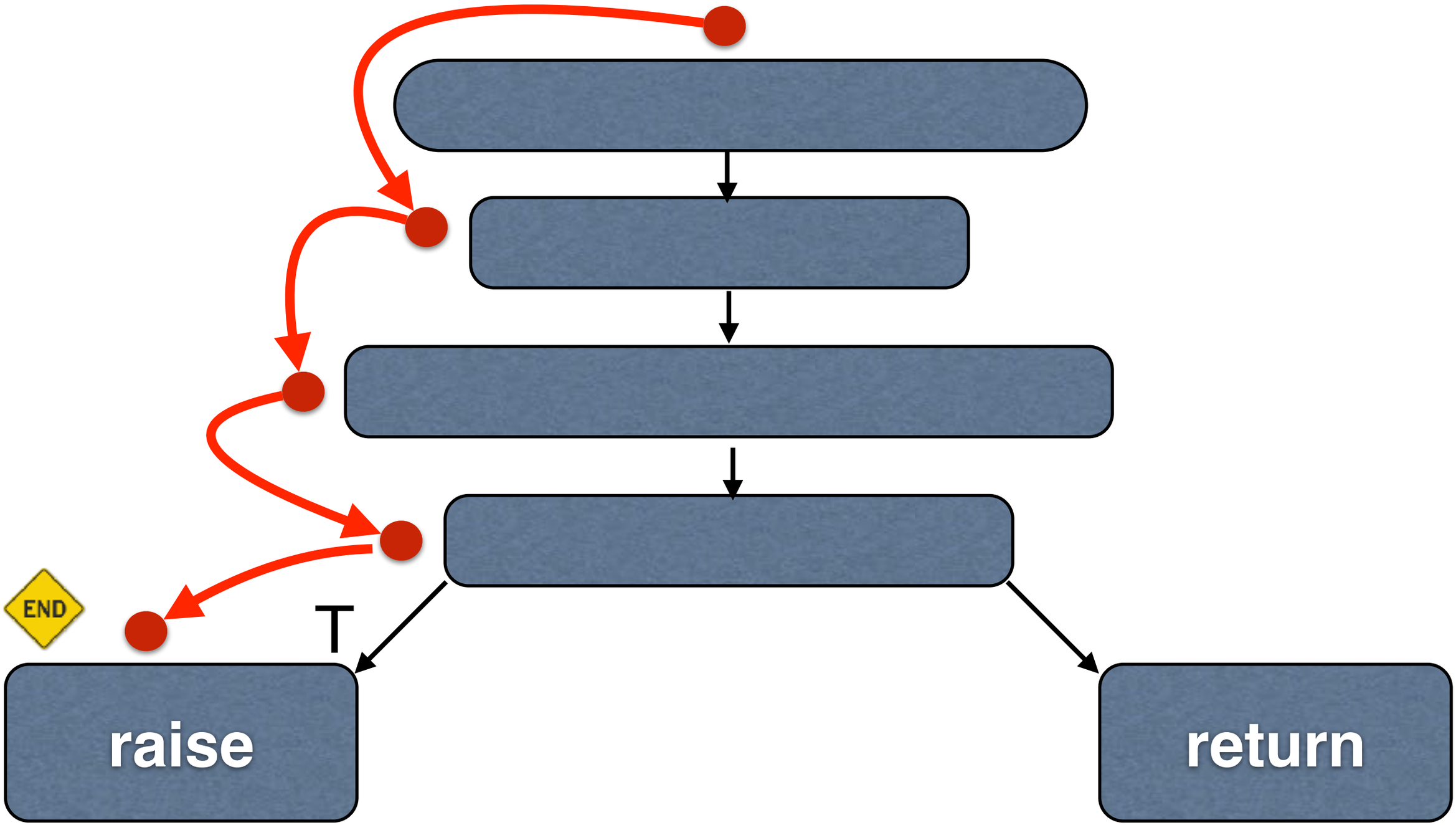
Ejecución Simbólica Dinámica

```
hashing(“”,”d41d8cd98f00b204e9800998ecf8427e”)
```



Ejecución Simbólica Dinámica

```
hashing(“”,”d41d8cd98f00b204e9800998ecf8427e”)
```



pseudocódigo de generador de tests c/

Ejecución Simbólica Dinámica

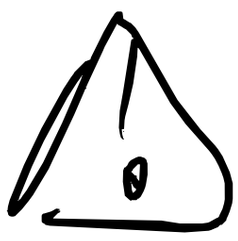
```
t = create_test(M)

Mientras budget es no vacío:
 path_condition = exec_concolic(t)
 Para i desde path_condition.size()-1 hasta 0
   branch = path_condition[i]
   Si neg(branch) is not covered:
     query = path_condition[0..i-1] && neg(branch)
     solution = solve(query)
     Si solution is SAT:
       t = create_test(M, solution)
       Agregar t a testSuite
       break

retornar testSuite
```

Ejecución Simbólica Dinámica

- La exploración (i.e. nuevas path conditions a resolver) es guiada por ejecuciones concretas
  - Concolic Execution: Concrete+Symbolic
- Algunas limitaciones de la ejecución simbólica clásica pueden ser superadas aproximando valores simbólicos usando **valores concretos**



  - Expresiones complejas
  - Información de runtime (files,sockets,native,etc)

¿Por qué Ejecución Concólica?

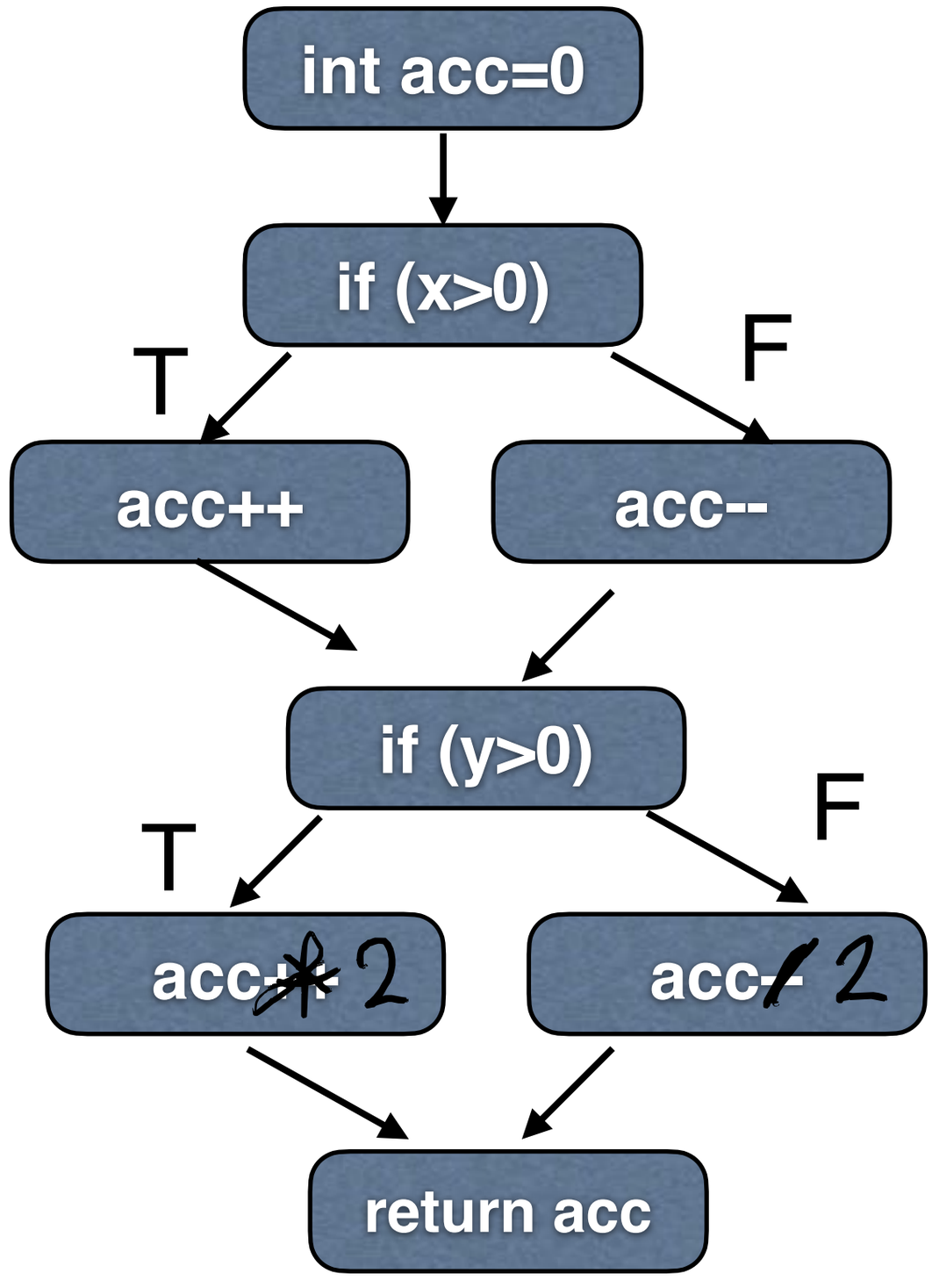
- Problema: si ejecutamos el input y solo obtenemos el camino recorrido en el CFG, entonces no sabemos cuales fueron los valores concretos en cada estado intermedio
- Por eso, si necesitamos "fallar" a un valor concreto, en ese momento no lo tenemos
- exec_concolic(t) hace ambas cosas a la vez!

Arbol de Cómputo

- Es una representación de la exploración del algoritmo de DSE (dynamic symbolic exec)
- Cada nodo representa una decisión (if, while, for). La rama izquierda es el "FALSE", la rama derecha es el "TRUE".
- Cada hoja puede ser:
  - Resultado UNSAT/UNKNOWN del solver
  - "X" si el camino está cerrado o ejecutado

CFG de test_me ≠ árbol

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc/2;
   }
   return acc;
}
```



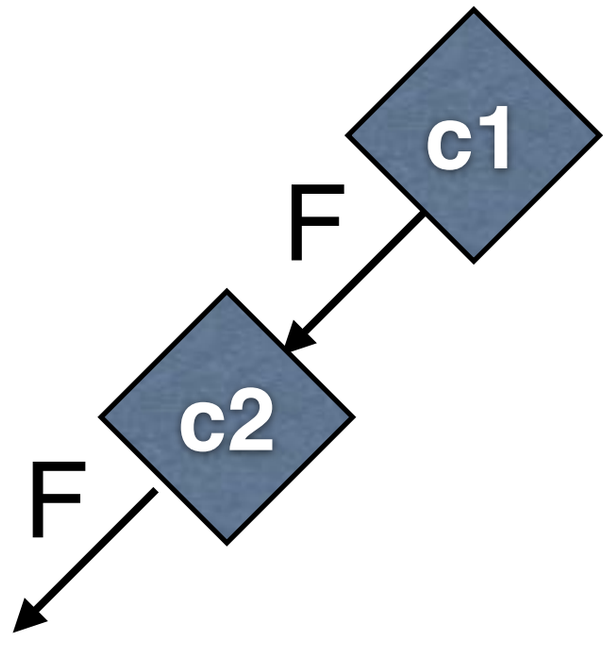
```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0			
2				
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

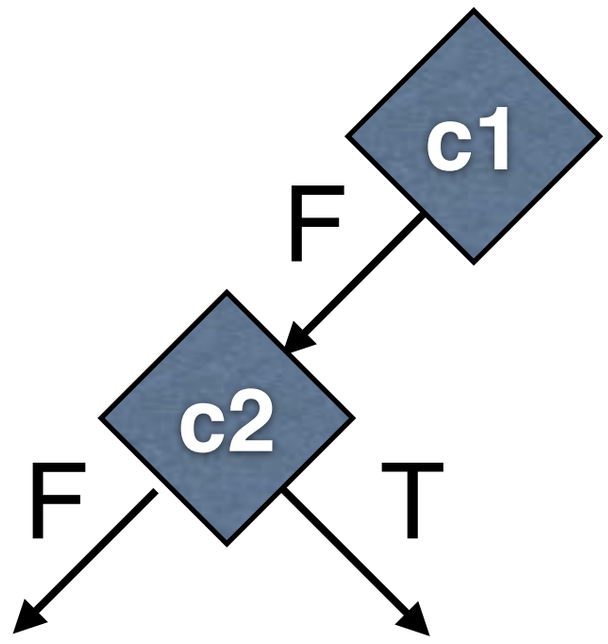
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)		
2				
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

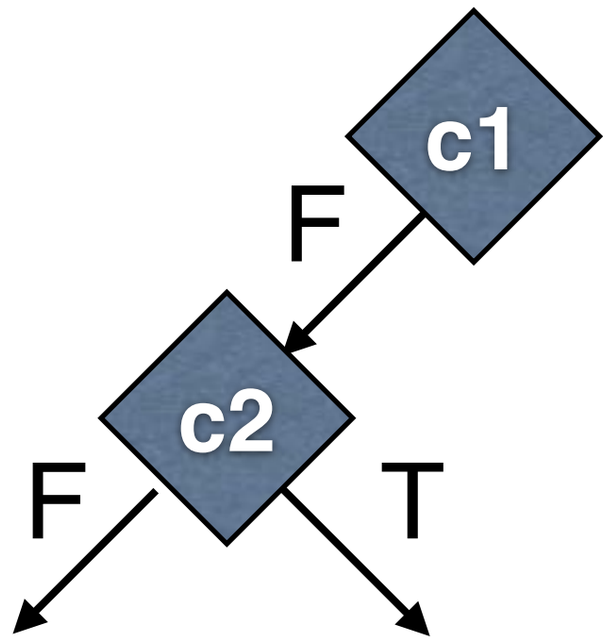


X ?

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	?	
2				
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

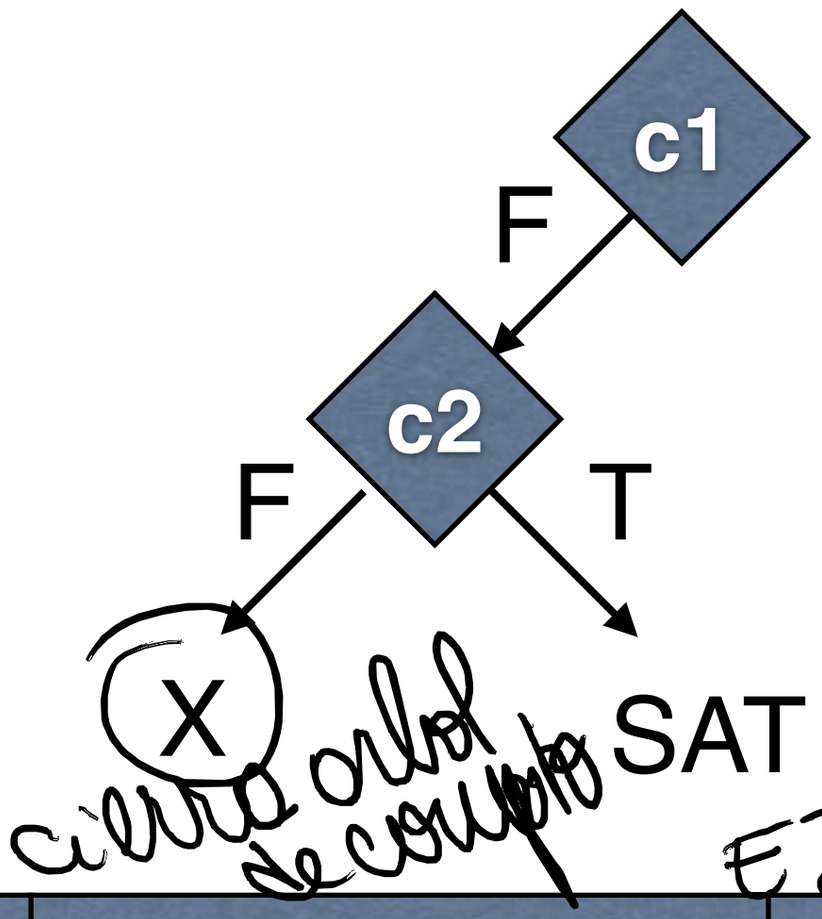


X ?

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	?
2				
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

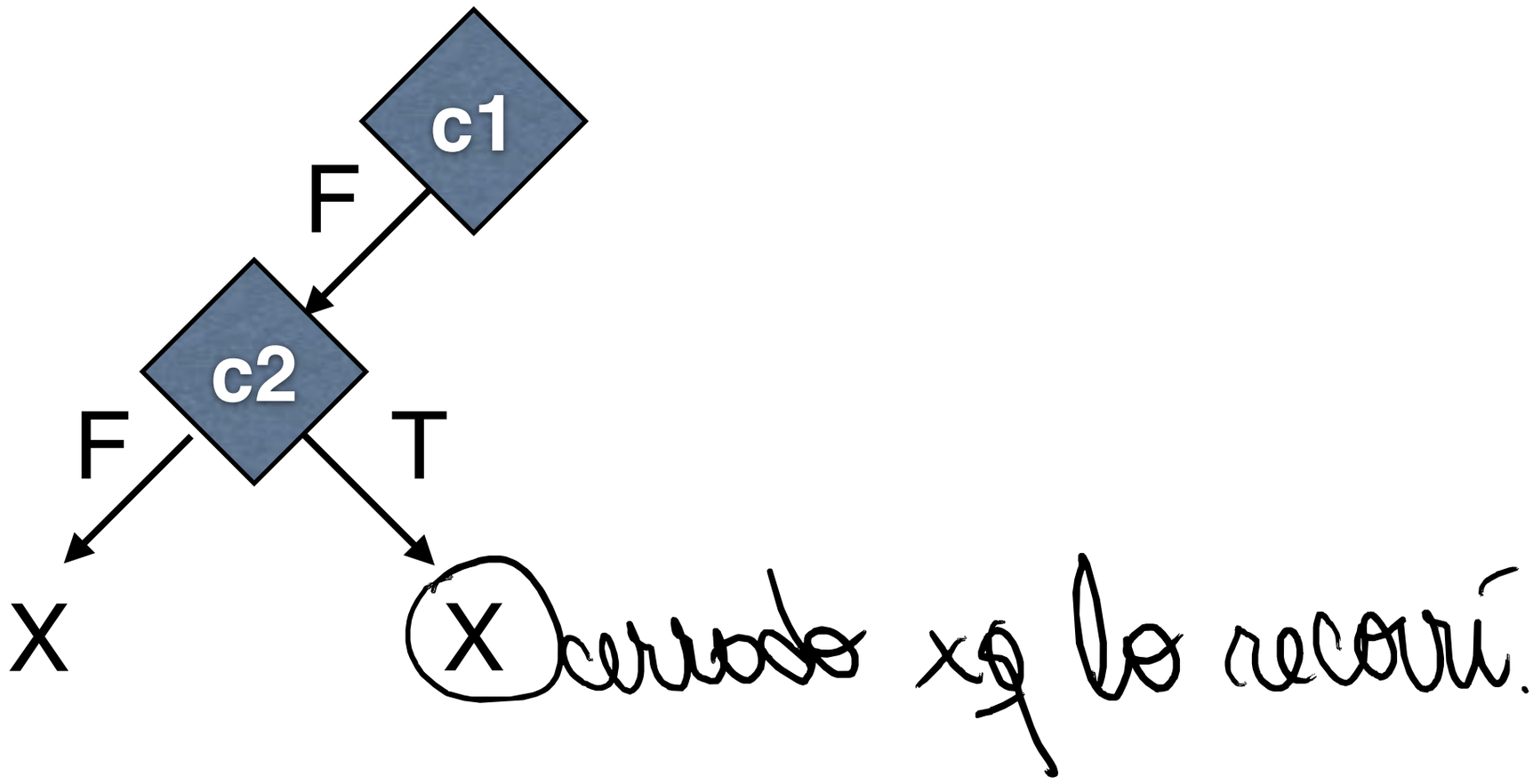


EJECUCIÓN CONCRETA

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2				
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

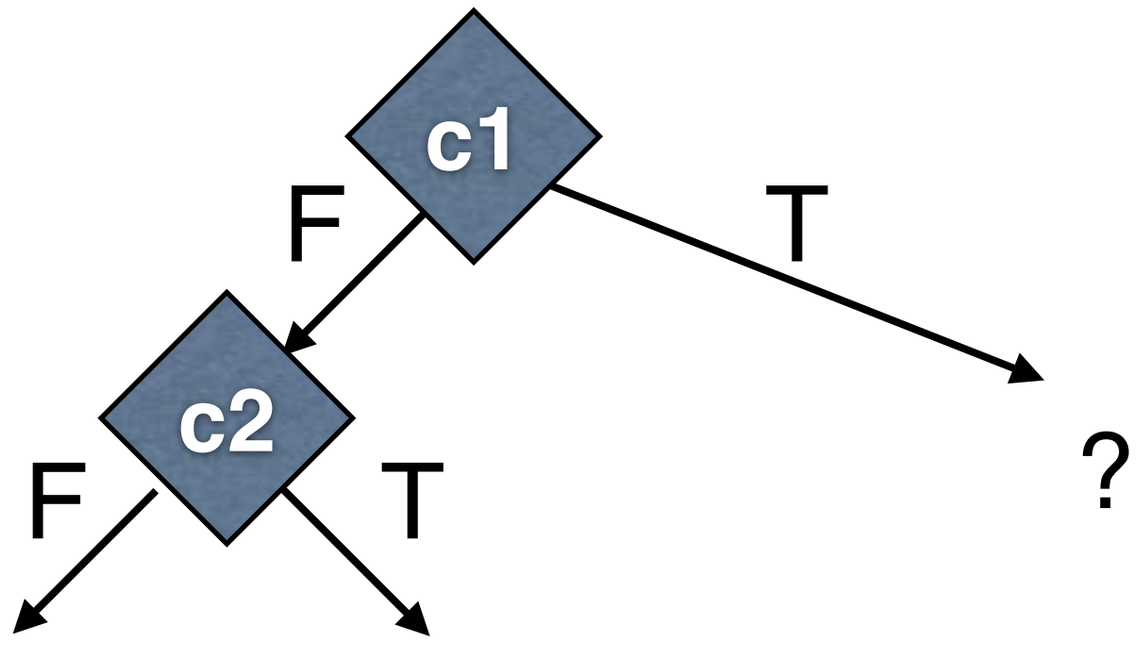
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)		
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

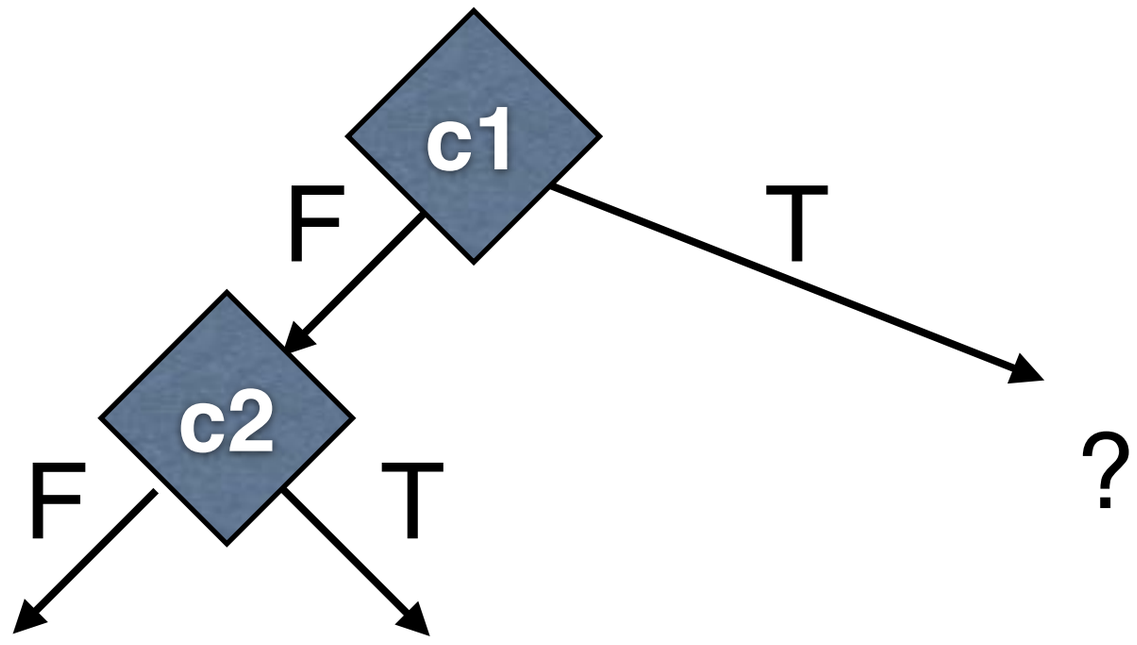
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	?	
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

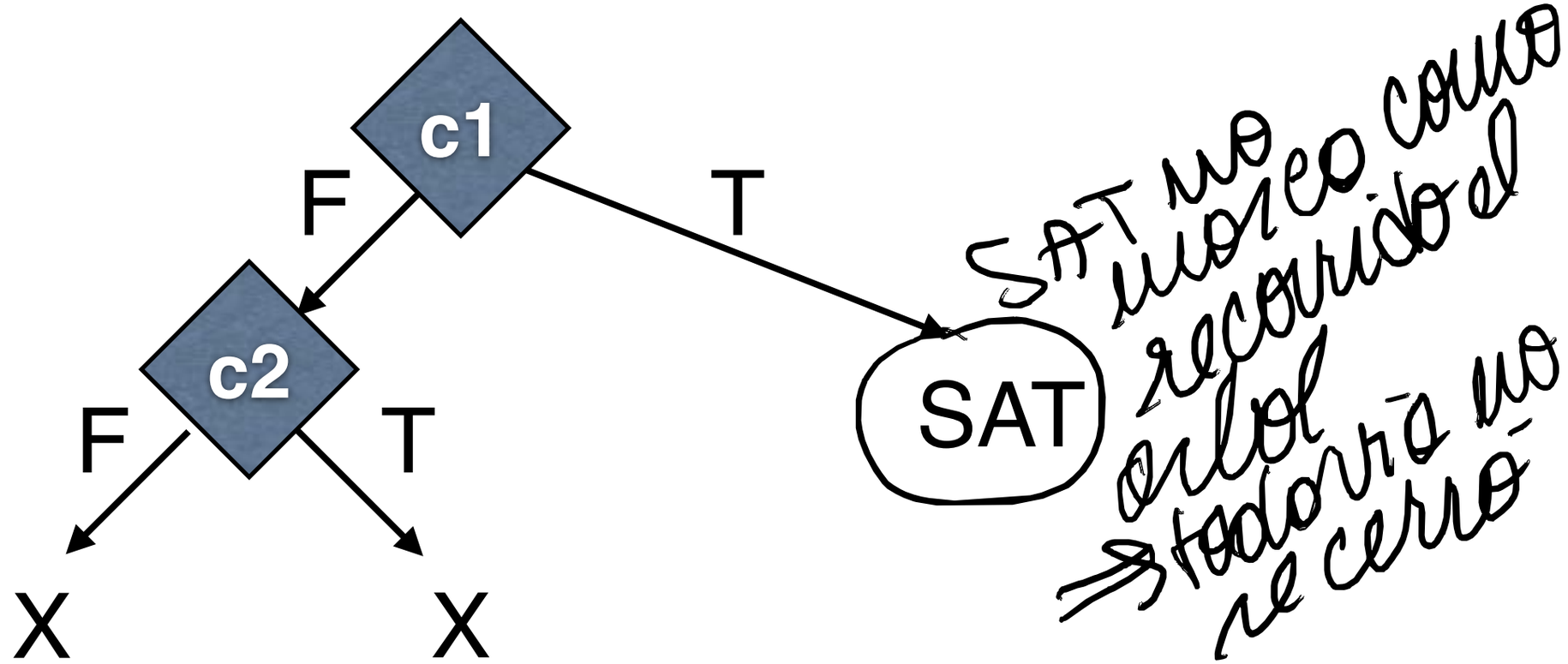
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	?
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

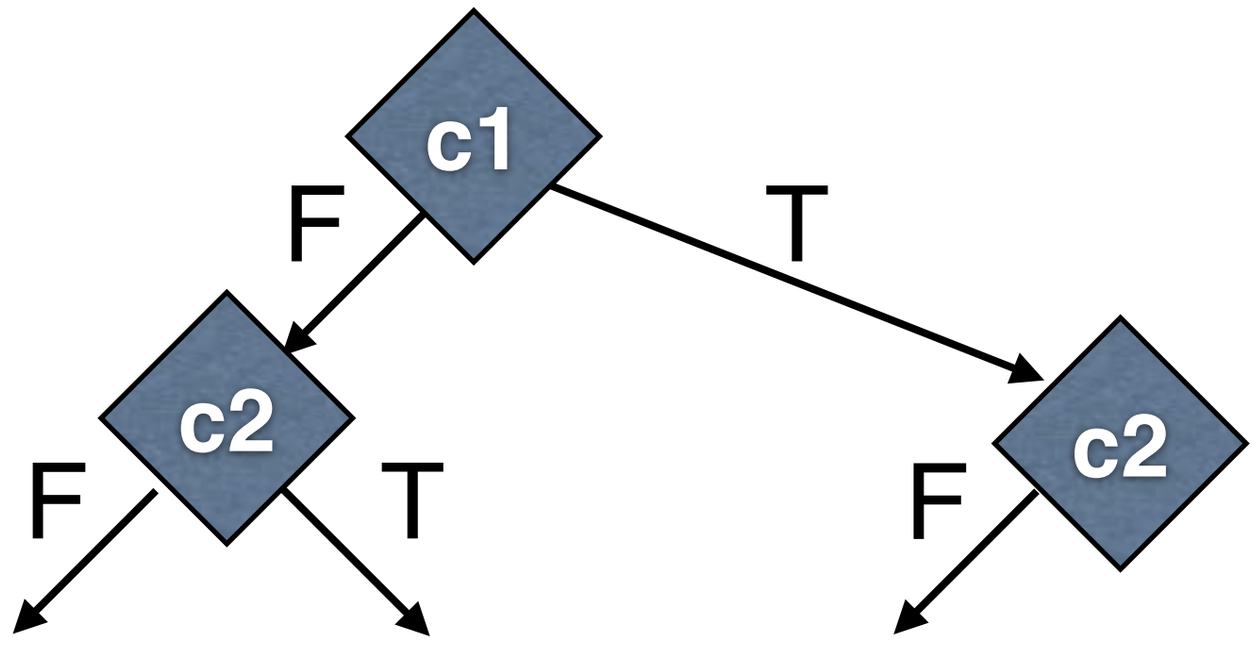
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3				
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

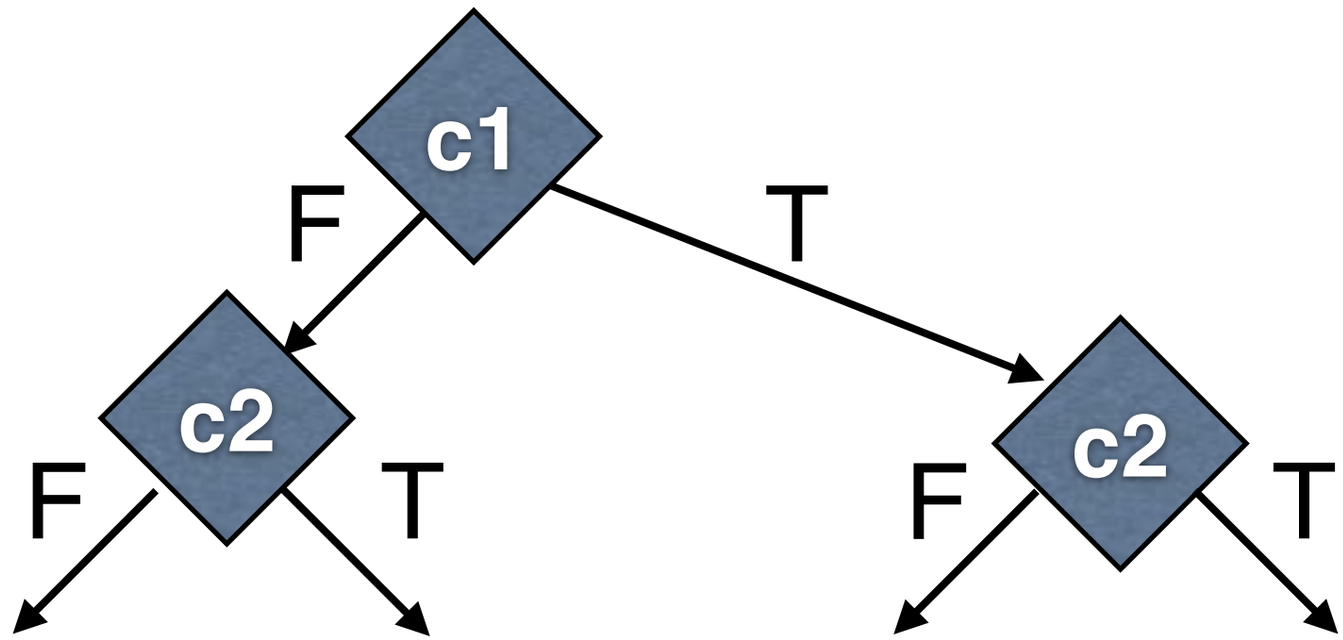


X X X

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)		
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

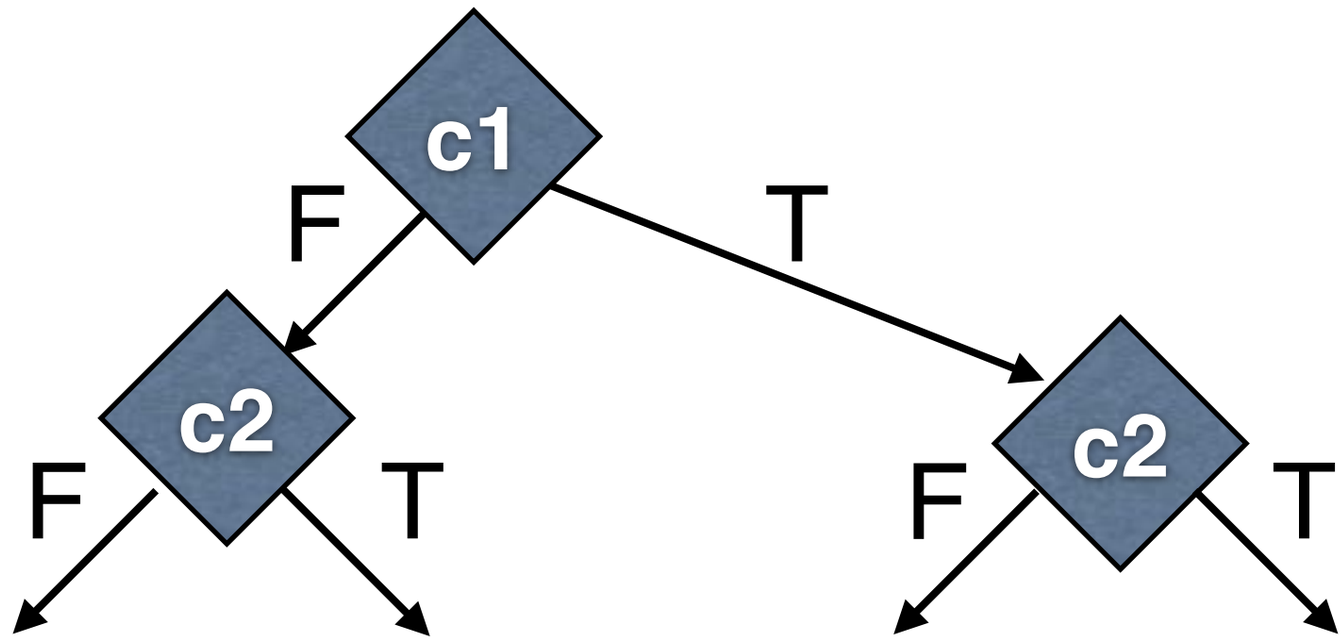


X X X ?

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)	?	
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

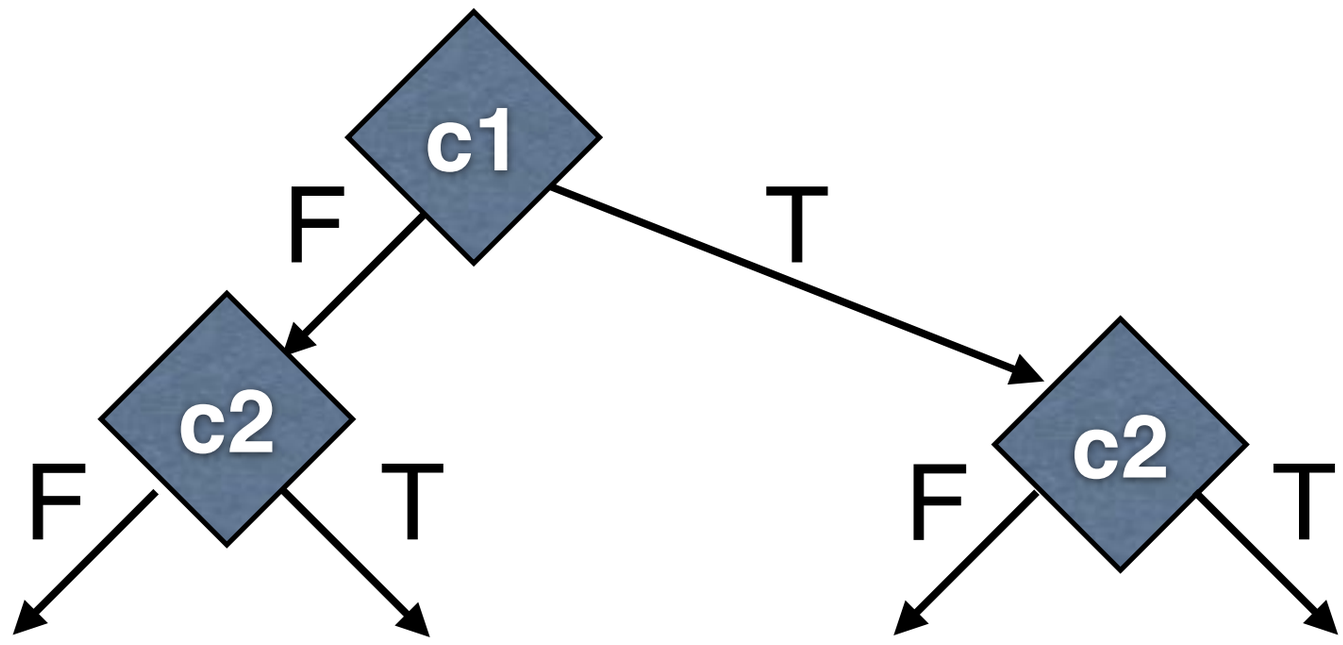


X X X ?

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)	(x0>0) &&(y0>0)	?
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado

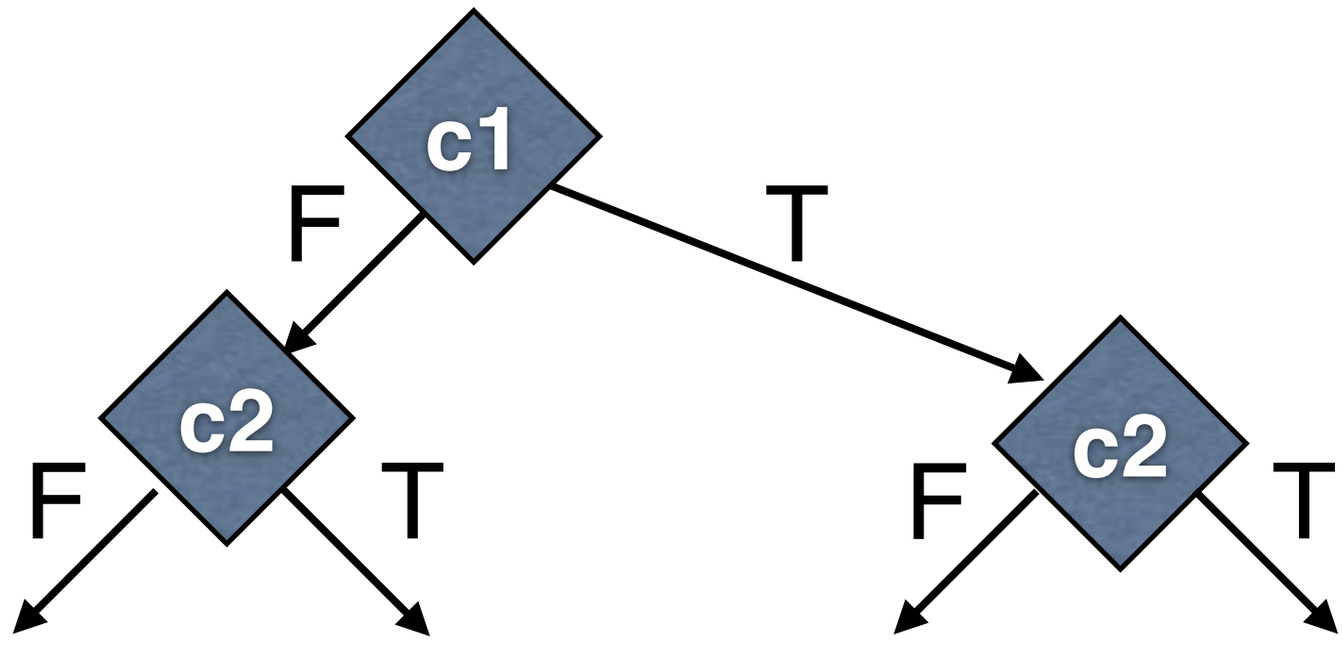


X X X SAT

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)	(x0>0) &&(y0>0)	x0=1,y0=1
4				

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

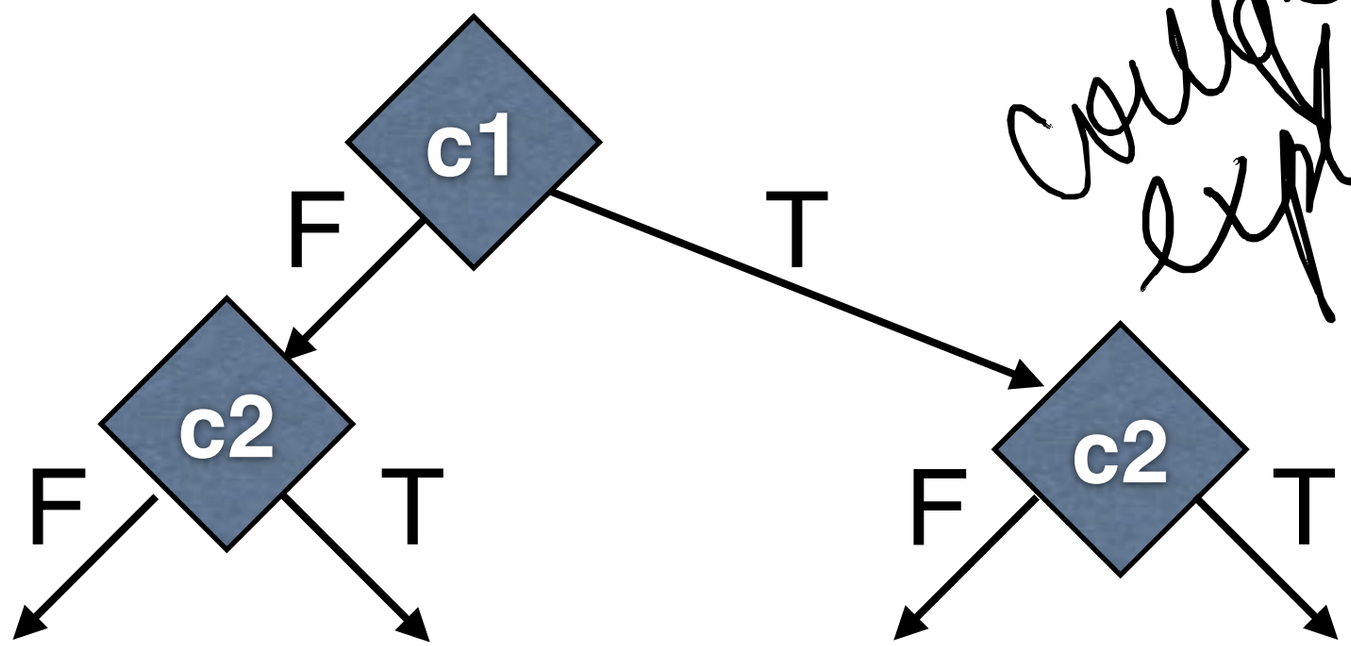
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)	(x0>0) &&(y0>0)	x0=1,y0=1
4	x=1,y=1	(x0>0) && (y0>0)		

```
int test_me(int x, int y ) {
   int acc=0;
   if (x>0) { // c1
      acc++;
   } else {
      acc--;
   }
   if (y>0) { // c2
      acc=acc*2;
   } else {
      acc=acc*2;
   }
}
```

árbol de cómputo explorado



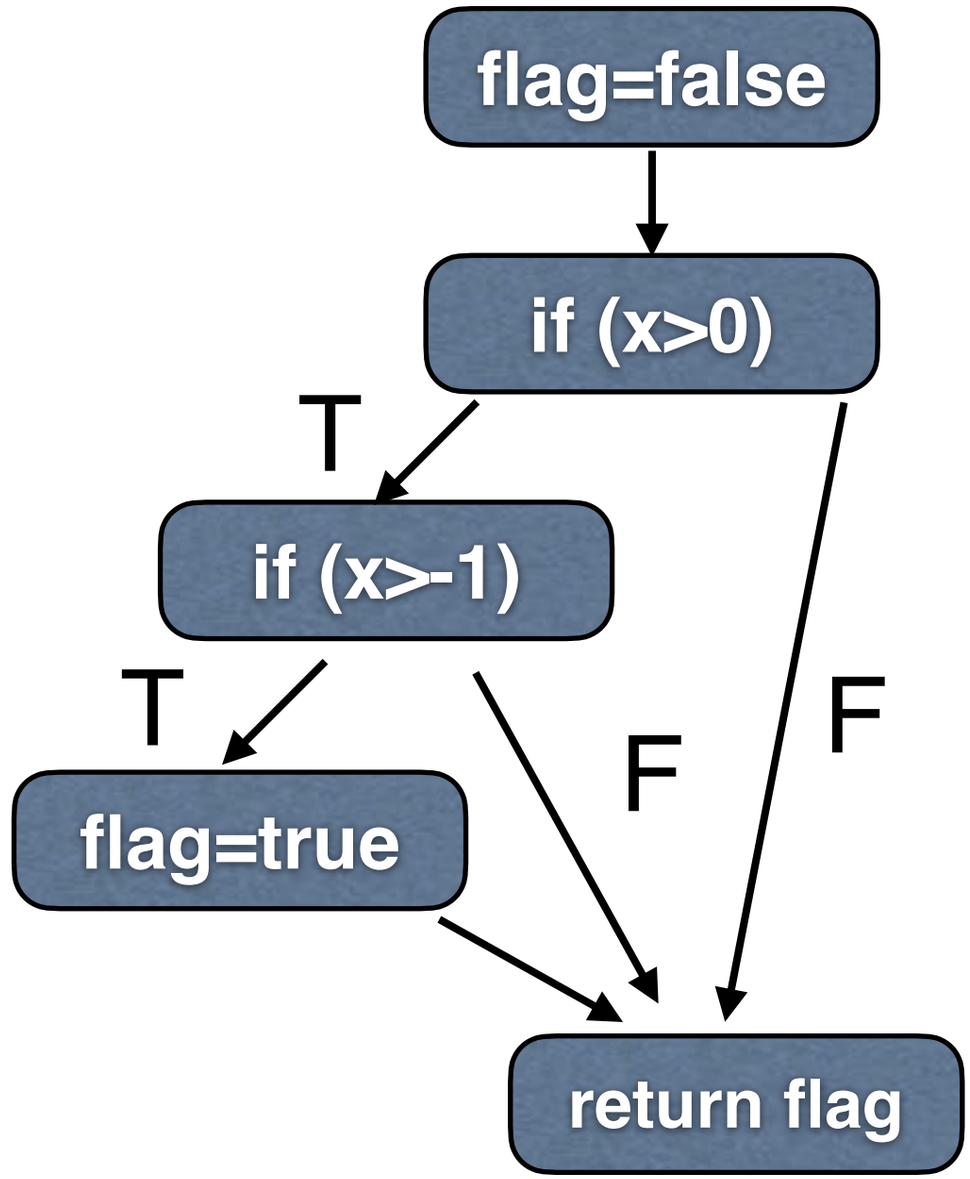
caminos explorados

X X X X

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,y=0	!(x0>0) && !(y0>0)	!(x0>0) && (y0>0)	x0=0,y0=1
2	x=0,y=1	!(x0>0) && (y0>0)	(x0>0)	x0=1,y0=0
3	x=1,y=0	(x0>0) && !(y0>0)	(x0>0) &&(y0>0)	x0=1,y0=1
4	x=1,y=1	(x0>0) && (y0>0)	FIN	

CFG de test_me

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```



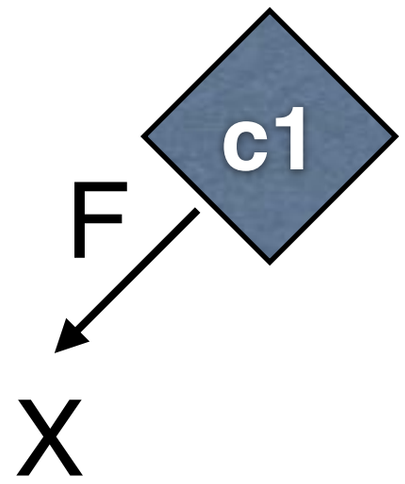
árbol de cómputo explorado

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0			
2				
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

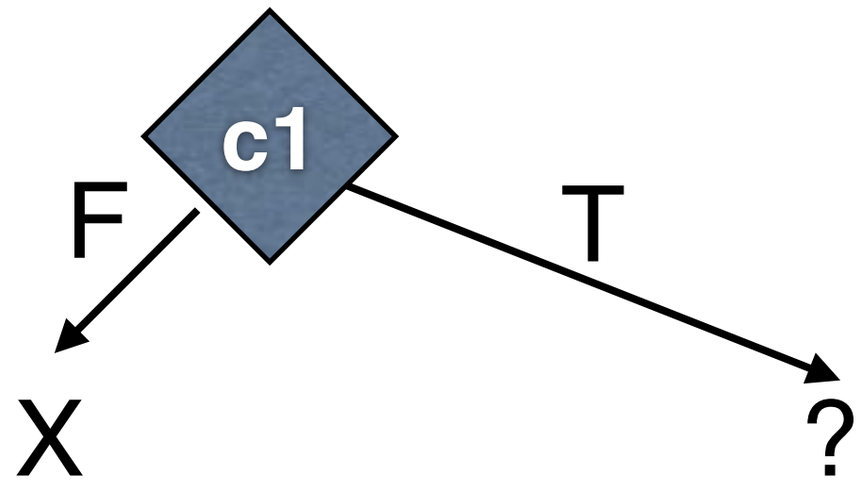
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)		
2				
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

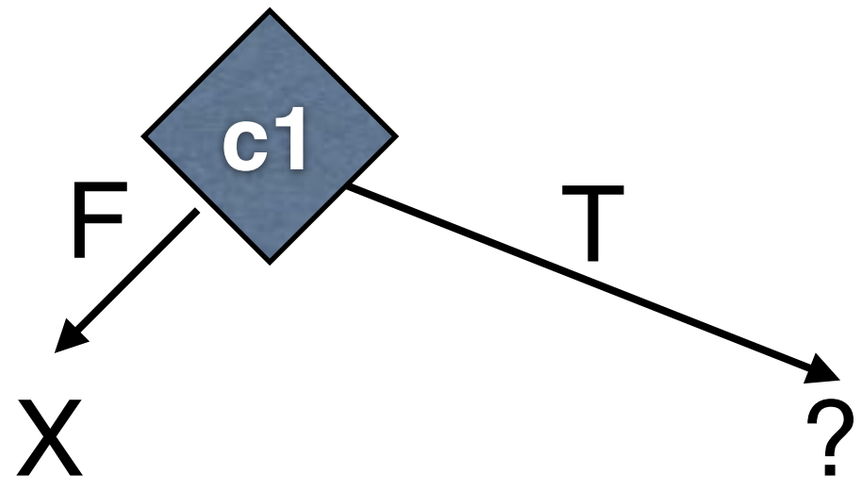
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)		
2				
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

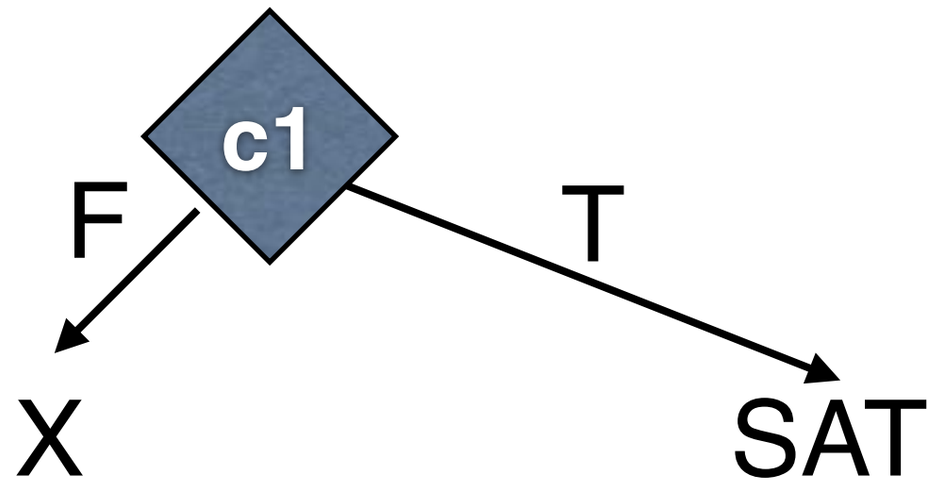
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	?
2				
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

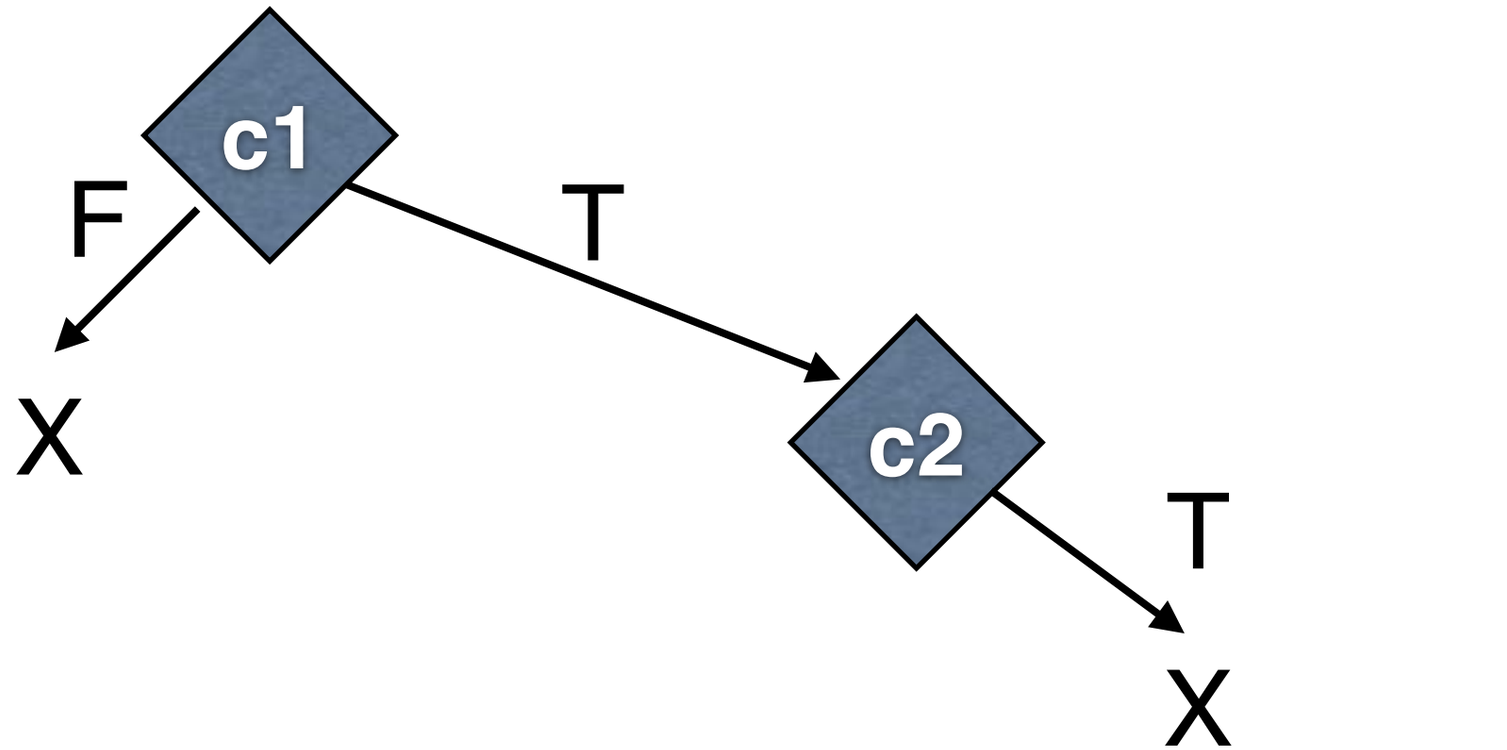
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2				
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

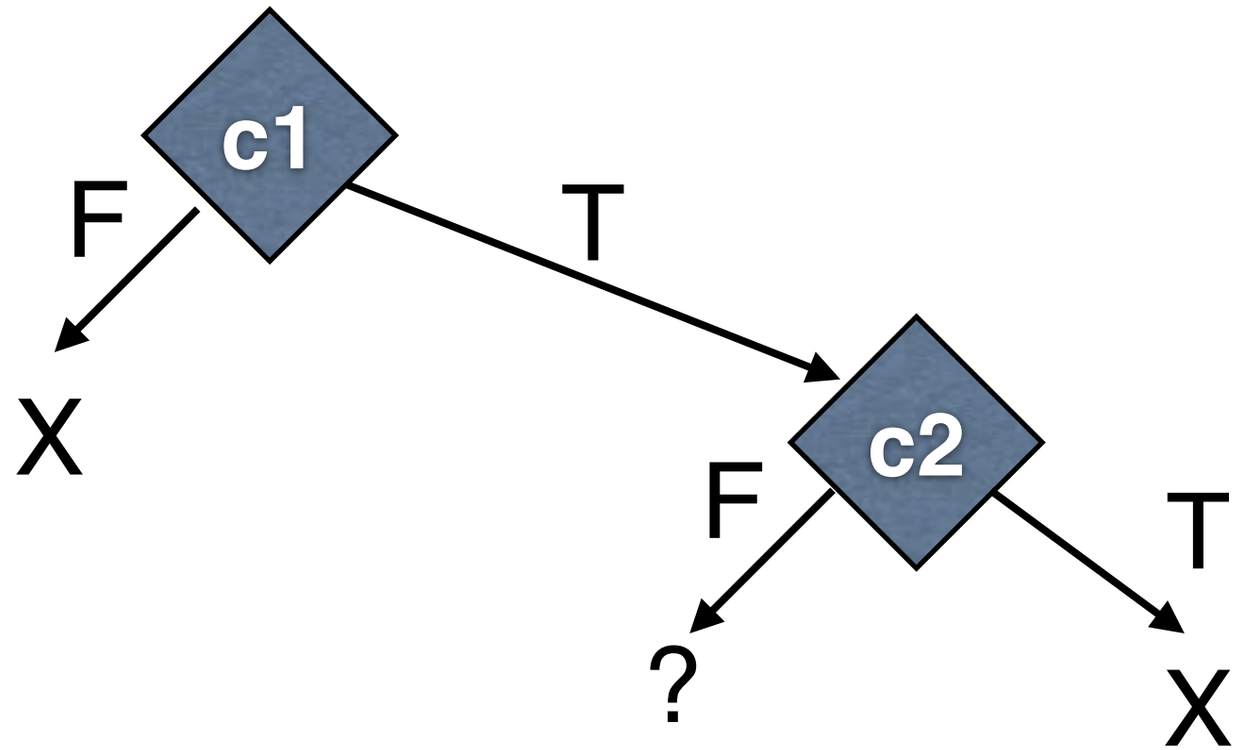
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2	x=1	(x0>0) && (x0>-1)		
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

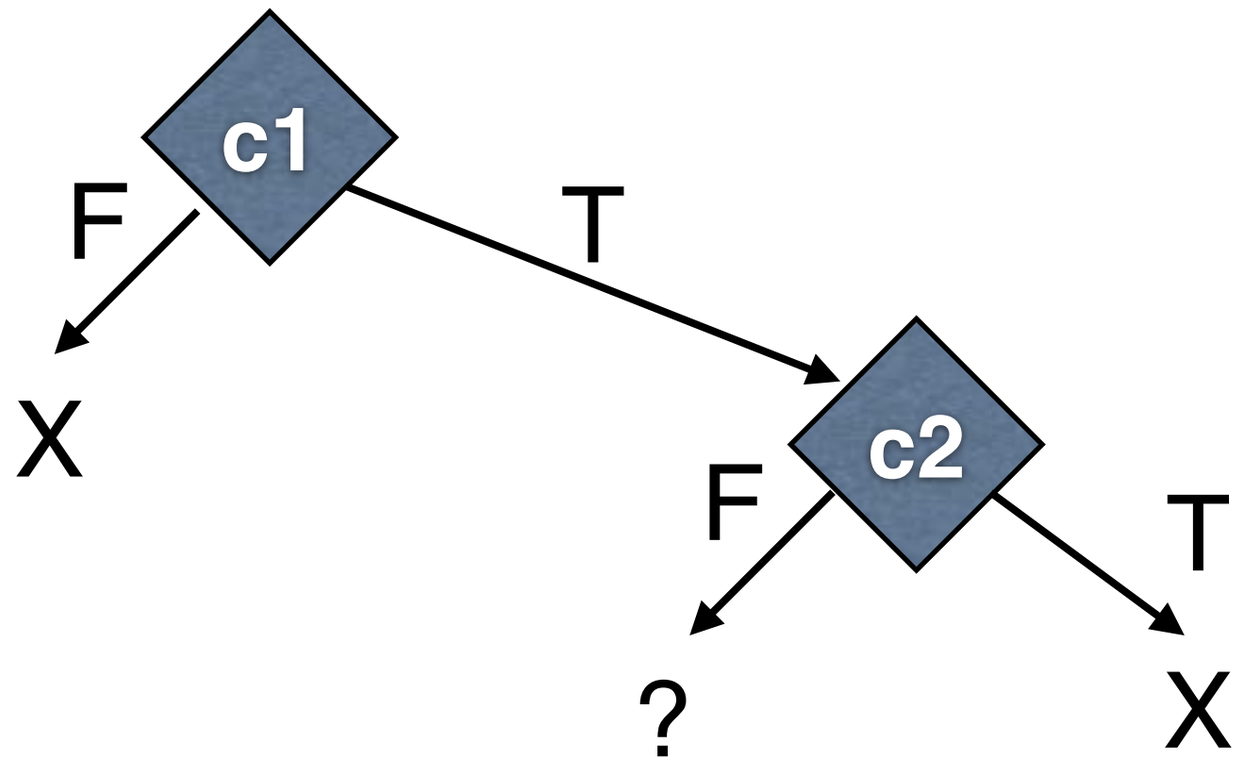
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2	x=1	(x0>0) && (x0>-1)	?	
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

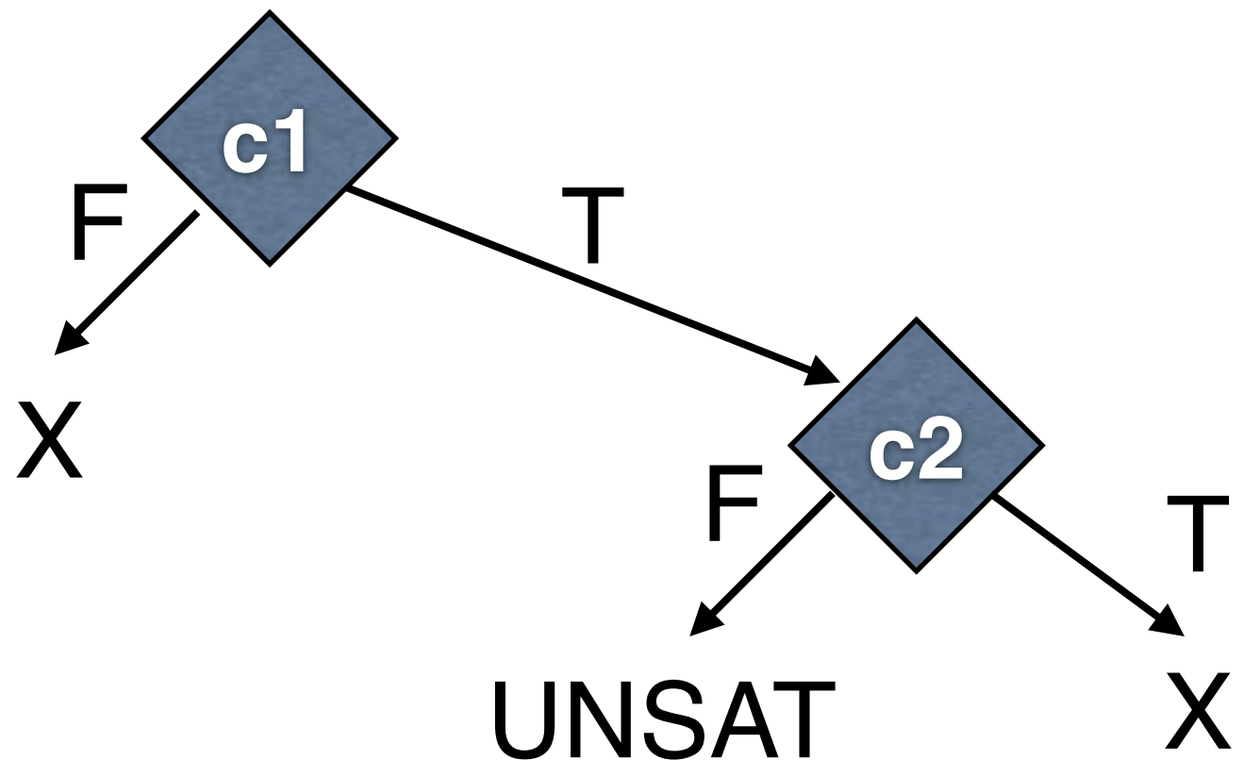
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2	x=1	(x0>0) && (x0>-1)	(x0>0) && !(x0>-1)	?
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

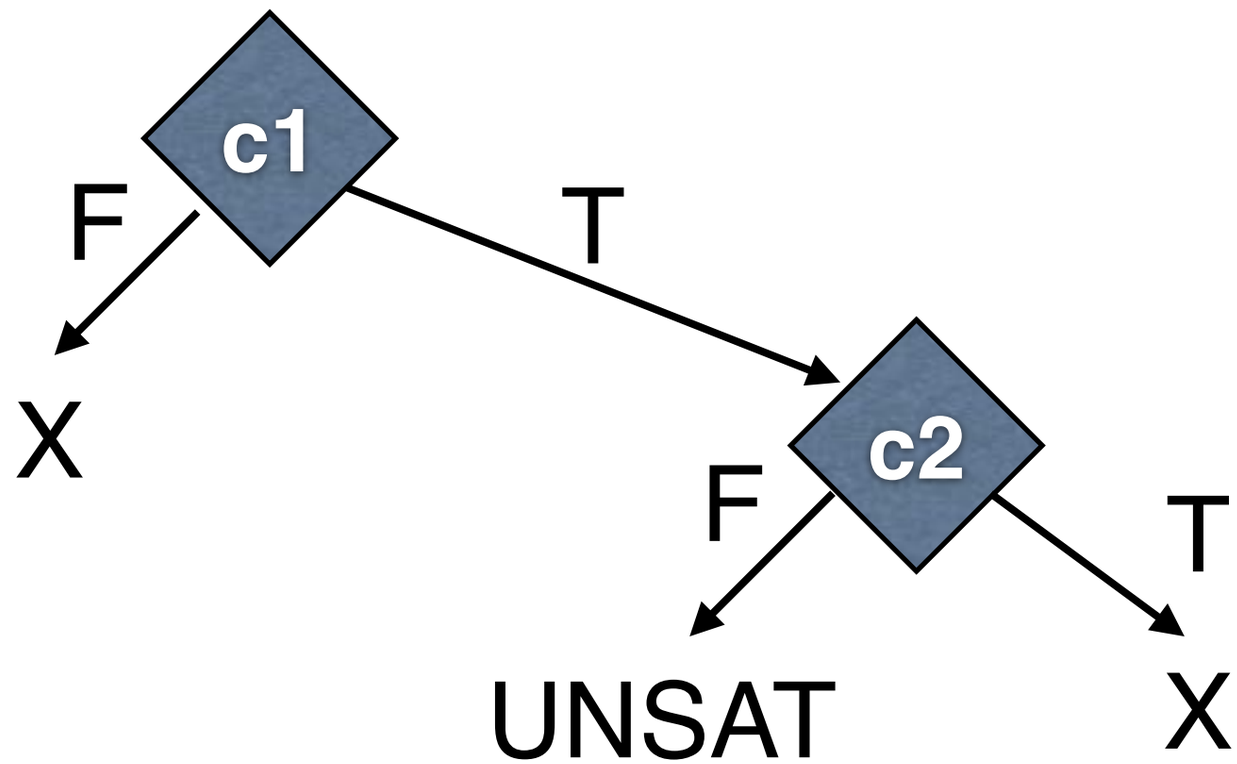
árbol de cómputo explorado



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2	x=1	(x0>0) && (x0>-1)	(x0>0) && !(x0>-1)	UNSAT
3				
4				

```
boolean test_me(int x) {
   boolean flag=false;
   if (x>0) { // c1
      if (x>-1) { // c2
         flag=true;
      }
   }
  return flag;
}
```

árbol de cómputo explorado

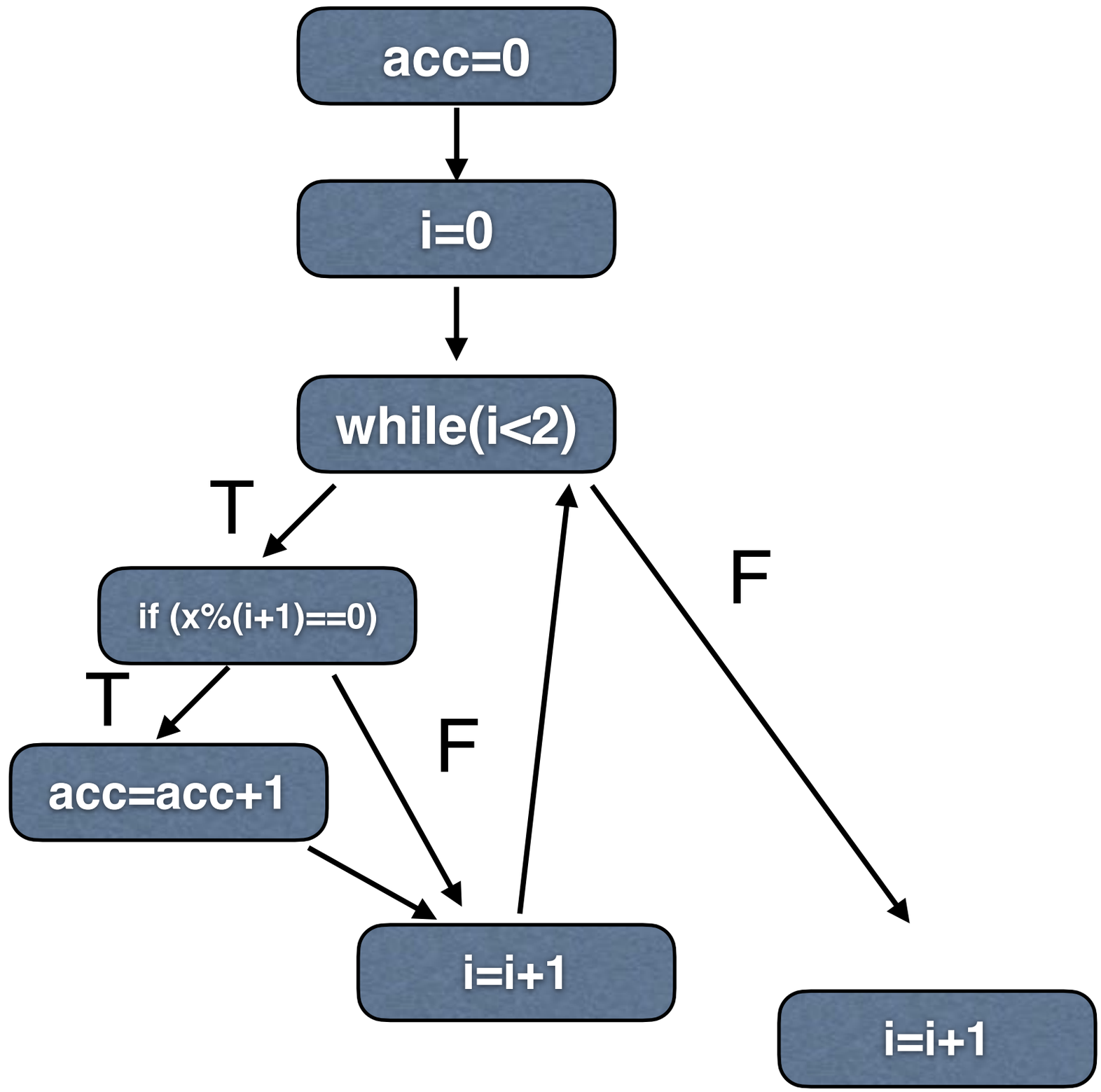


Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0	!(x0>0)	x0>0	x0=1
2	x=1	(x0>0) && (x0>-1)	(x0>0) && !(x0>-1)	UNSAT
3	FIN			
4				

con ciclos

CFG de test_me

```
int test_me(int x) {
  int acc=0;
  int i=0;
  while (i<2) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



Ciclos/Recursión

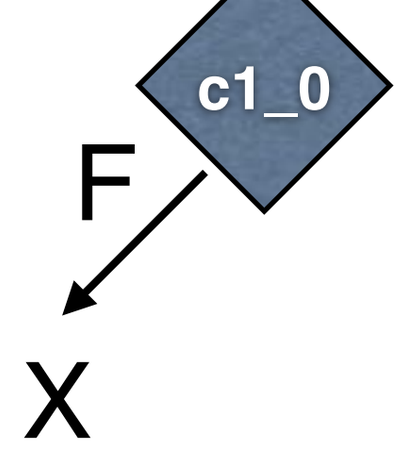
- El árbol de cómputo de un programa con ciclos/recursión es potencialmente infinito.
- Por este motivo, debemos limitar la cantidad de veces que un ciclo se ejecuta.
- Cada vez que tengamos un ciclo/recursión, limitaremos la profundidad del árbol de cómputo durante la exploración.
- Por ejemplo, si U=1, a lo sumo un ciclo se puede ejecutar una sola vez.
- Para esto, contamos la cantidad de veces que el arco TRUE de un ciclo se ejecutó en el árbol de cómputo

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```

Max u(c1)=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0			
2				
3				
4				

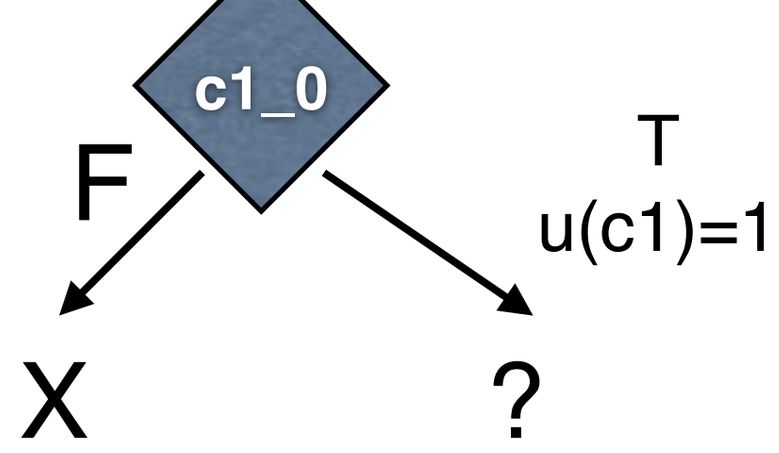
```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



Max u(c1)=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)		
2				
3				
4				

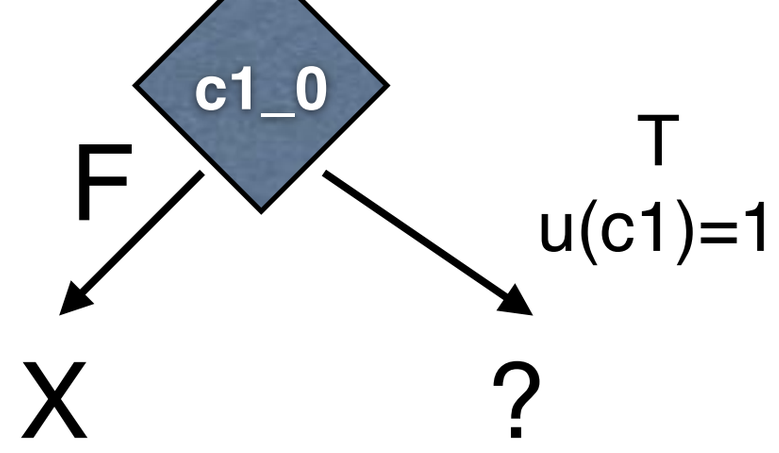
```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



Max u(c1)=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	?	
2				
3				
4				

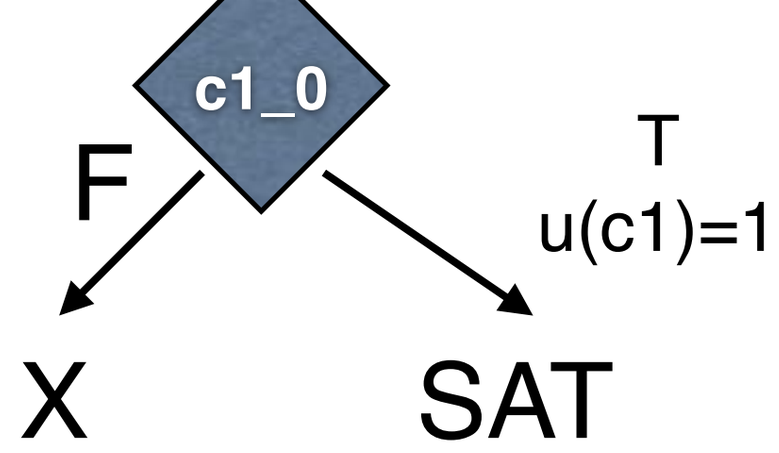
```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
    if (x%(i+1))==0 { //c2
      acc=acc+1;
    }
    i=i+1;
  }
  return acc;
}
```



Max u(c1)=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	?
2				
3				
4				

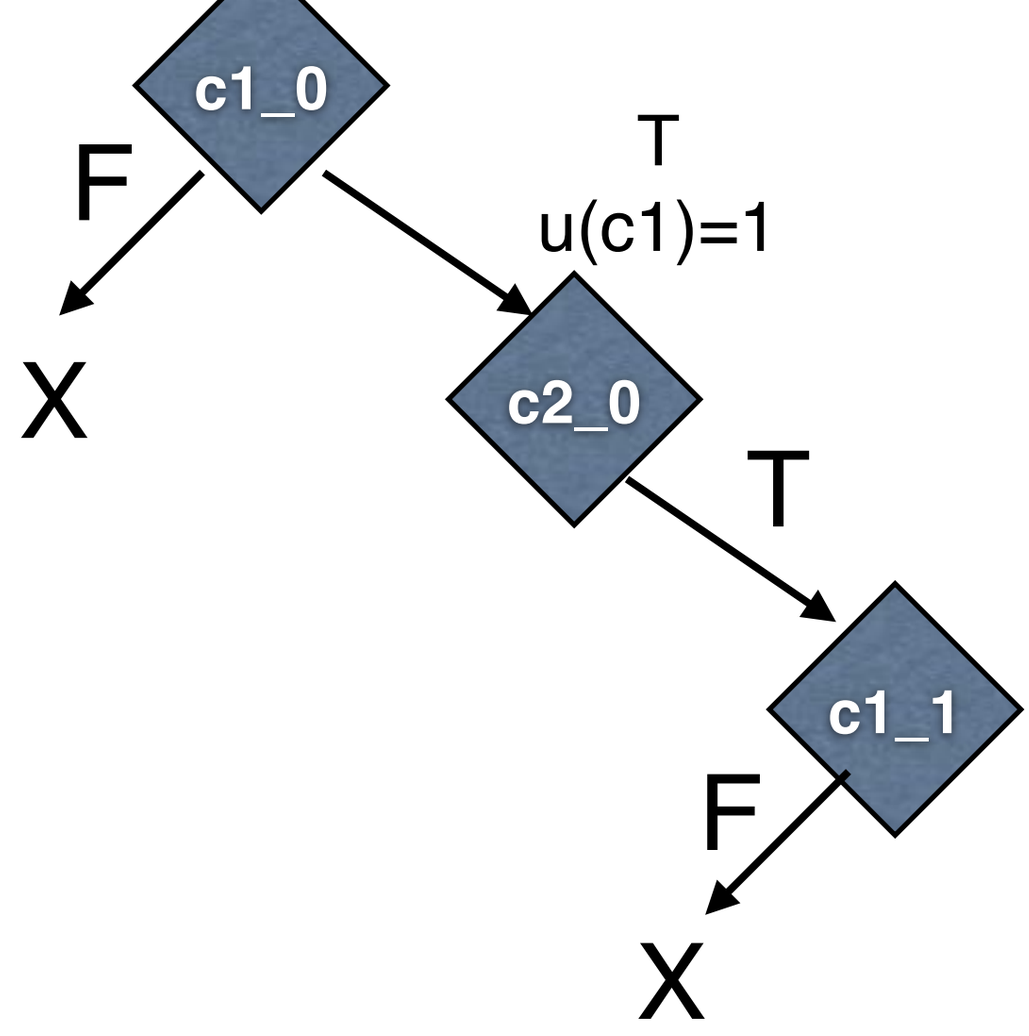
```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
    if (x%(i+1))==0 { //c2
      acc=acc+1;
    }
    i=i+1;
  }
  return acc;
}
```



Max u(c1)=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2				
3				
4				

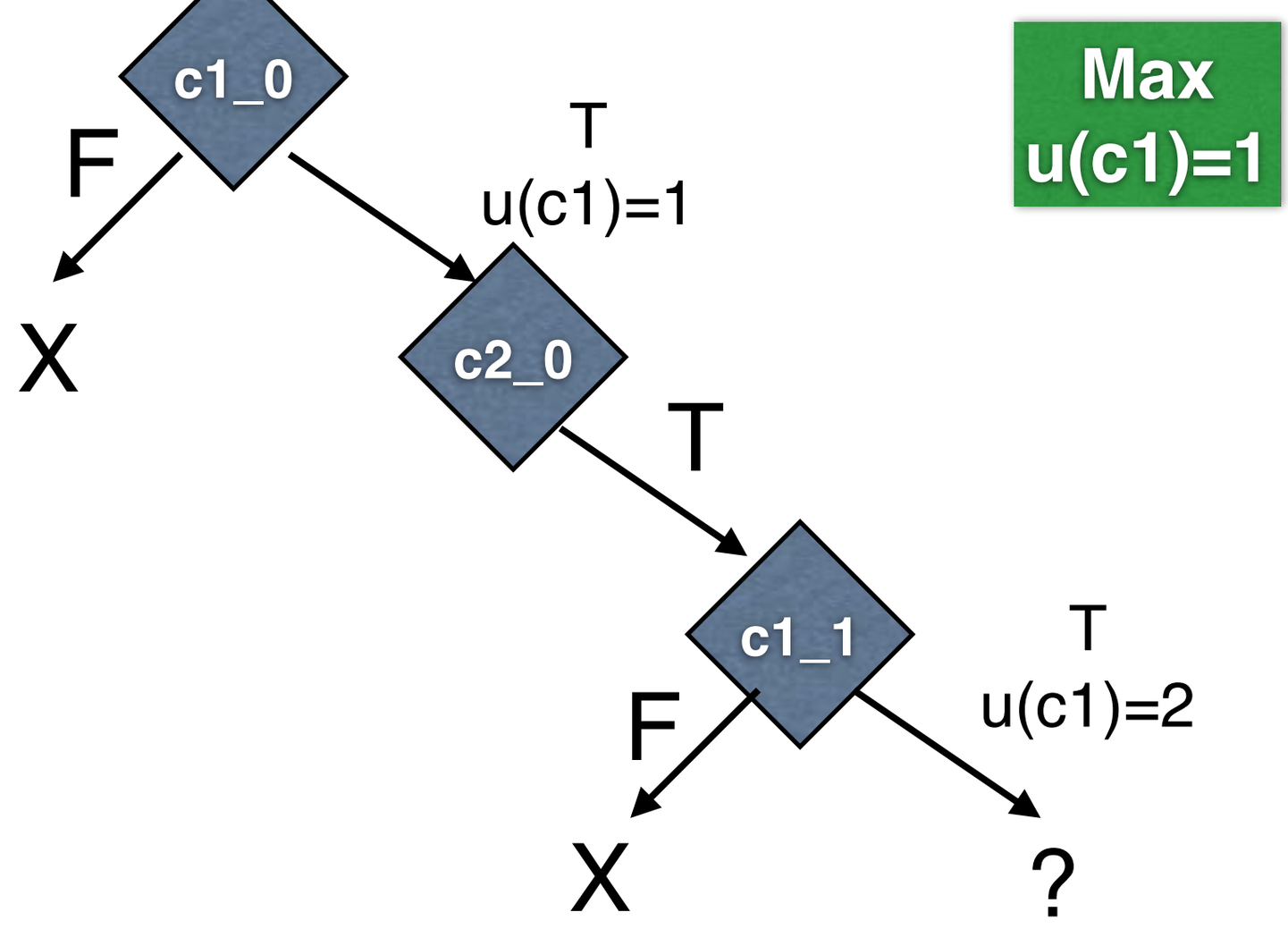
```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



Max u(c1)=1

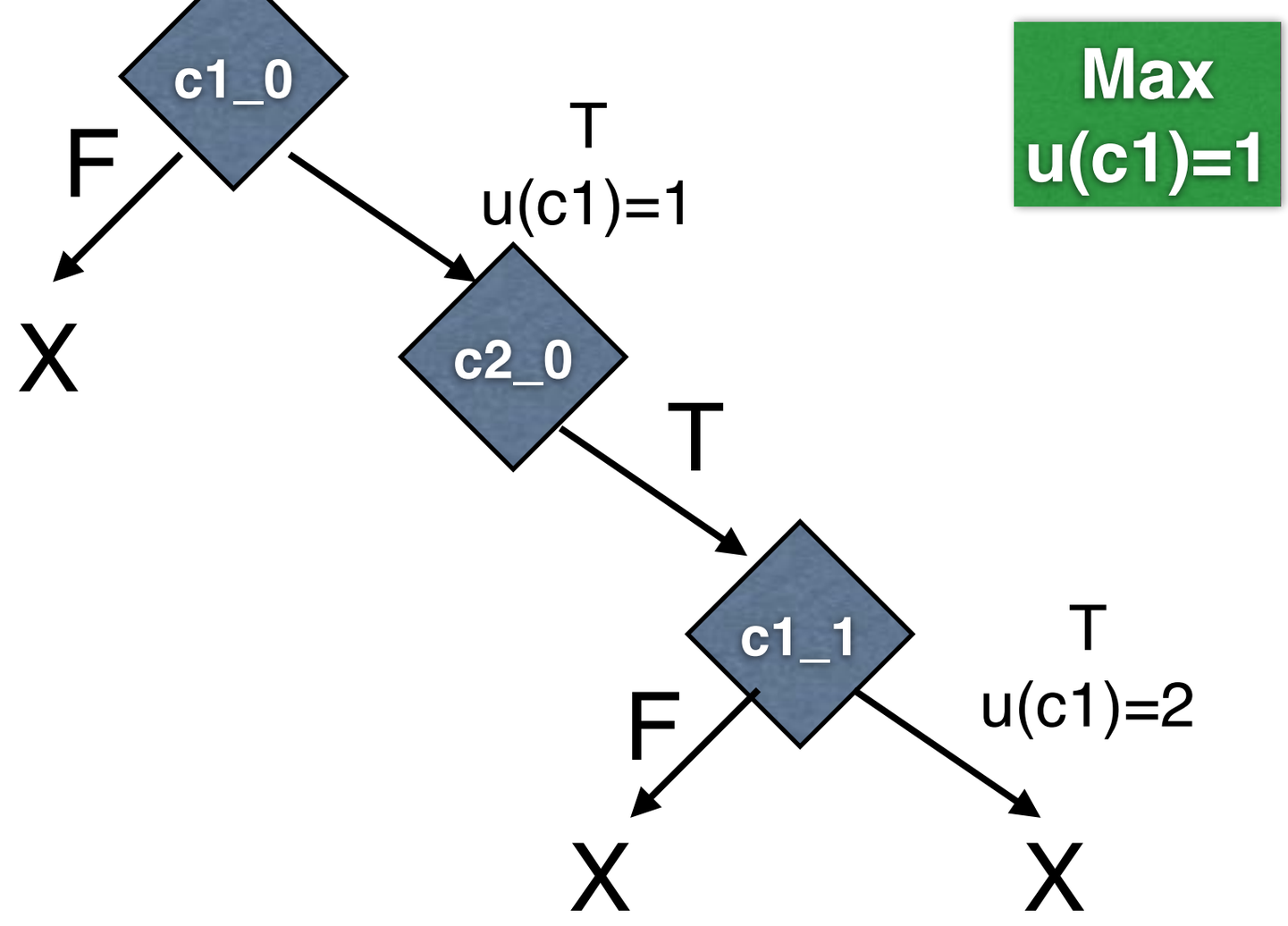
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)		
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



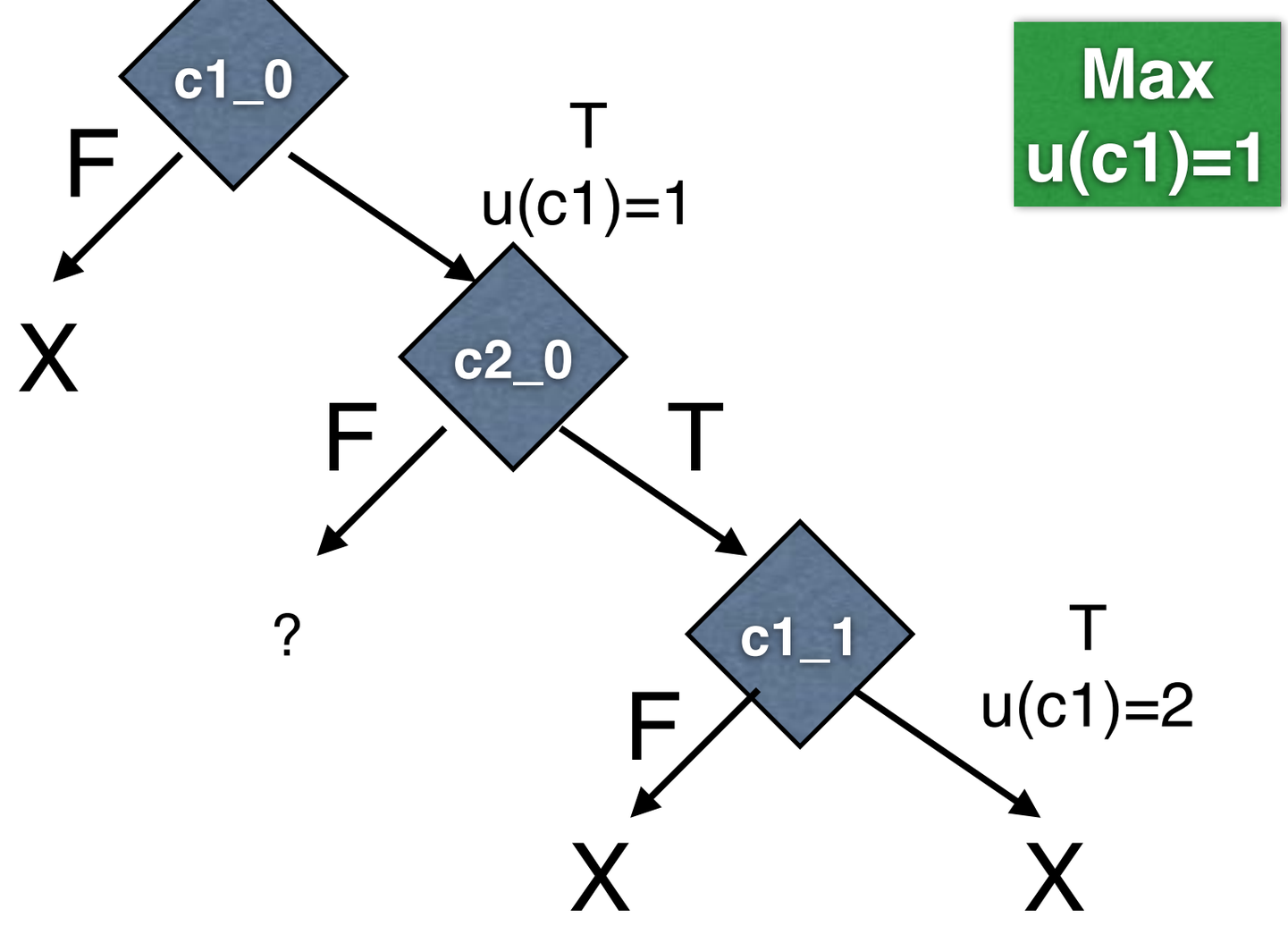
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)		
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



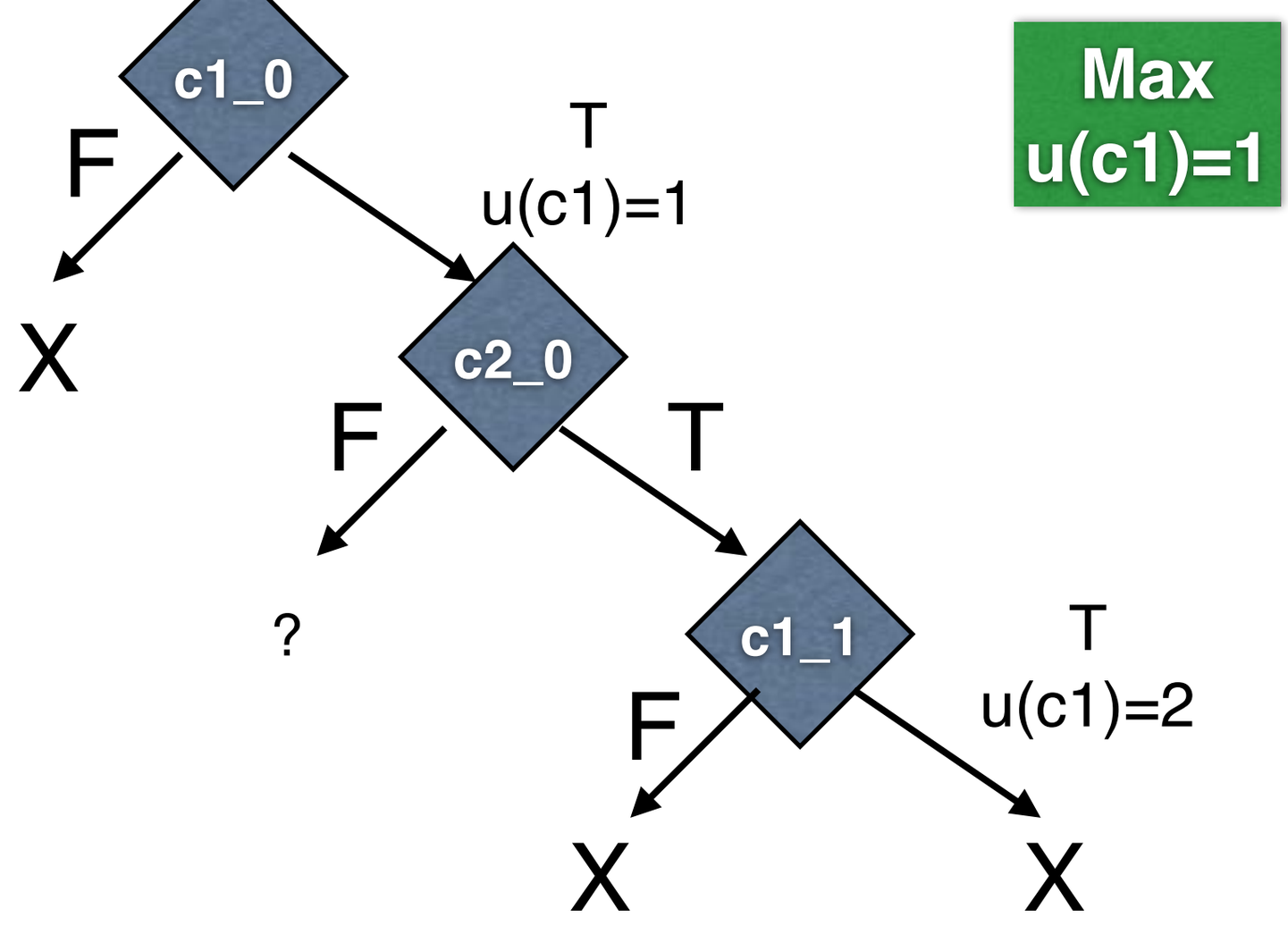
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)		
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



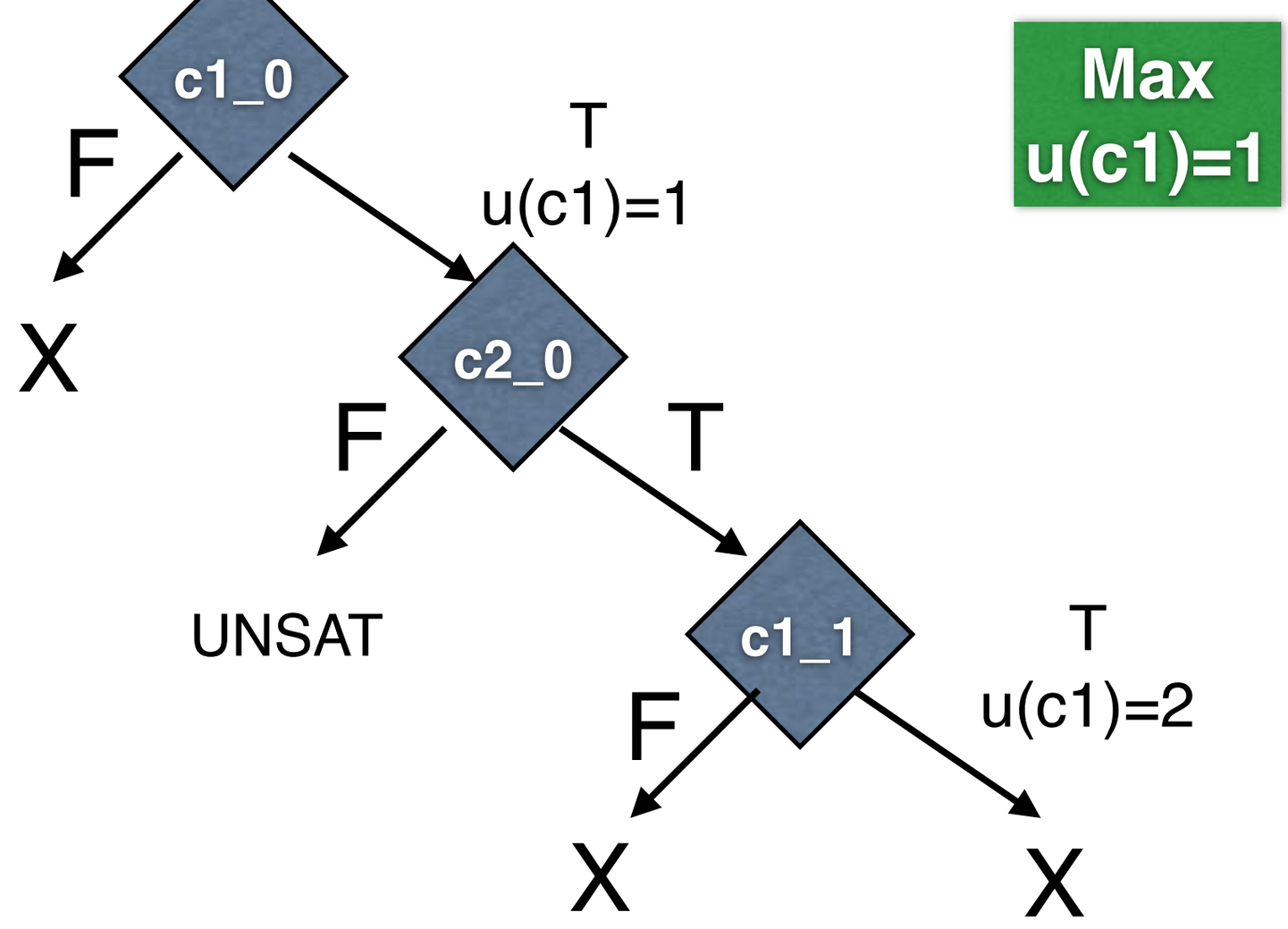
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)	?	
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



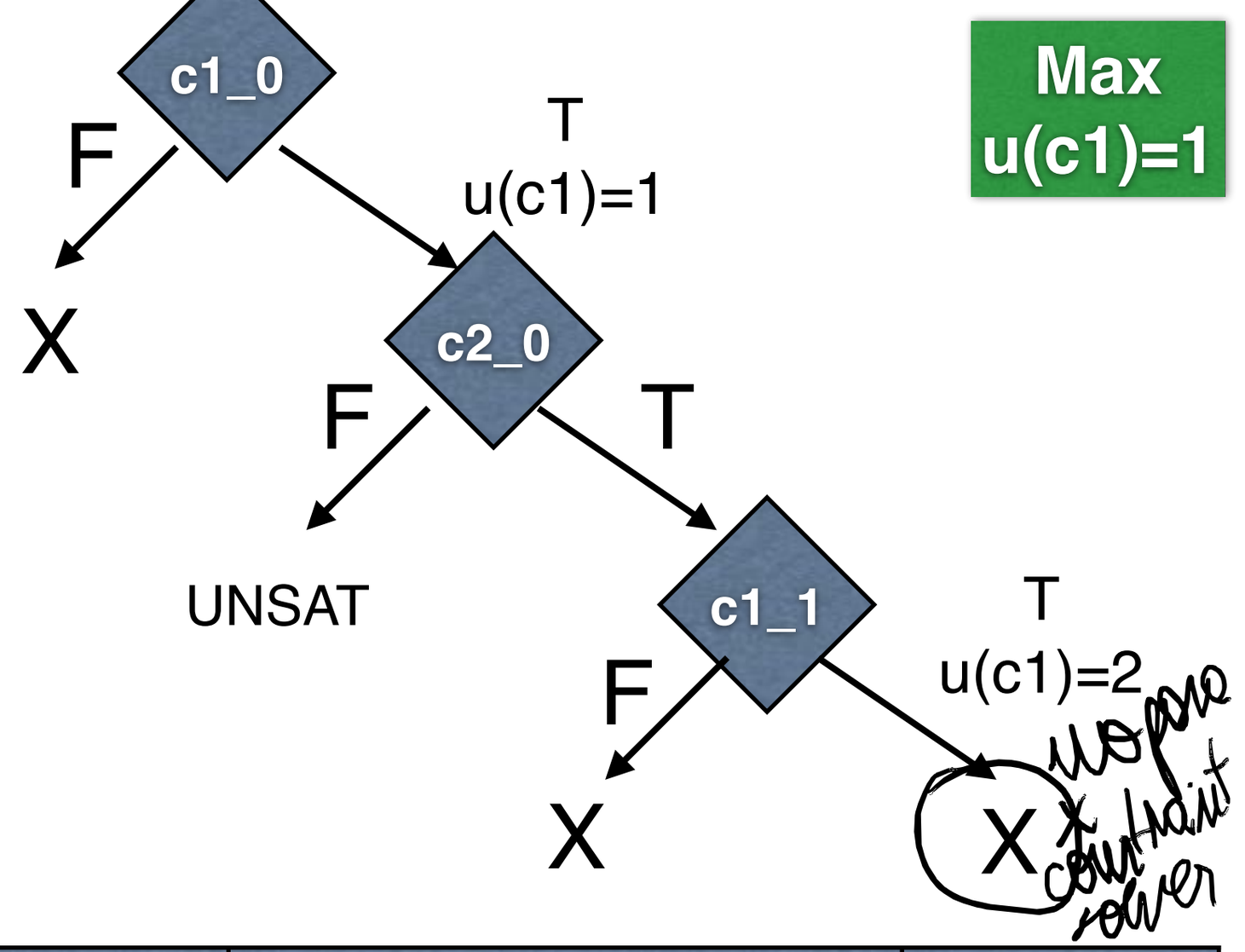
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)	(0<k0) && !(x0%1==0)	?
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
     if (x%(i+1))==0 { //c2
        acc=acc+1;
     }
     i=i+1;
  }
  return acc;
}
```



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)	(0<k0) && !(x0%1==0)	UNSAT
3				
4				

```
int test_me(int x, int k) {
  int acc=0;
  int i=0;
  while (i<k) { //c1
    if (x%(i+1))==0 { //c2
      acc=acc+1;
    }
    i=i+1;
  }
  return acc;
}
```



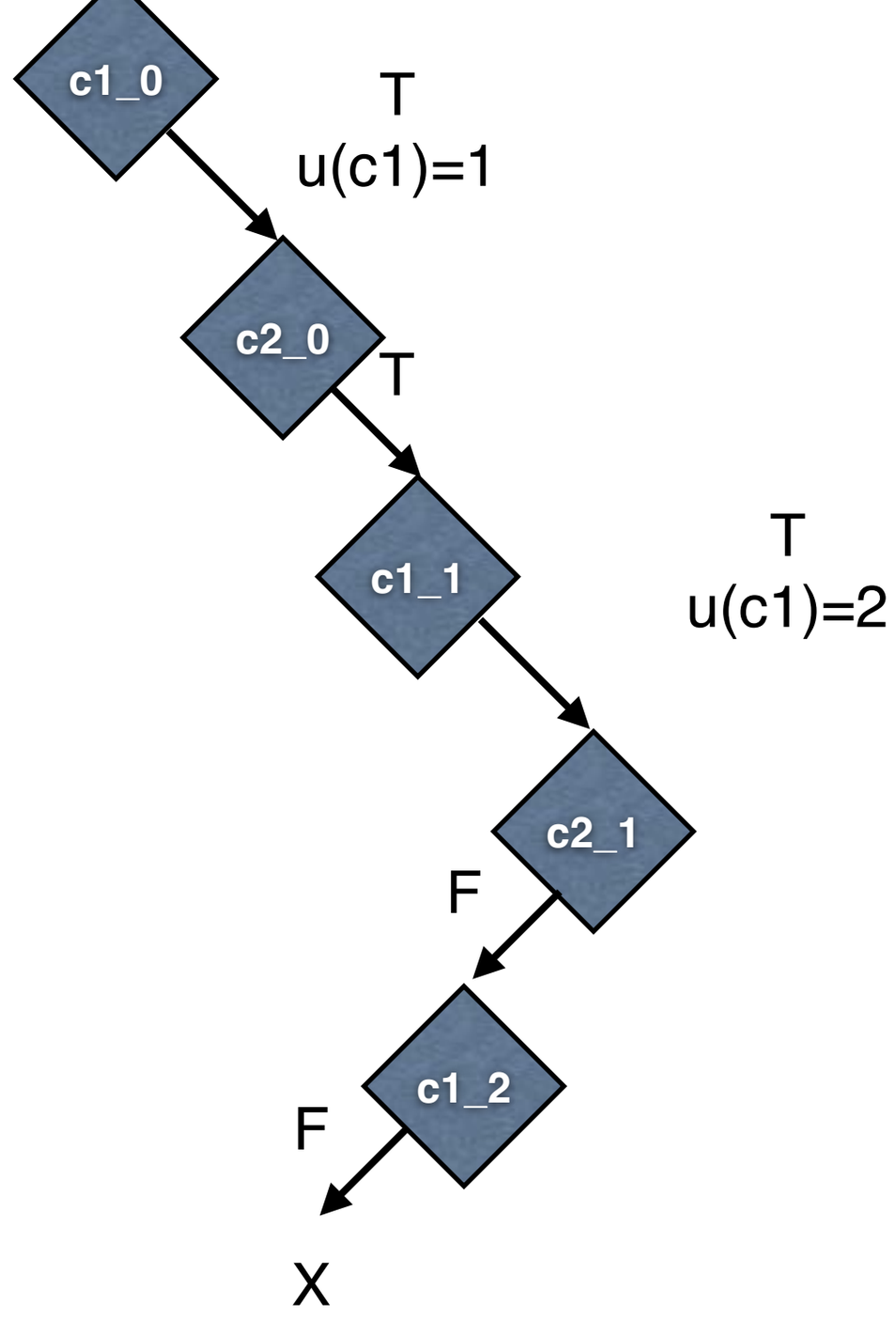
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	x=0,k=0	!(0<k0)	0<k0	k0=1
2	x=0,k=1	(0<k0) && (x0%1==0) && !(1<k0)	(0<k0) && !(x0%1==0)	UNSAT
3	FIN			
4				

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```

Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	?		

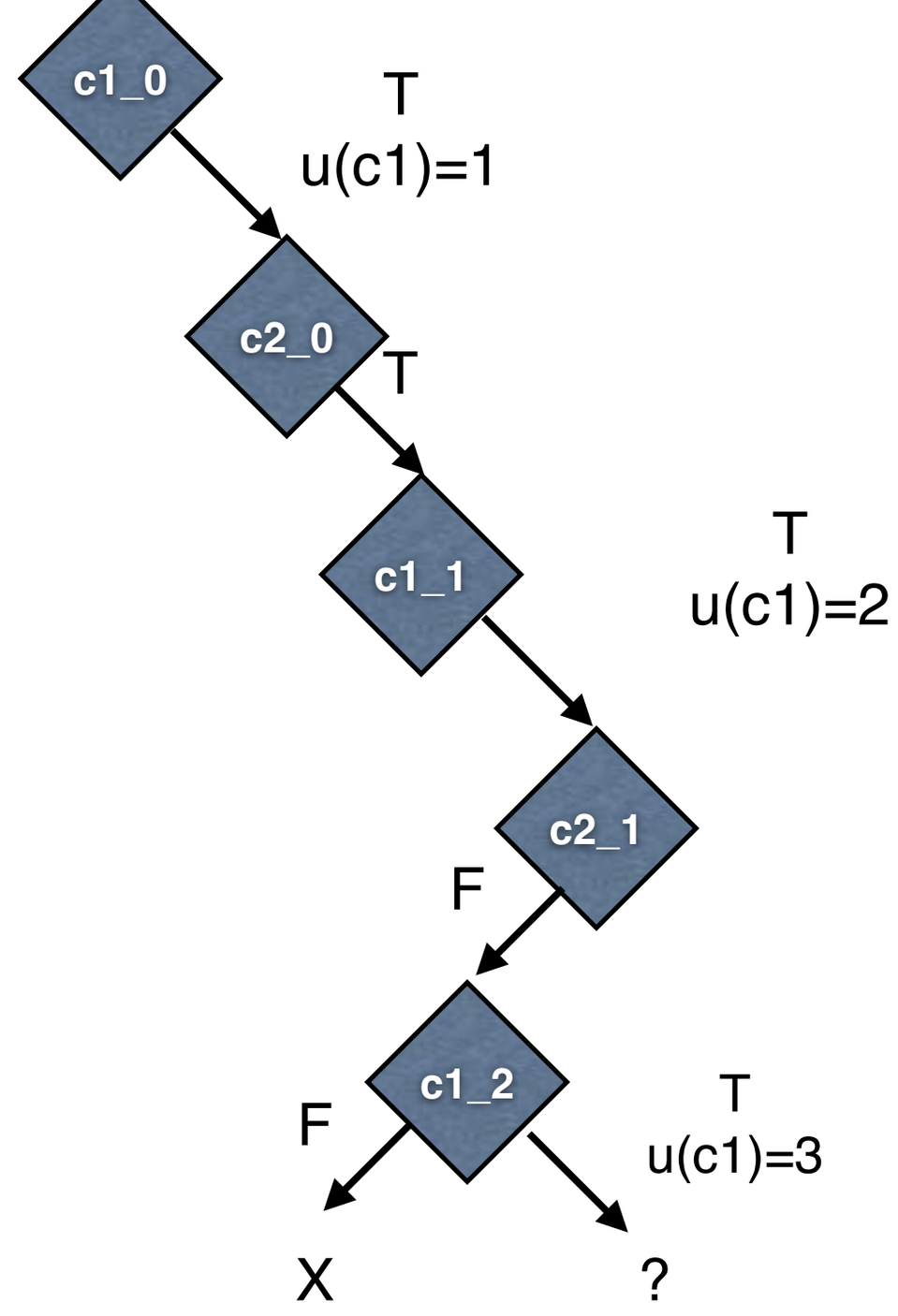
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)		

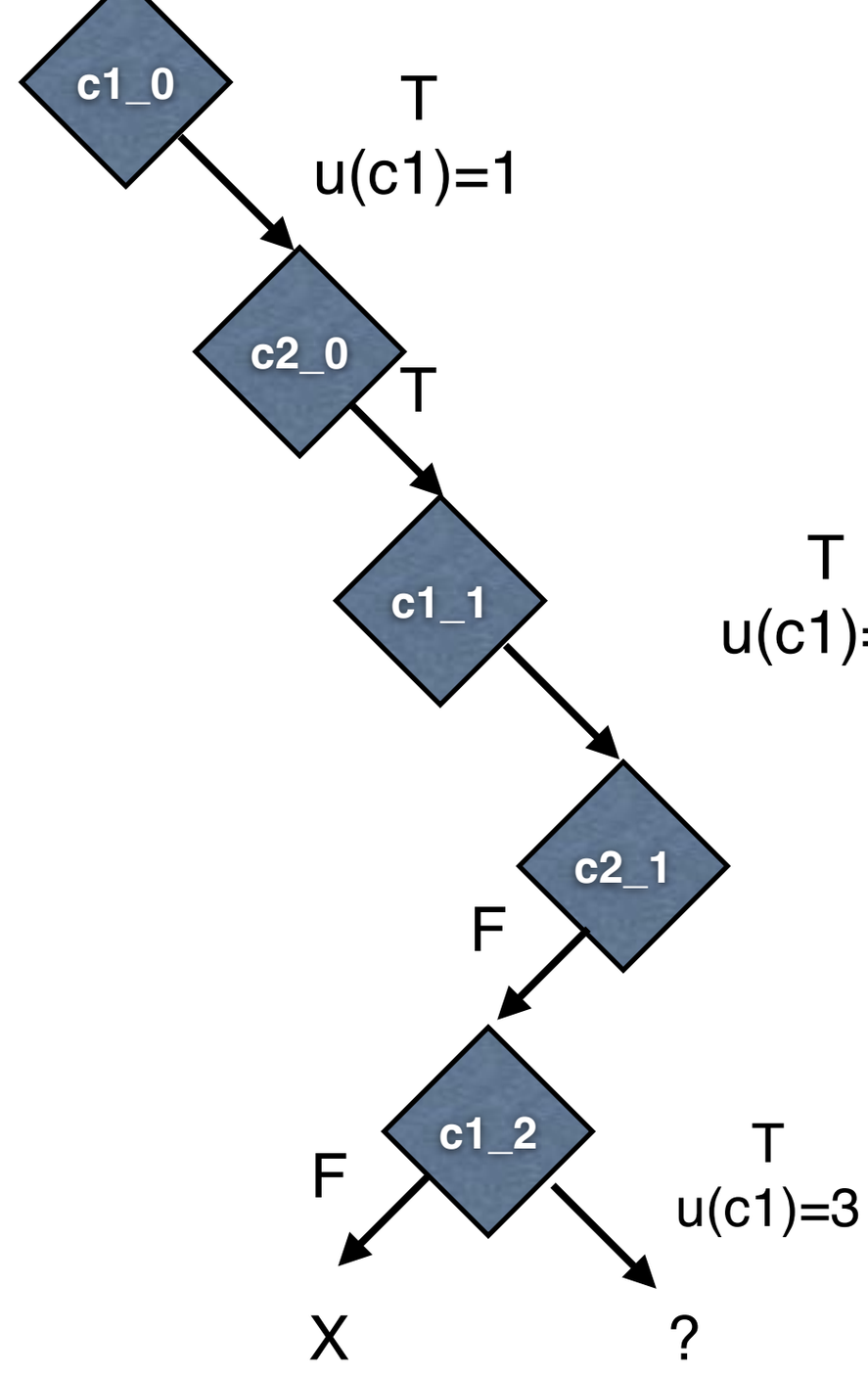
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	?	

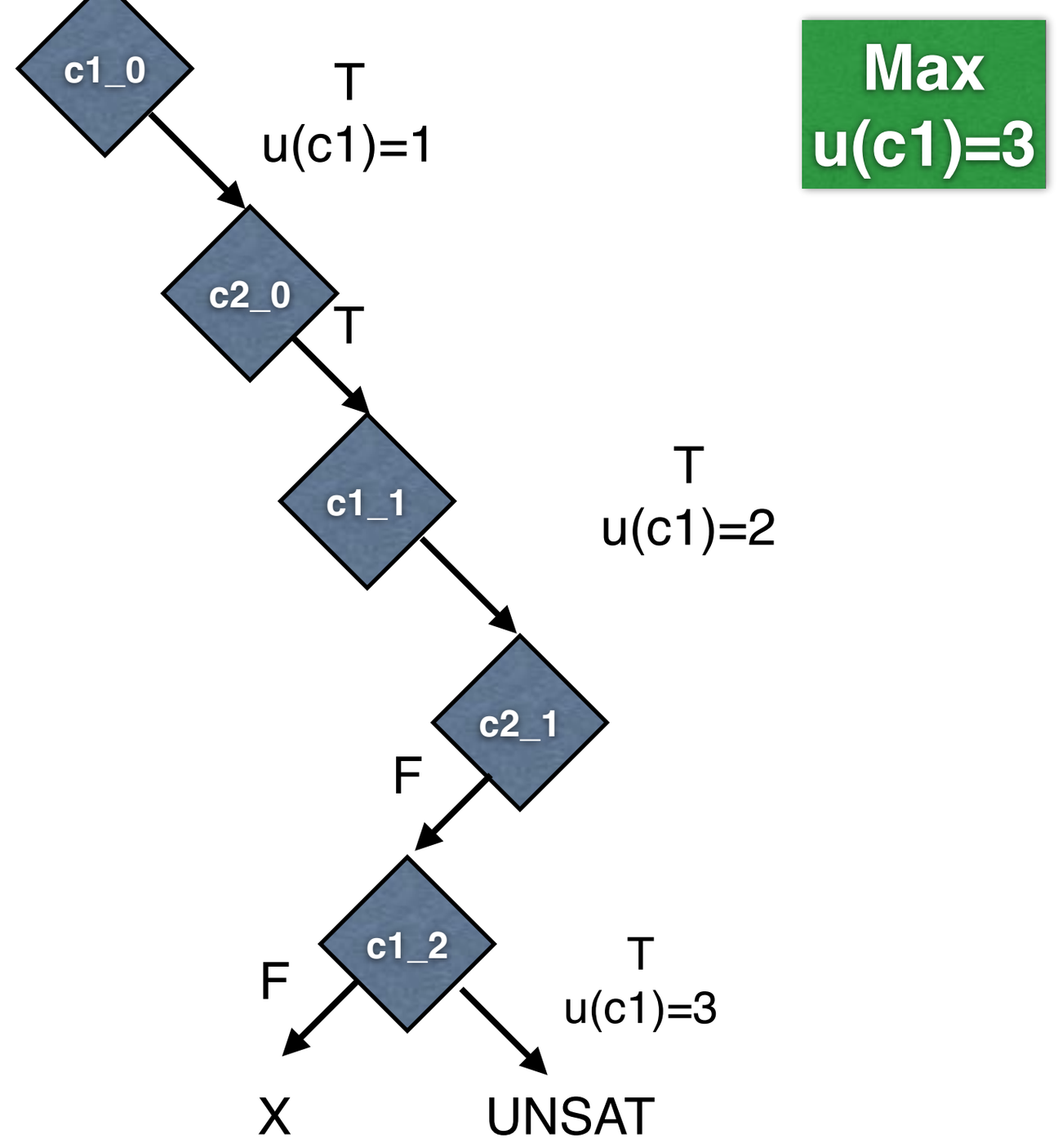
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	?

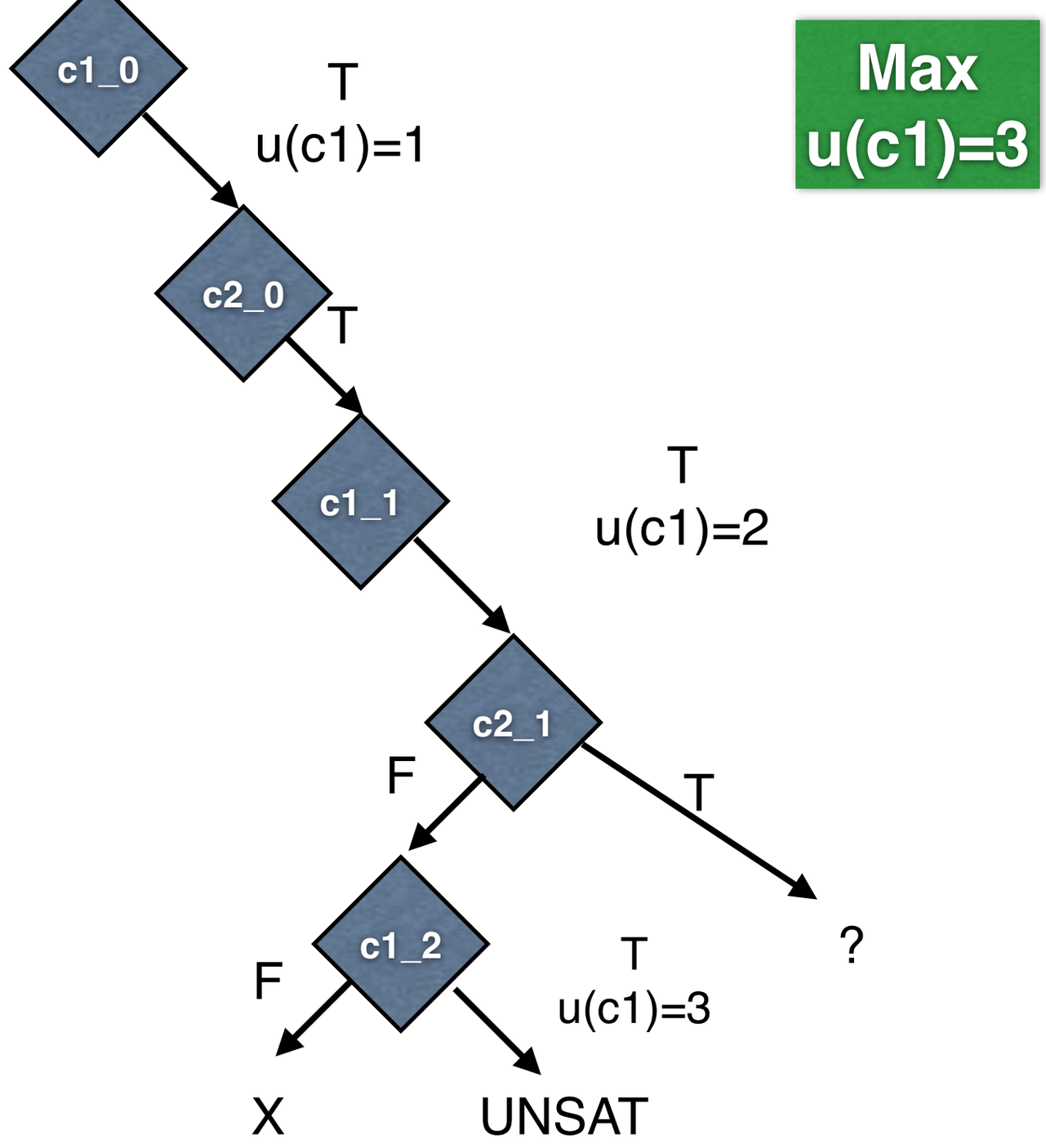
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT

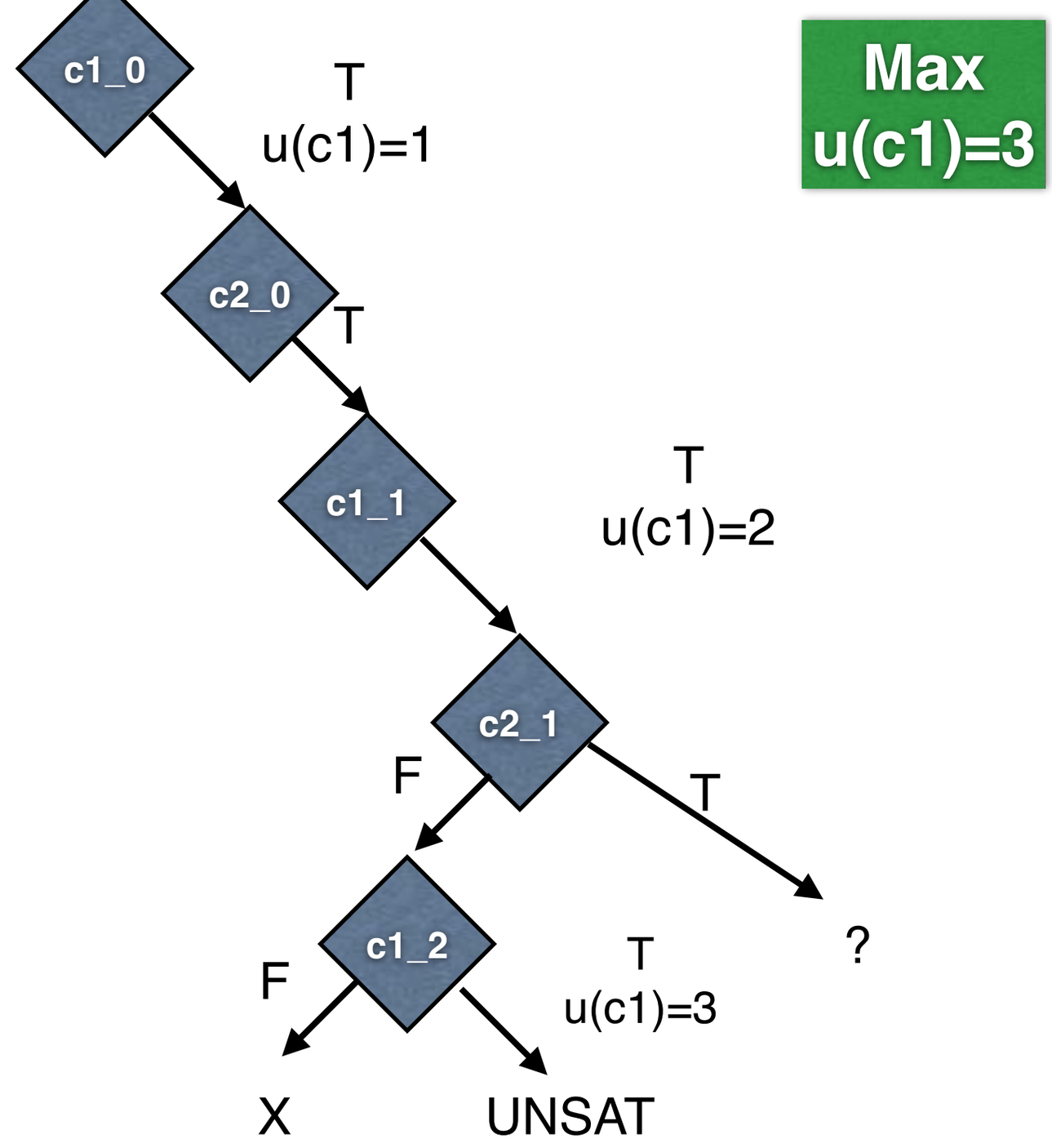
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			?	

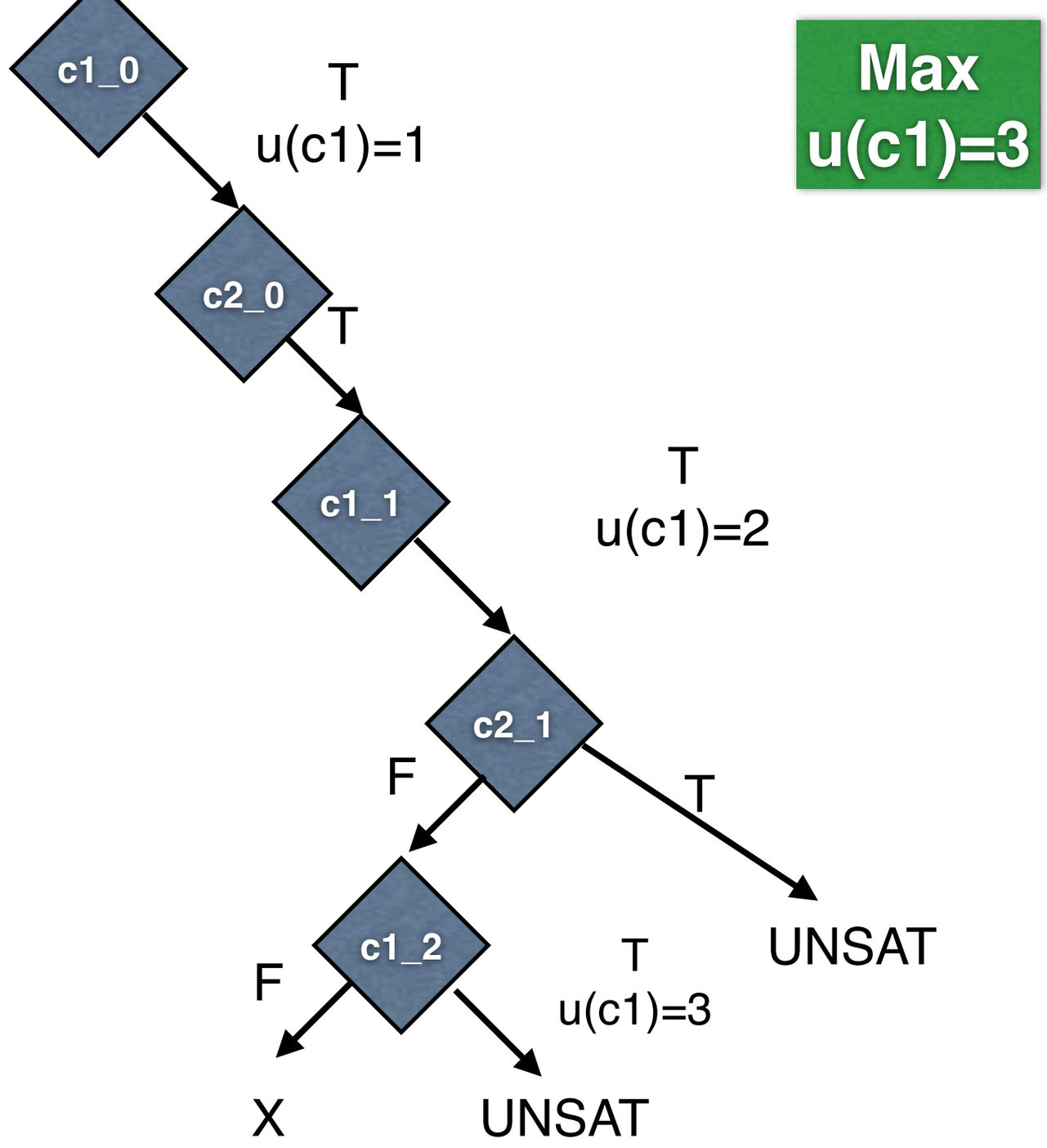
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	?

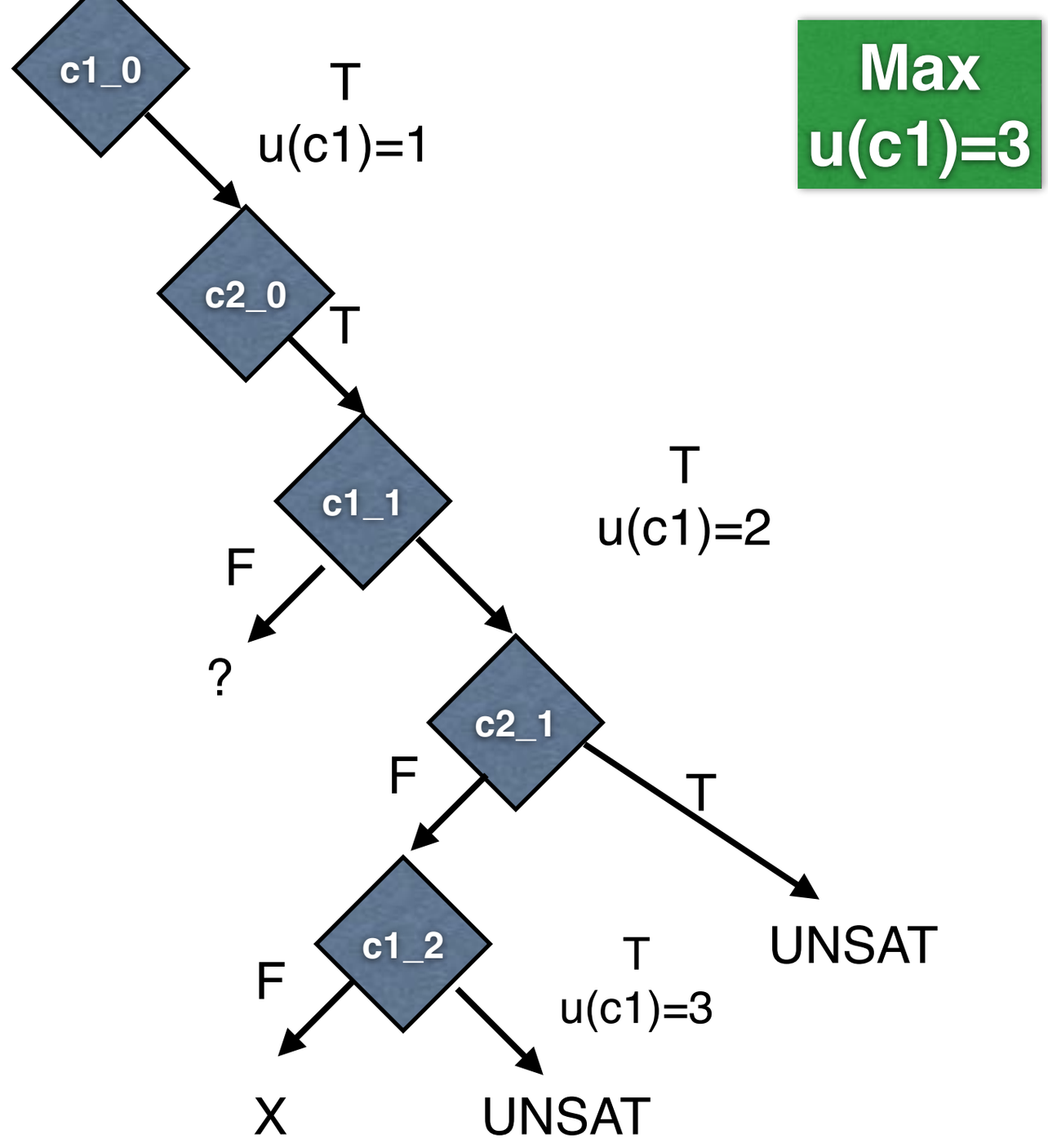
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT

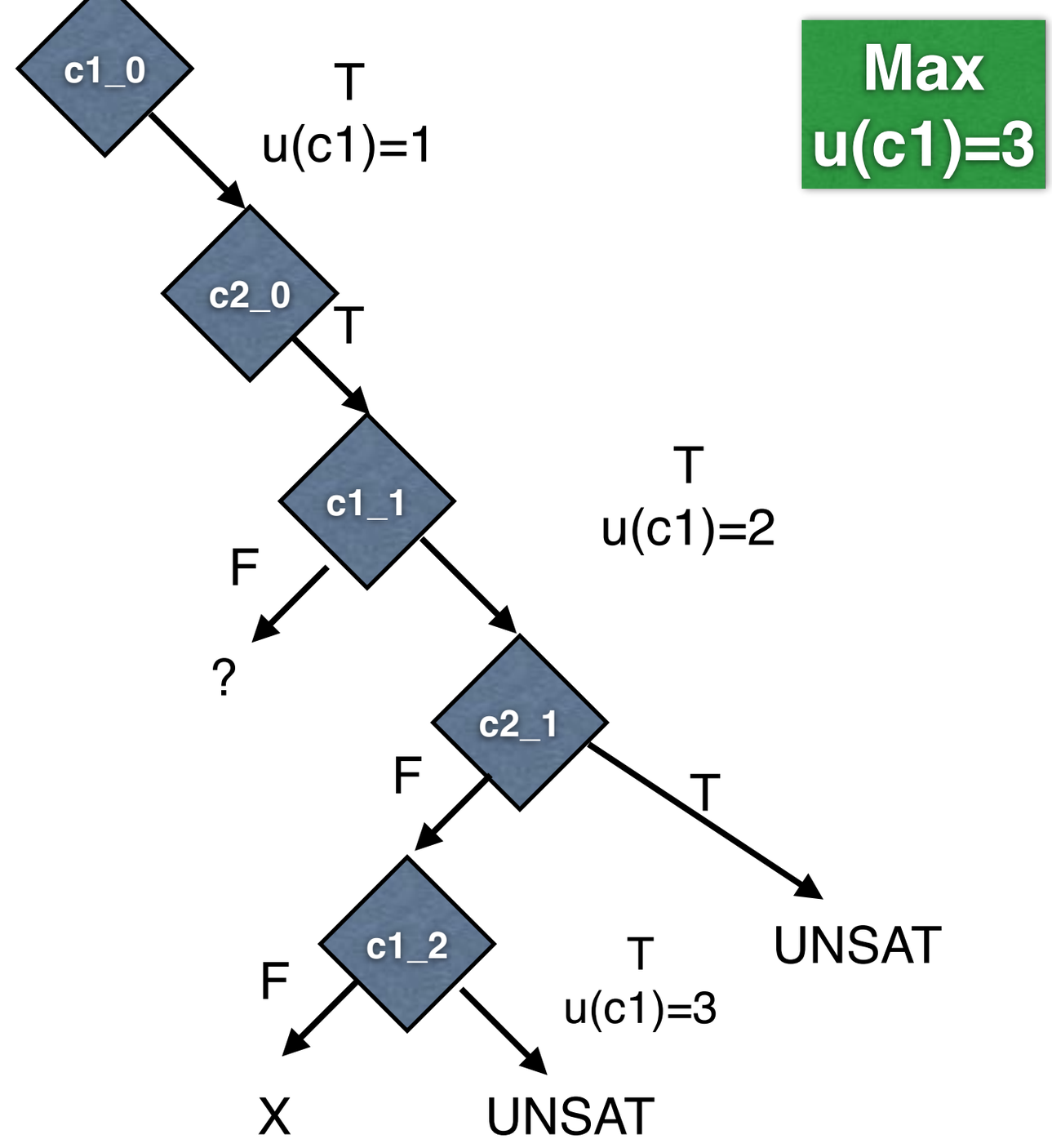
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			?	

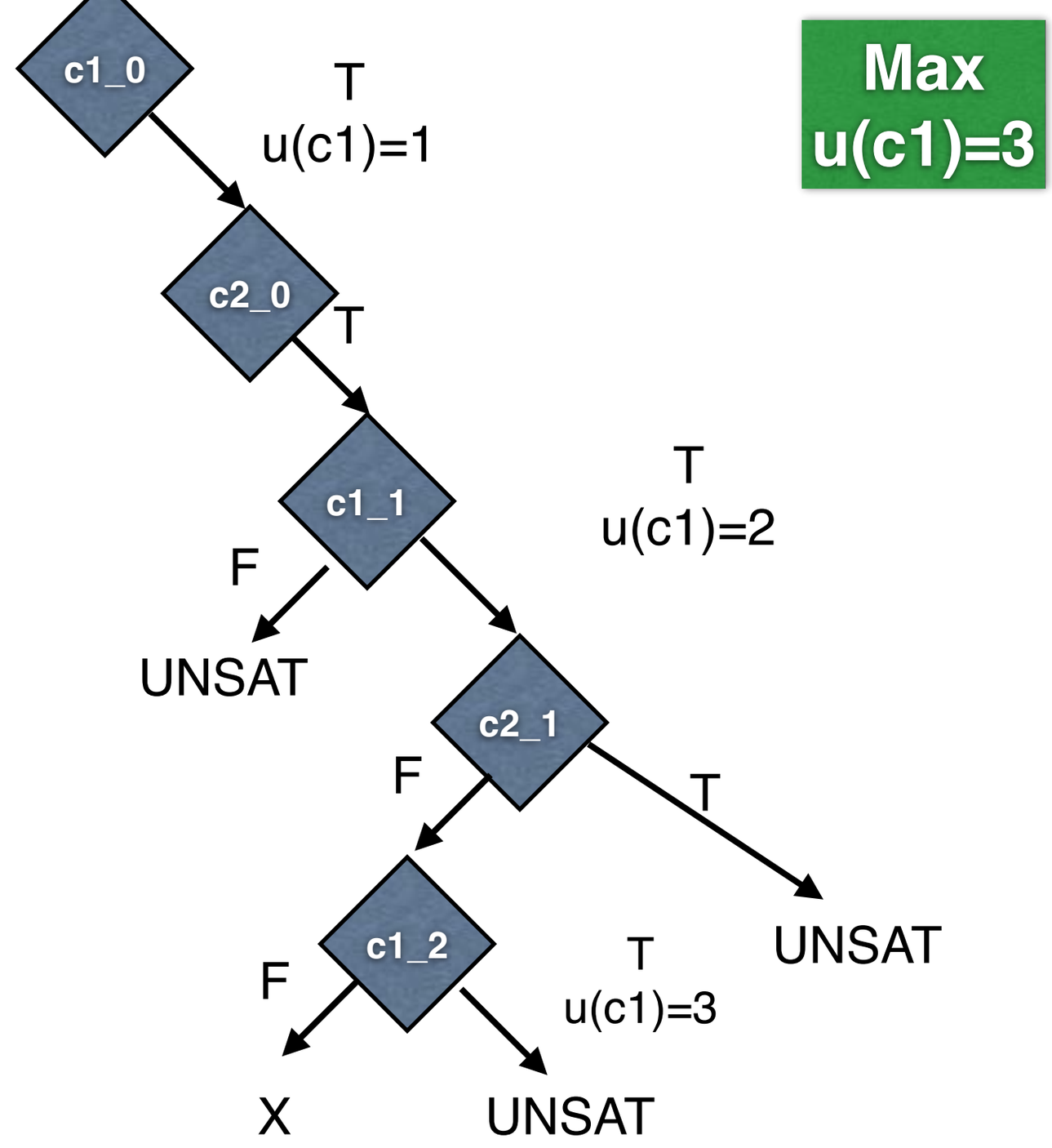
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	?

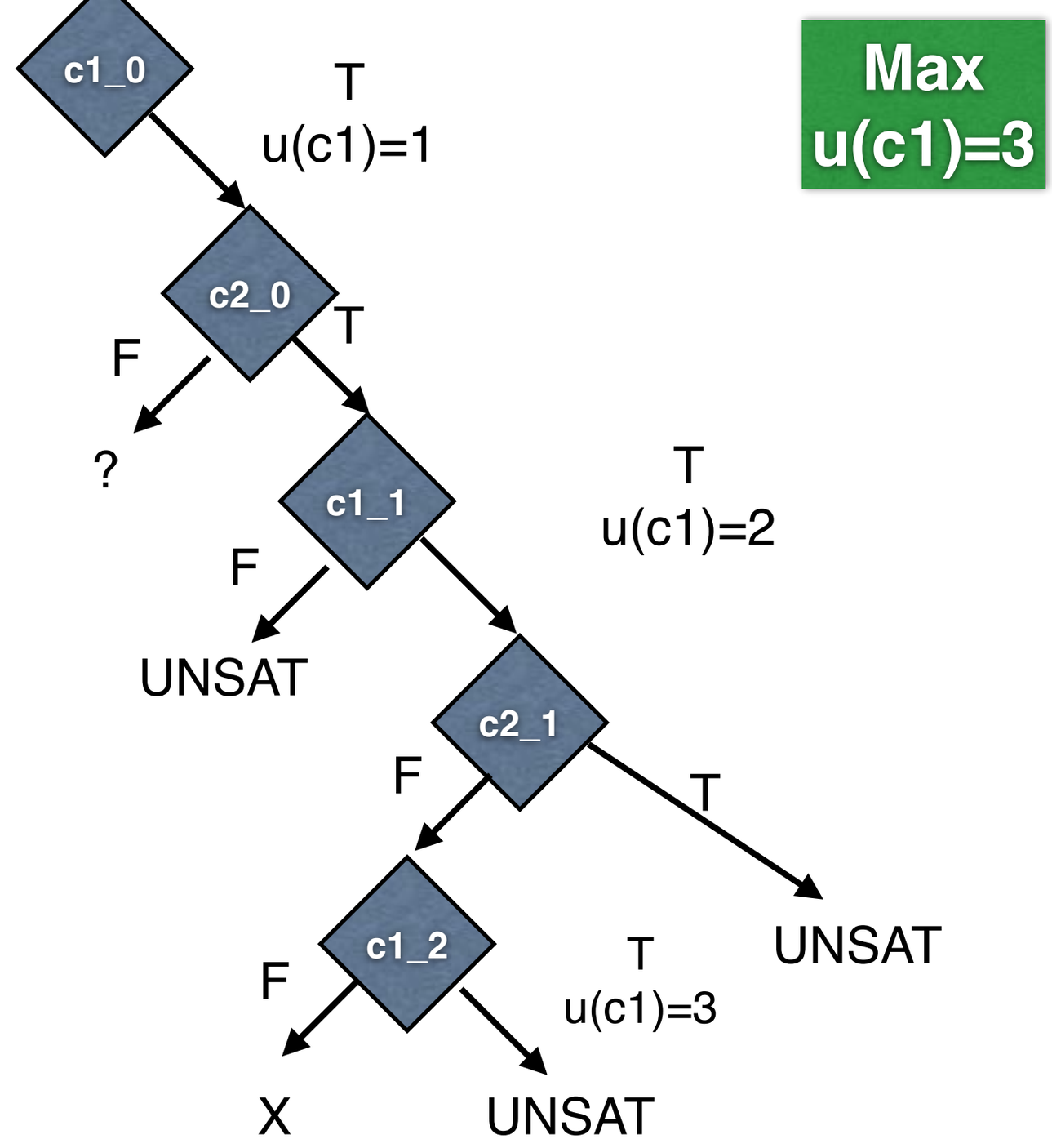
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(1<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(1<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	UNSAT

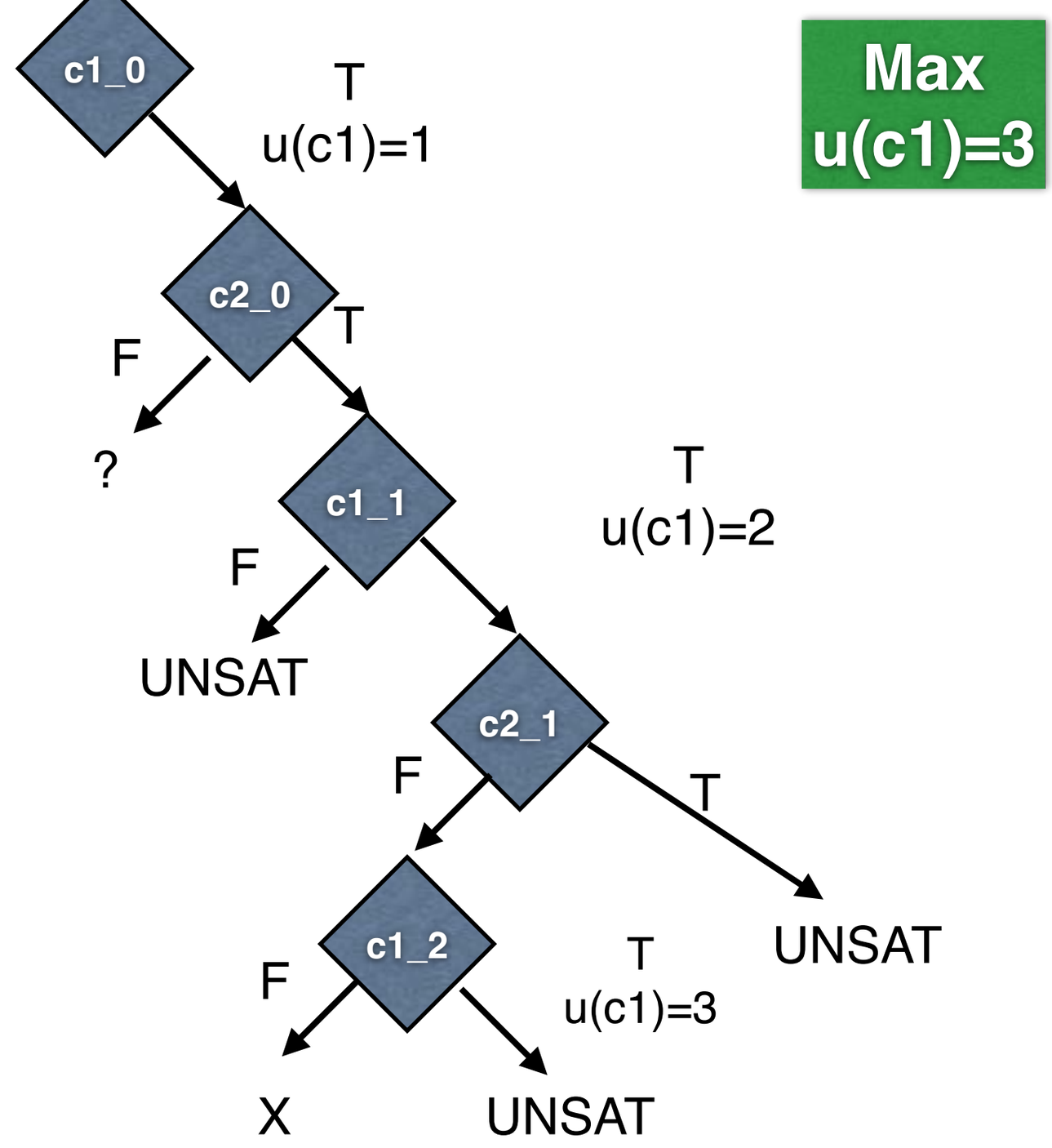
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	UNSAT
			?	

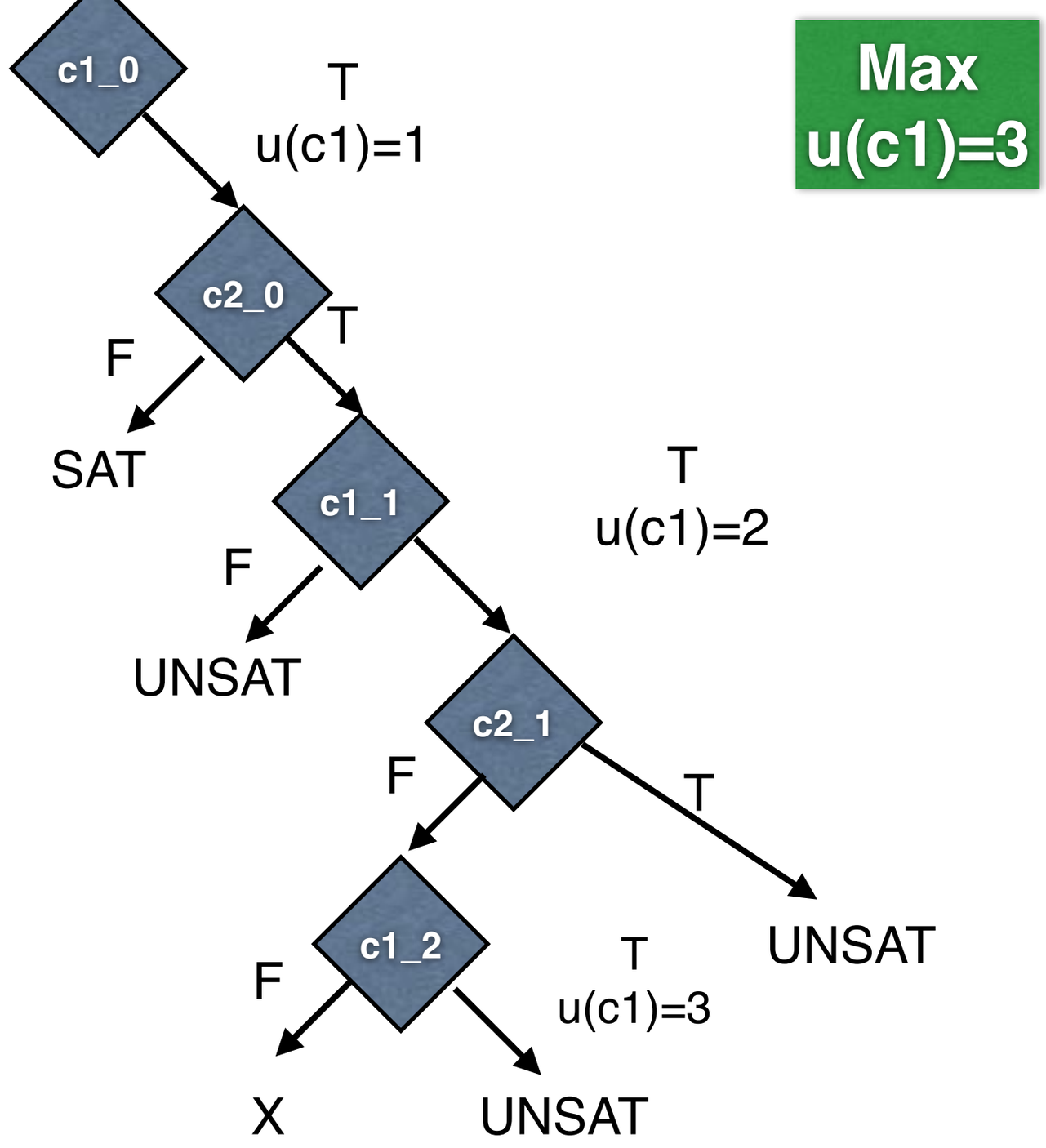
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	UNSAT
			(0<2)&&!(0==j0)	?

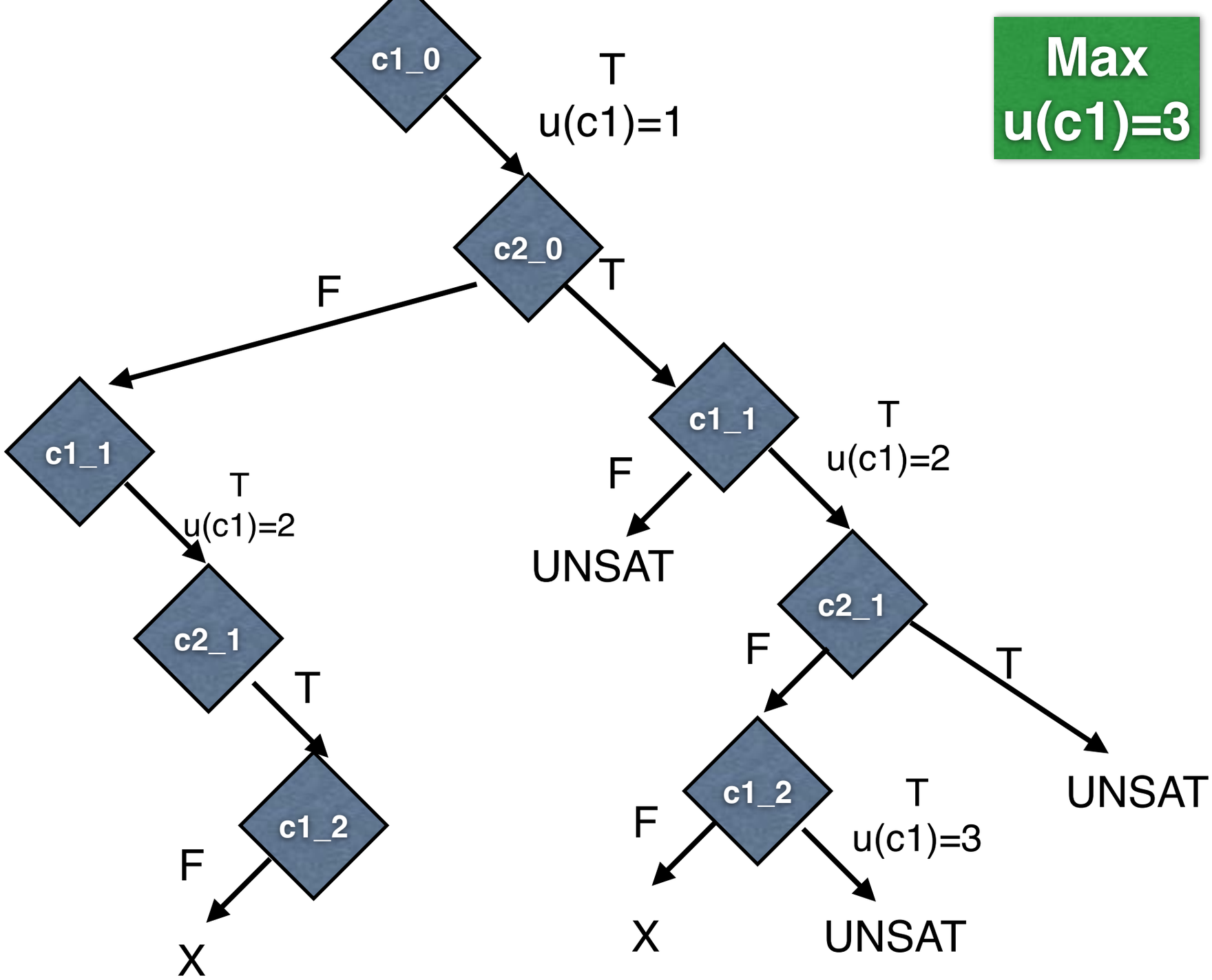
```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Max u(c1)=3

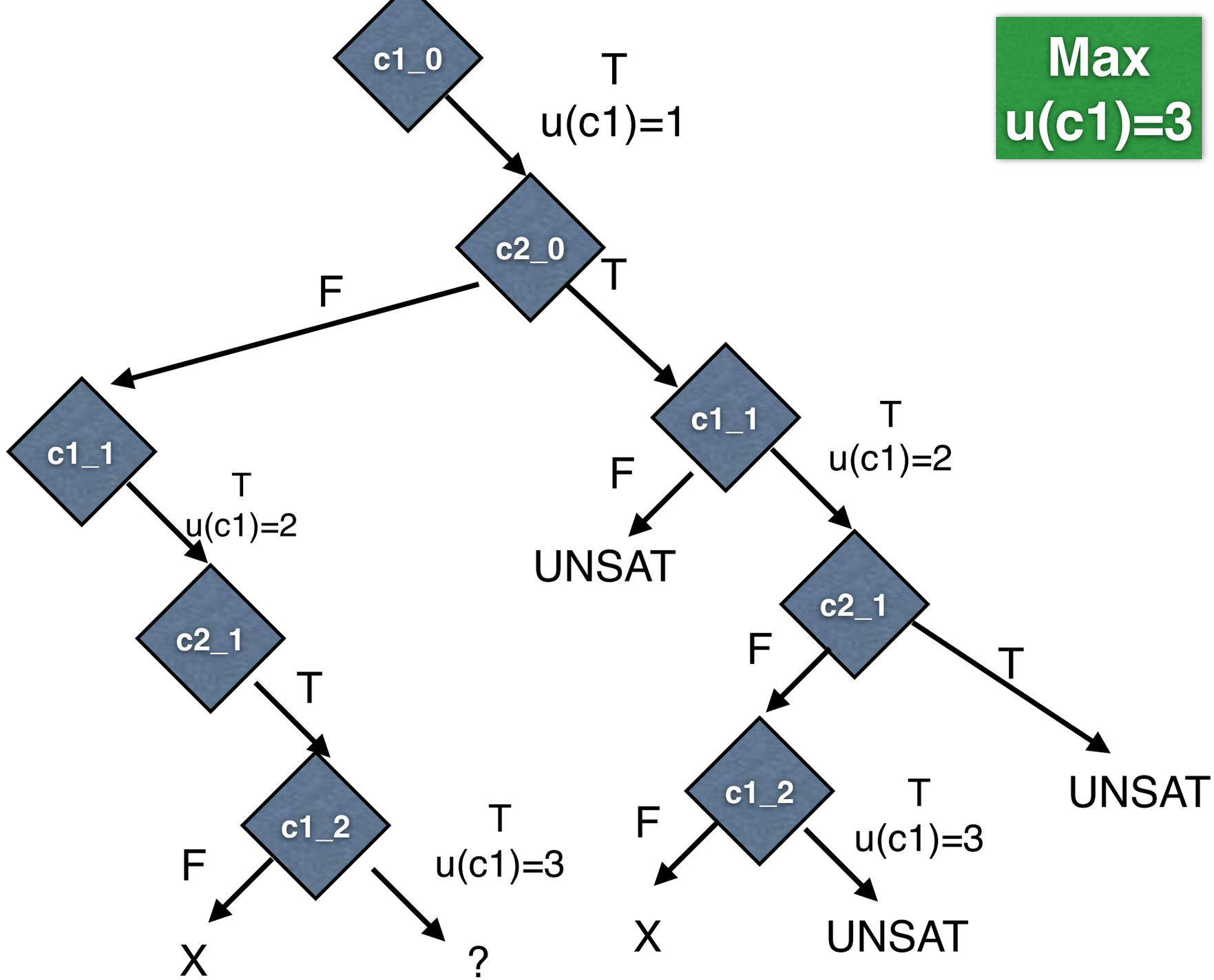
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(1<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(1<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	UNSAT
			(0<2)&&!(0==j0)	j0=1

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



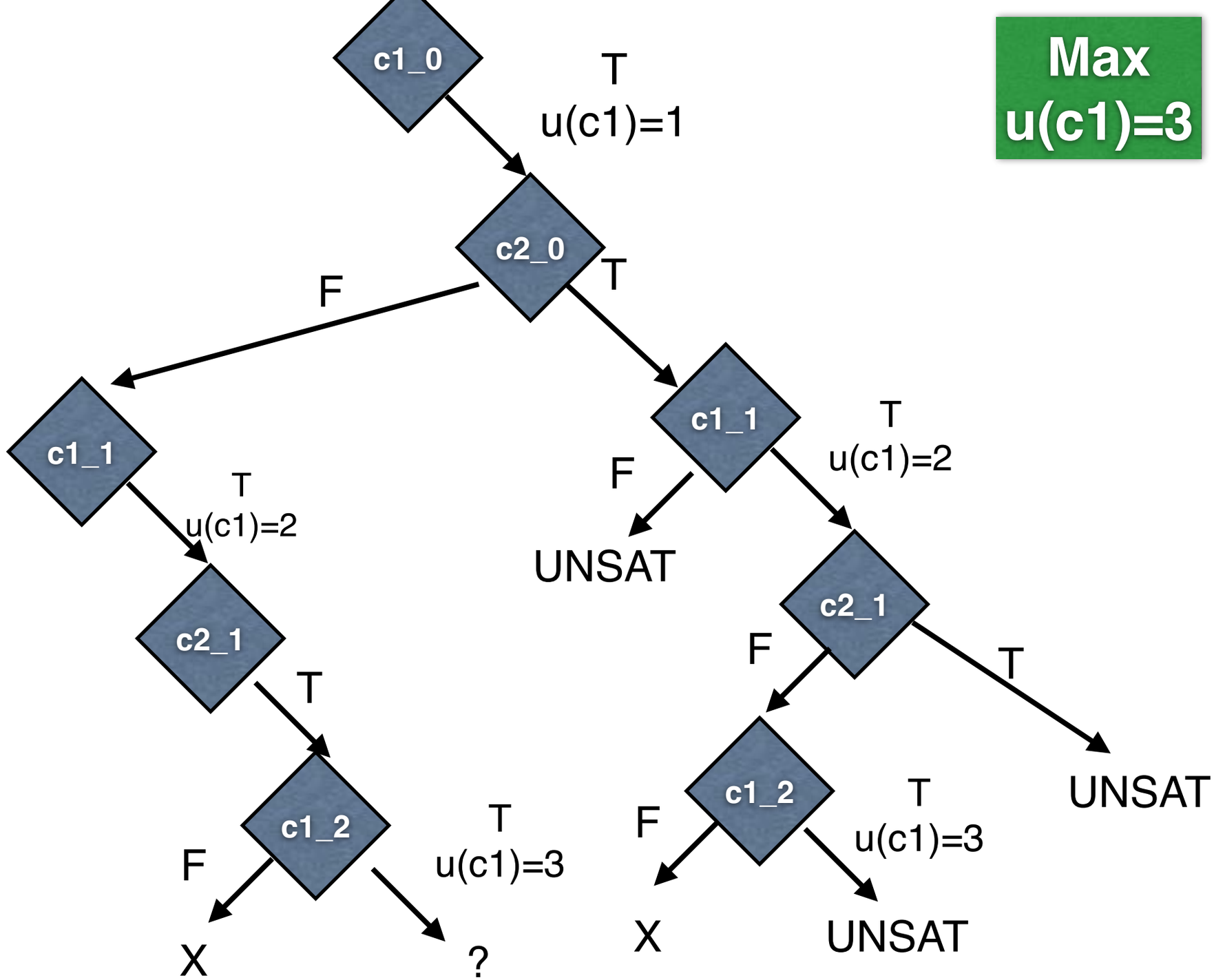
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)		

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



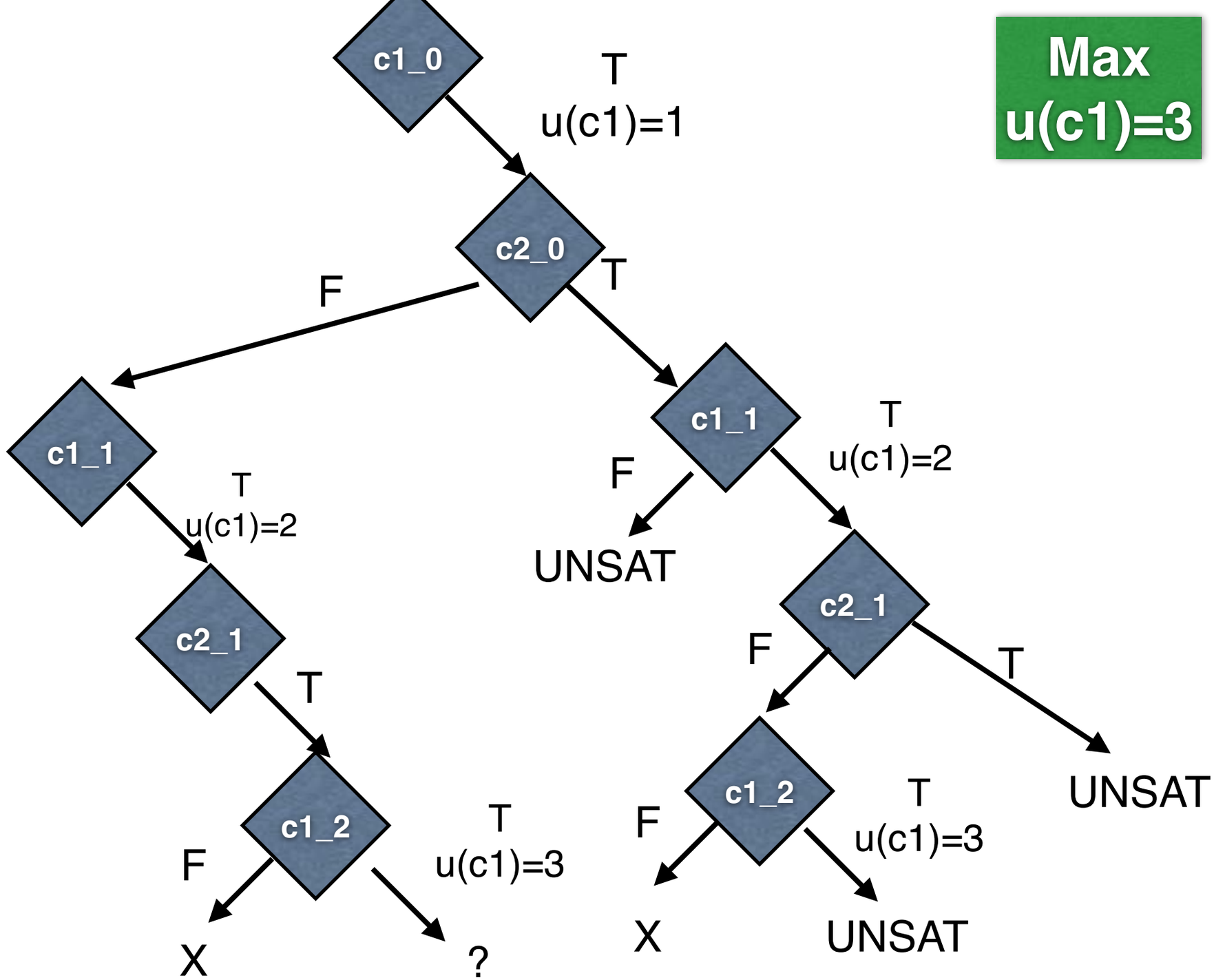
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)		

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



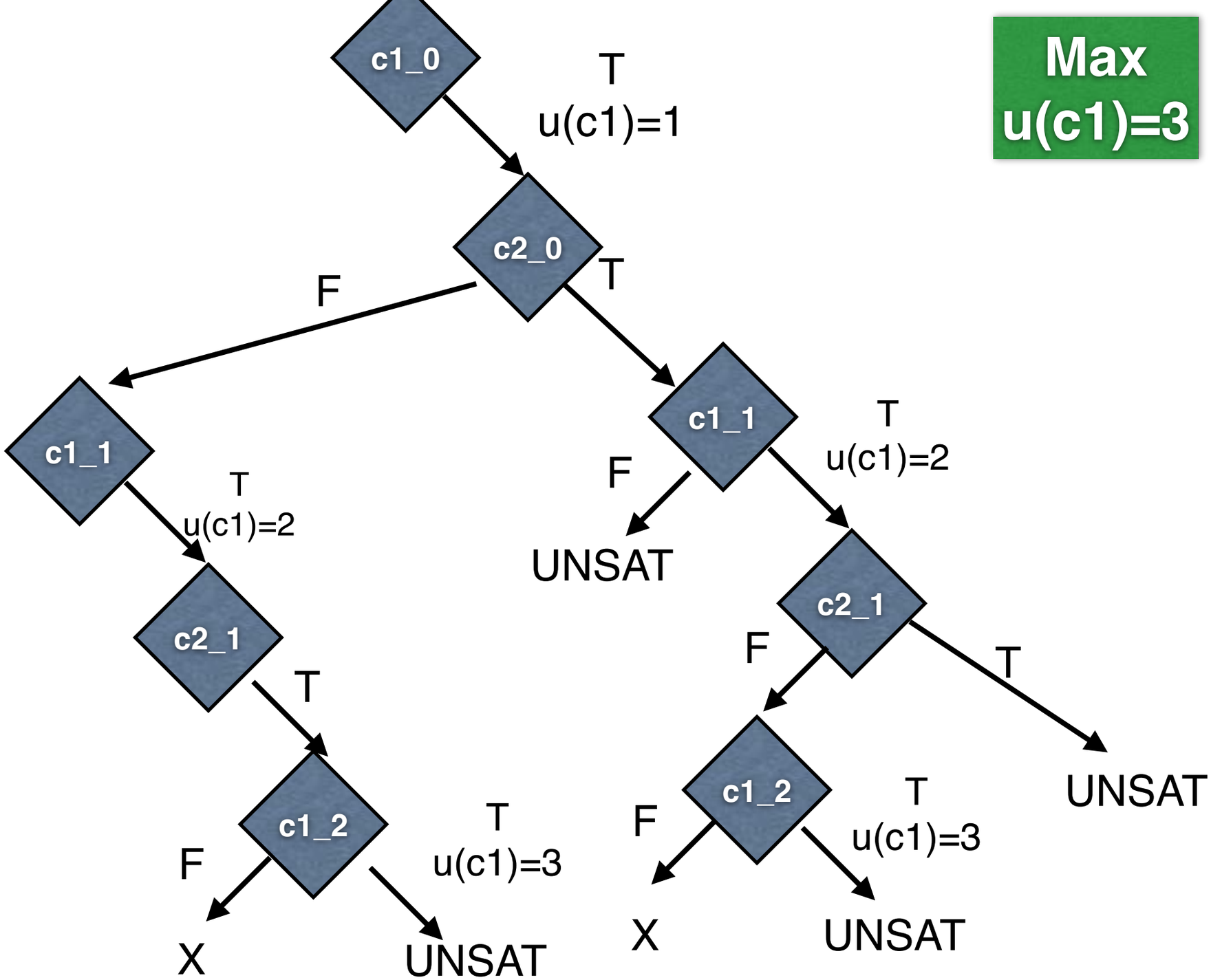
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	?	

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



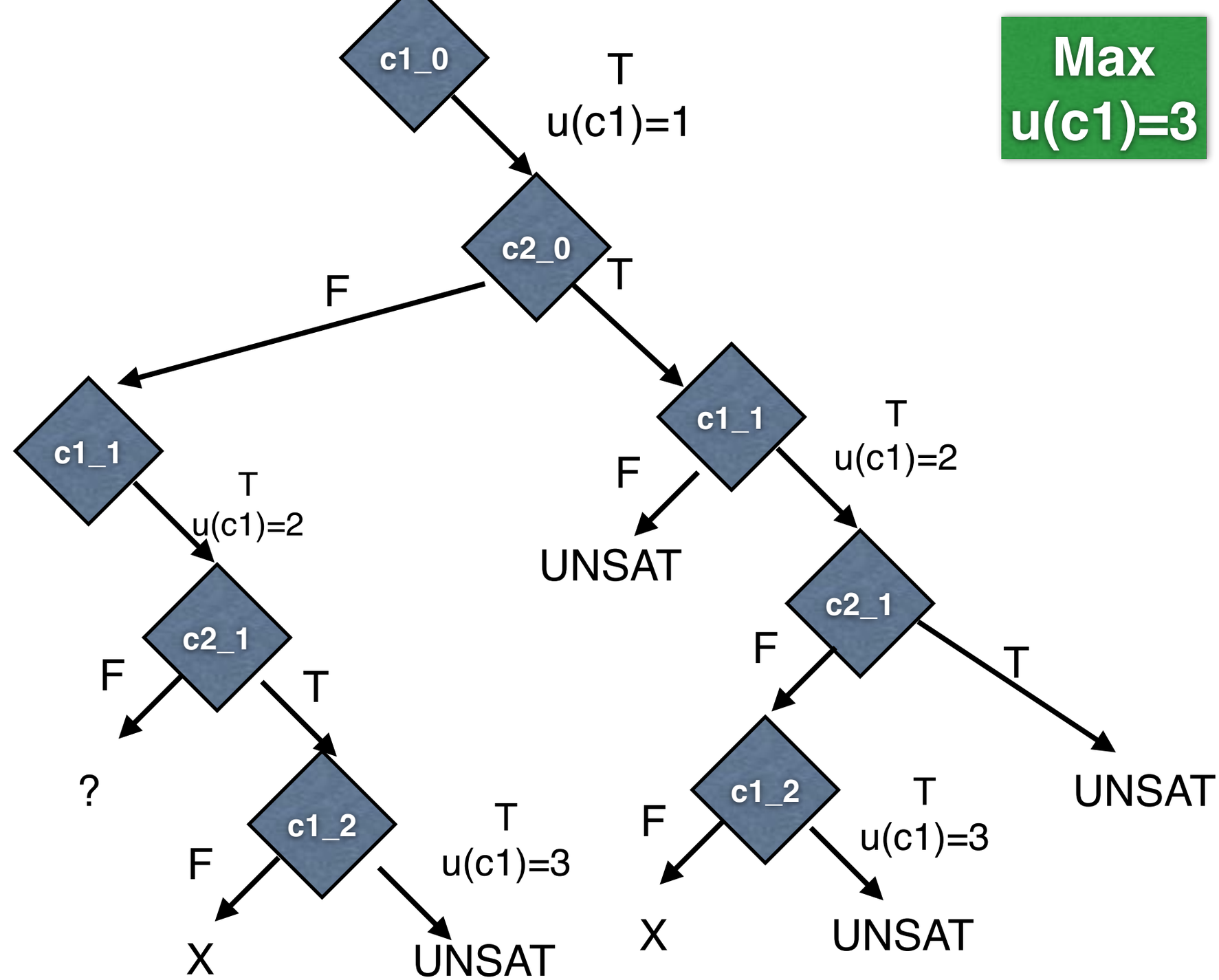
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	?

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



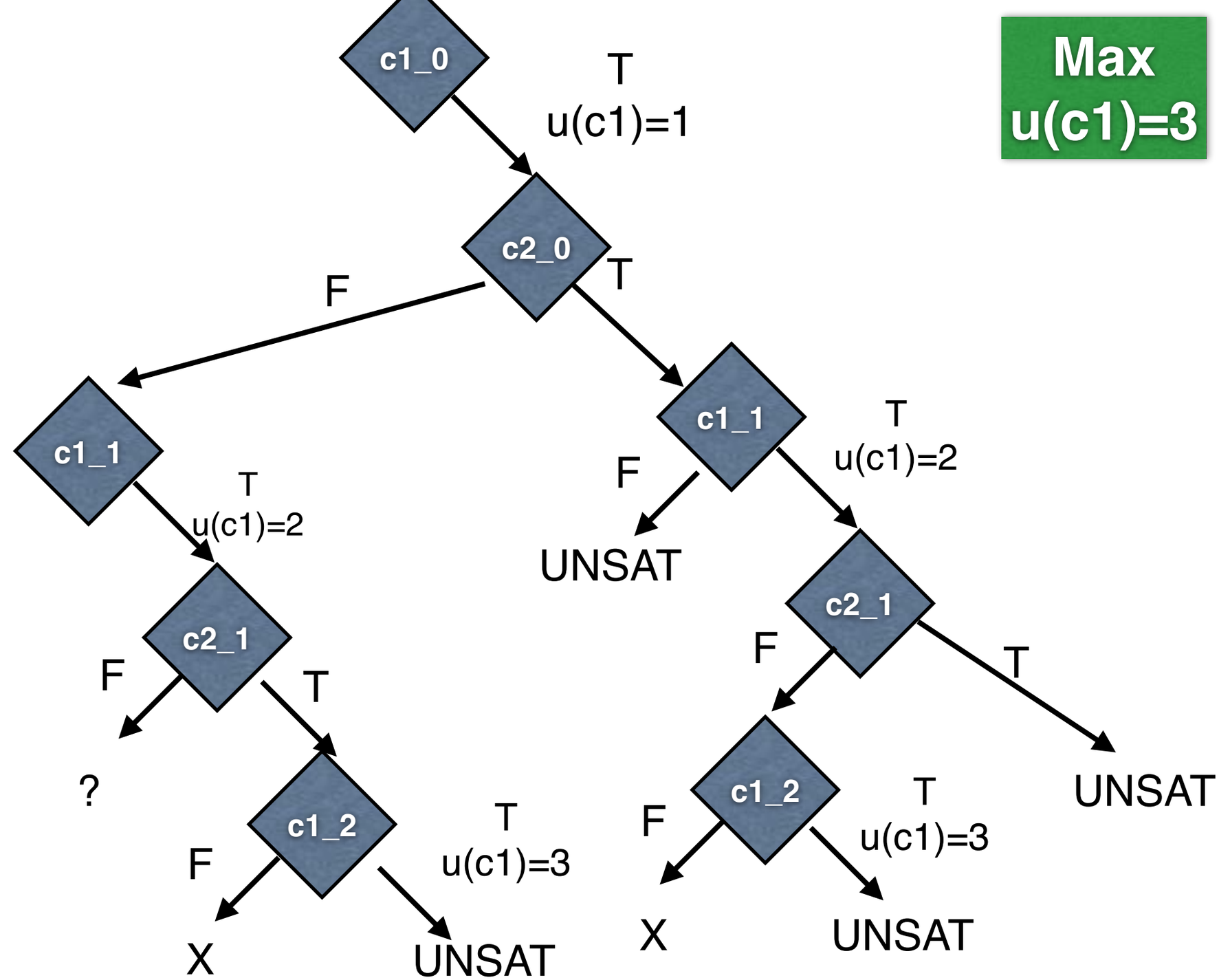
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



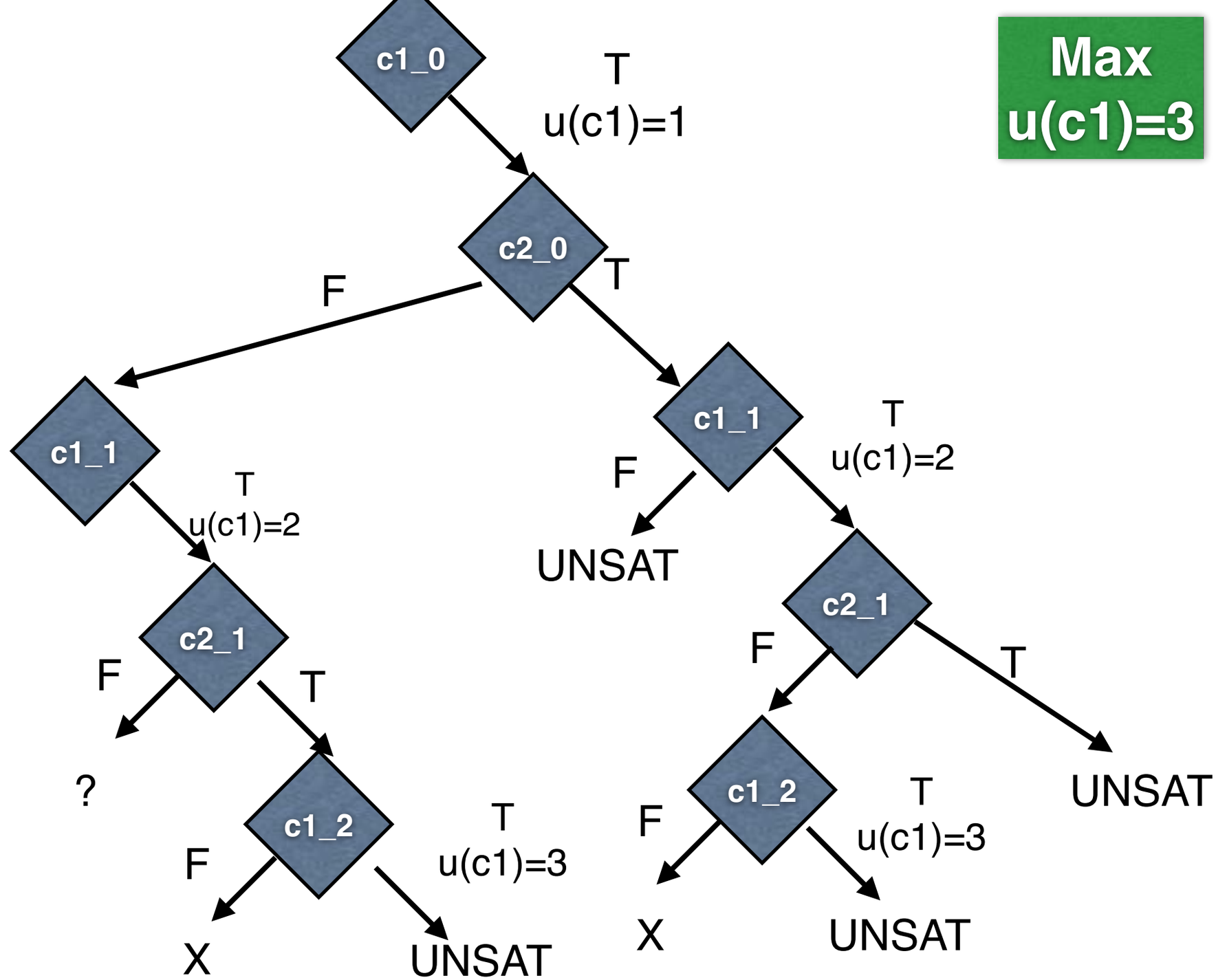
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



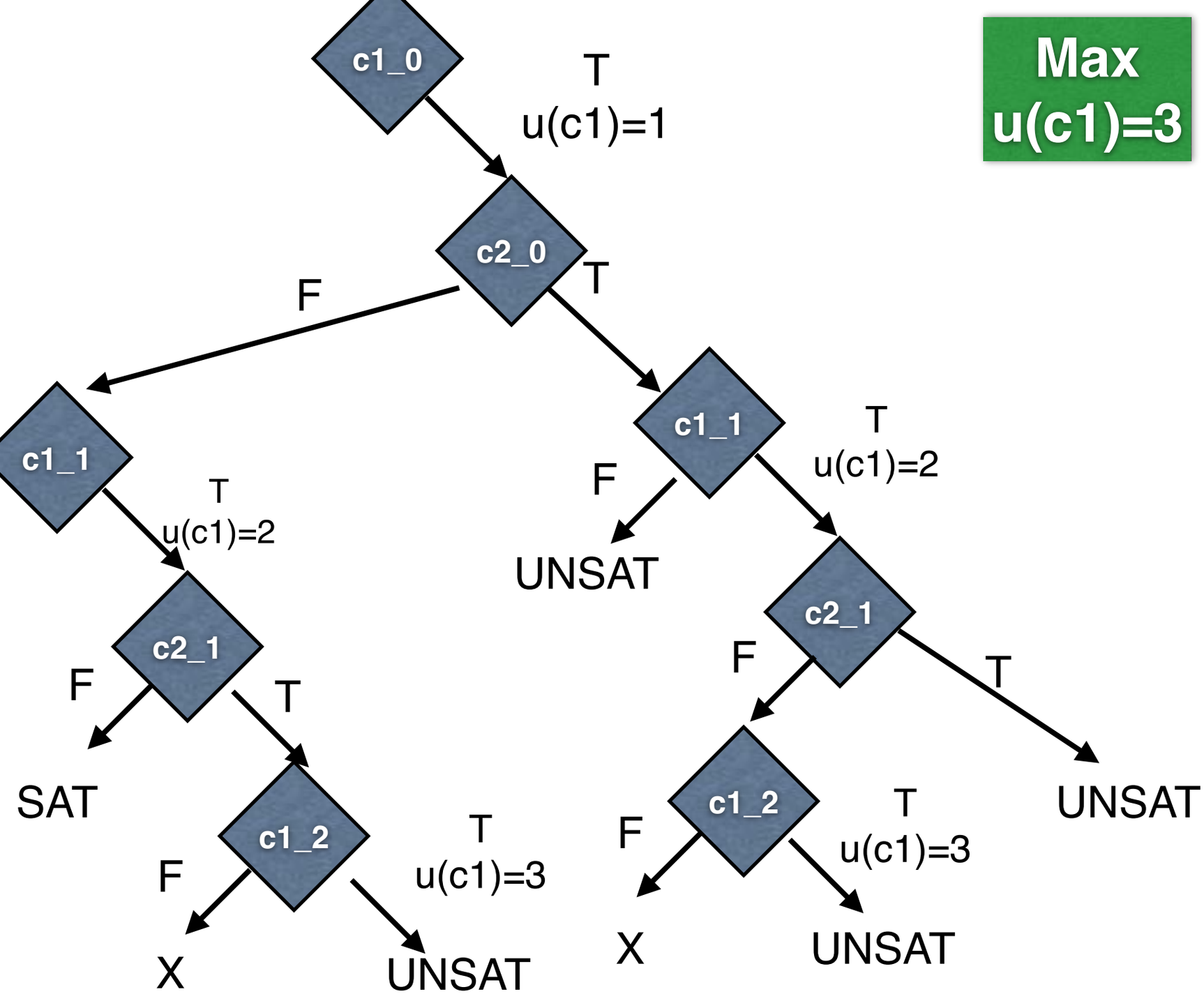
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			?	

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```



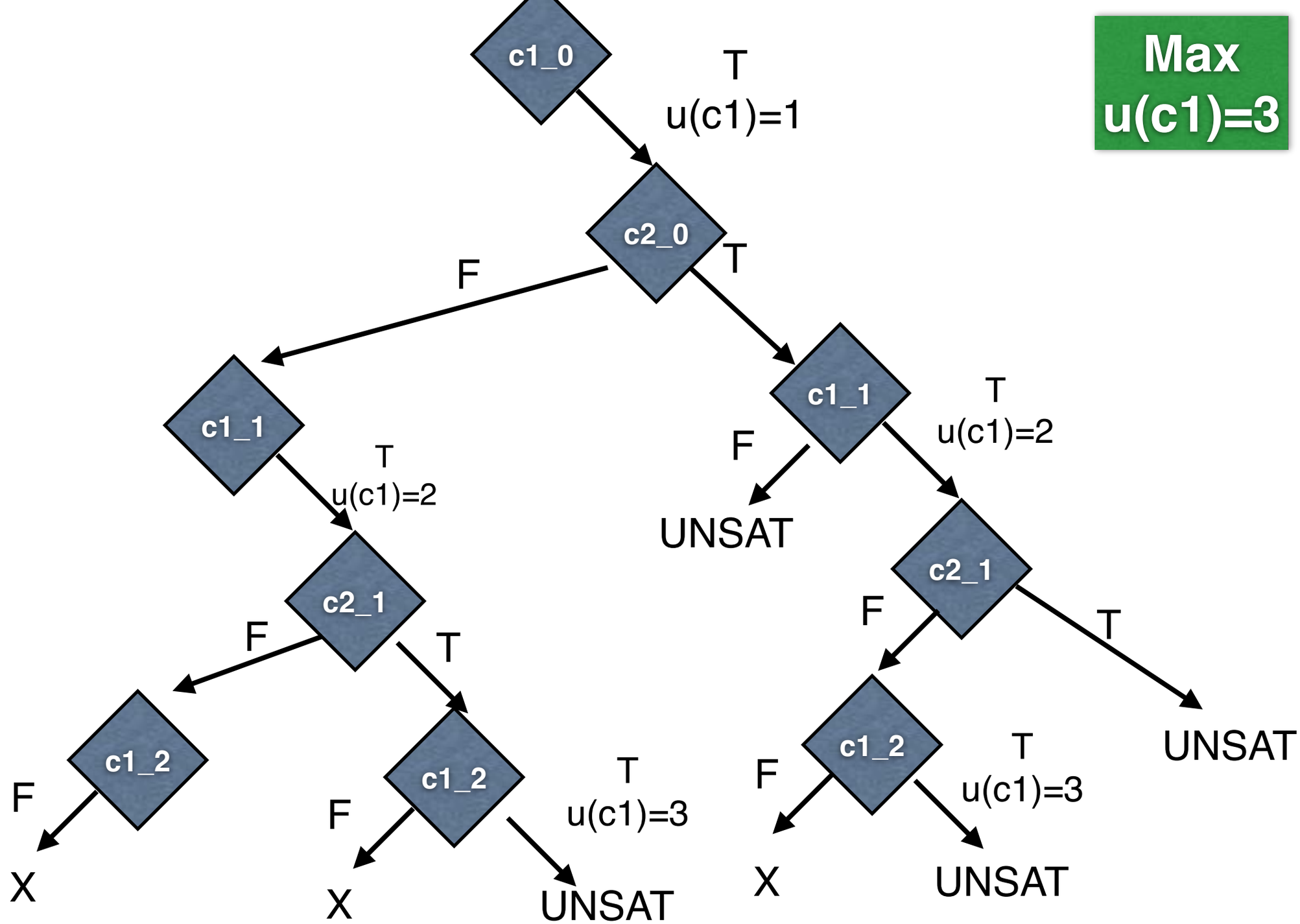
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)	?

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



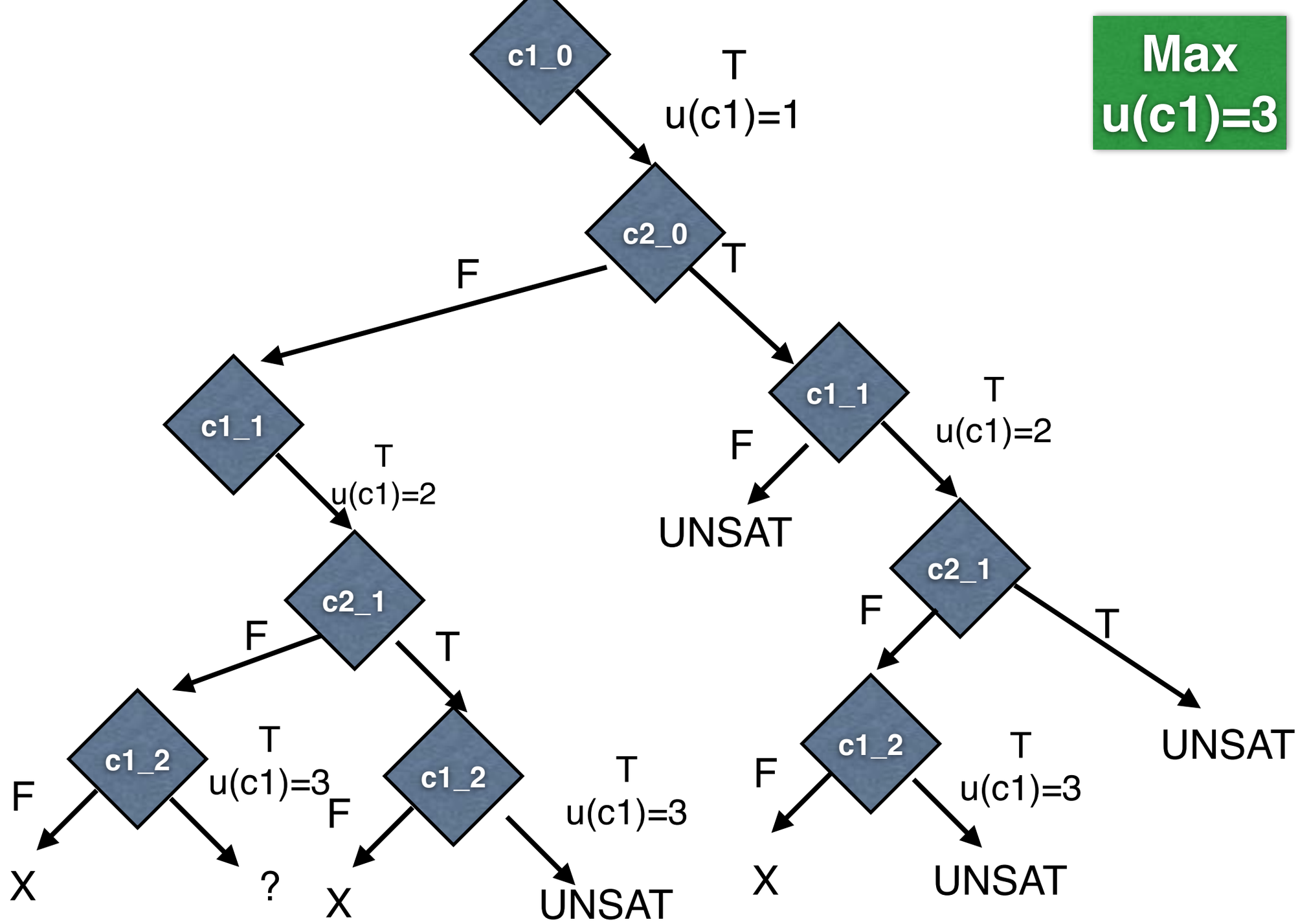
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)	j0=2

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)		

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)		

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  int r=0;
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        r=r+1;
     }
     i=i+1;
  }
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}
```

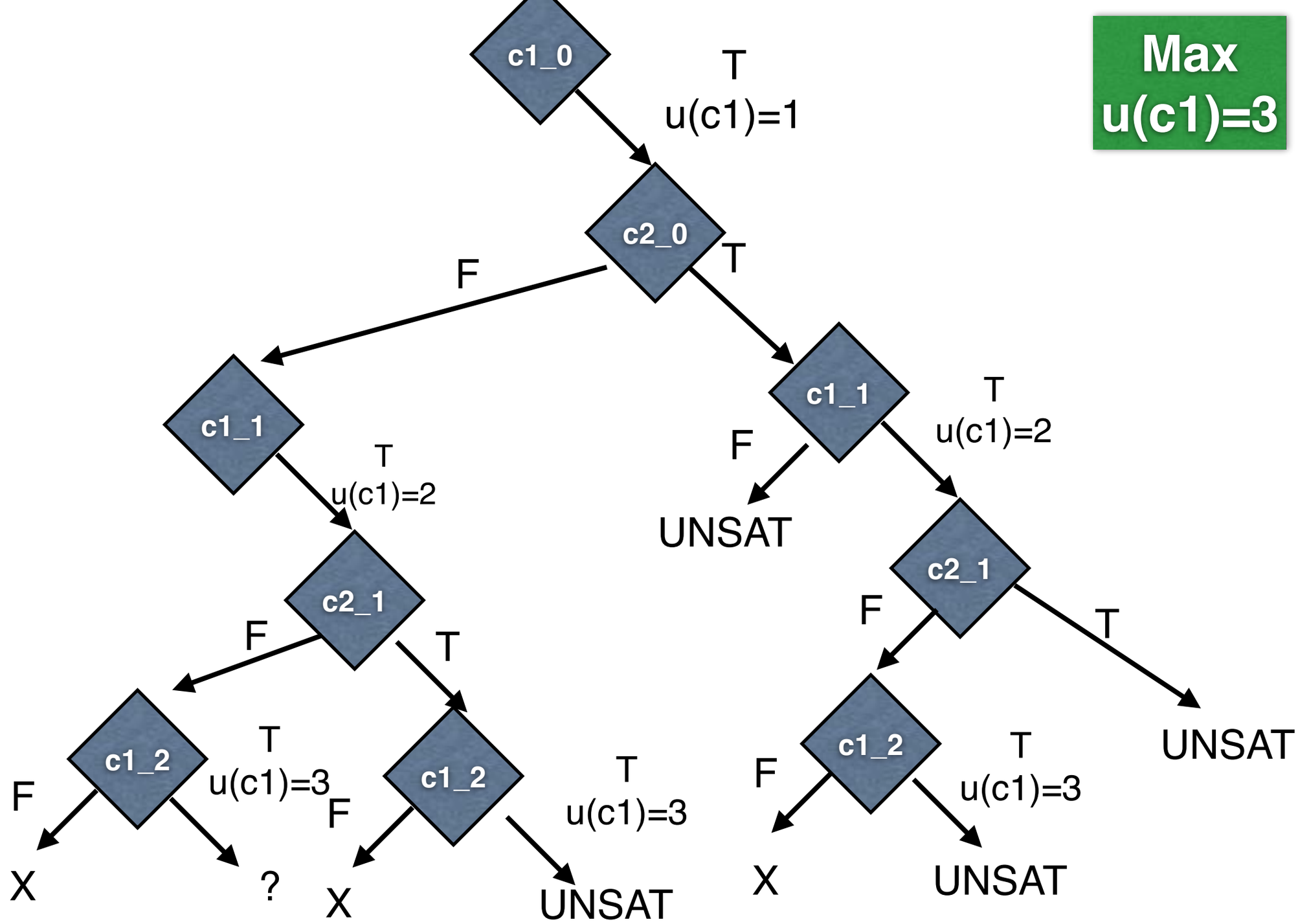

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
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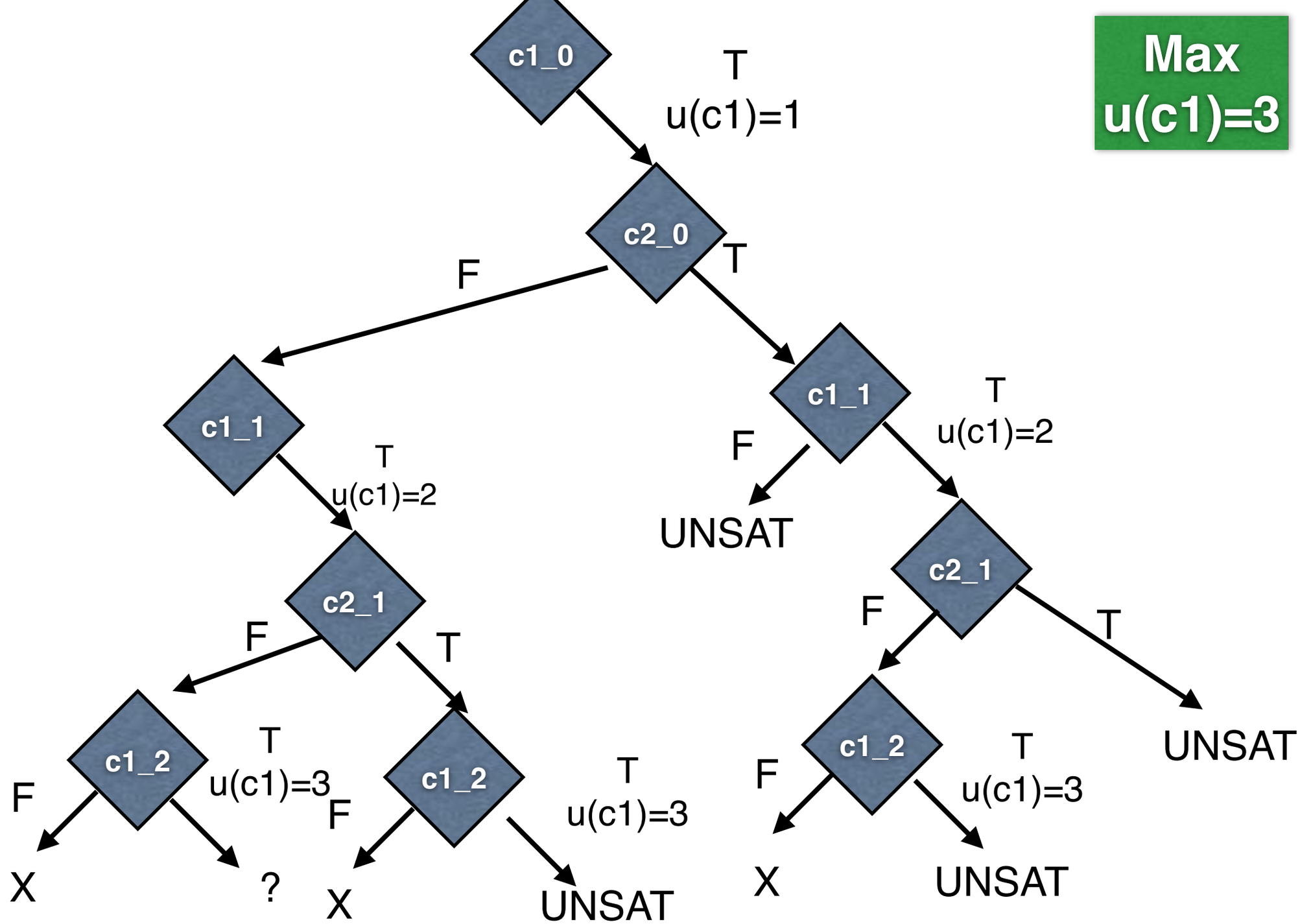
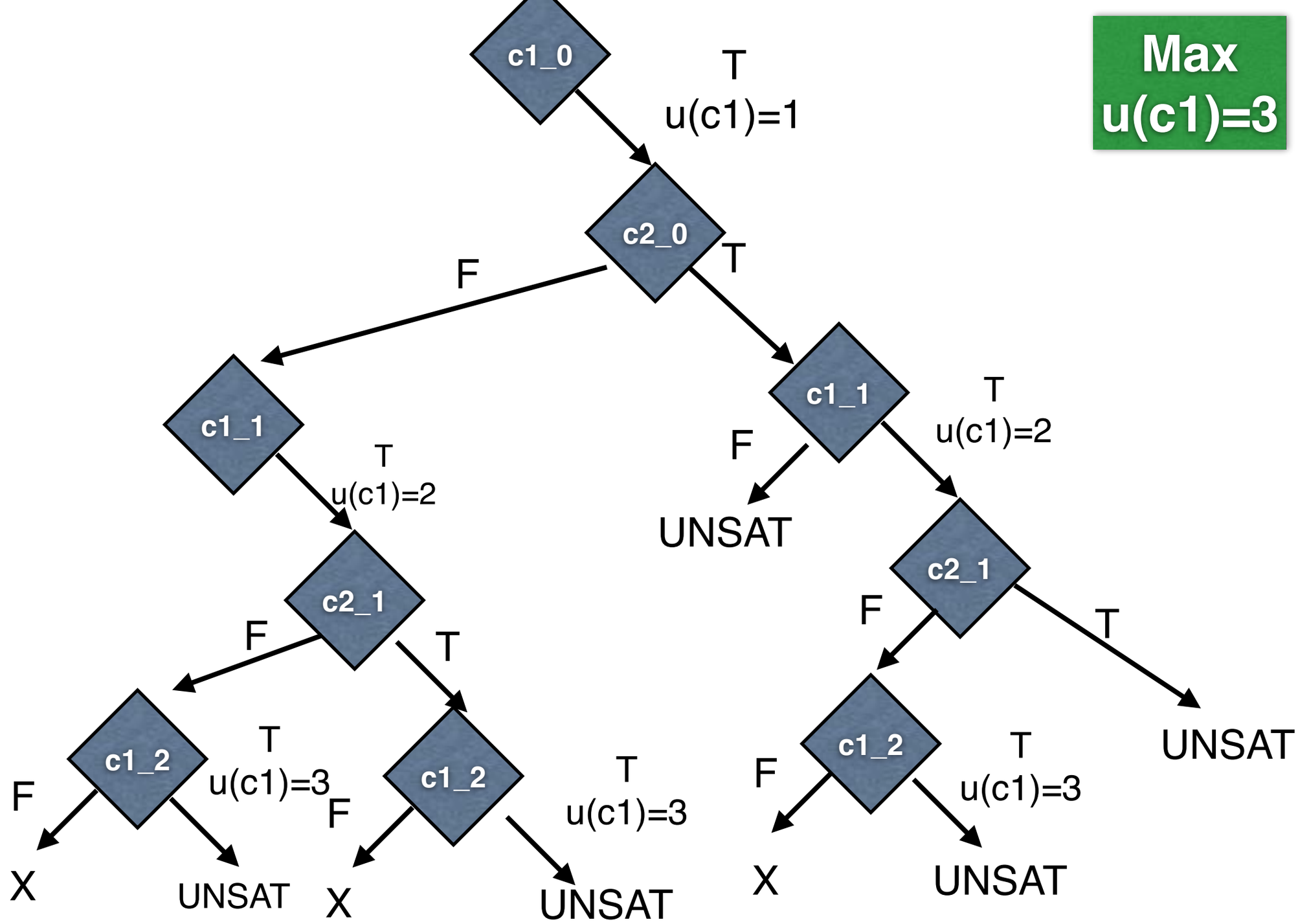
```



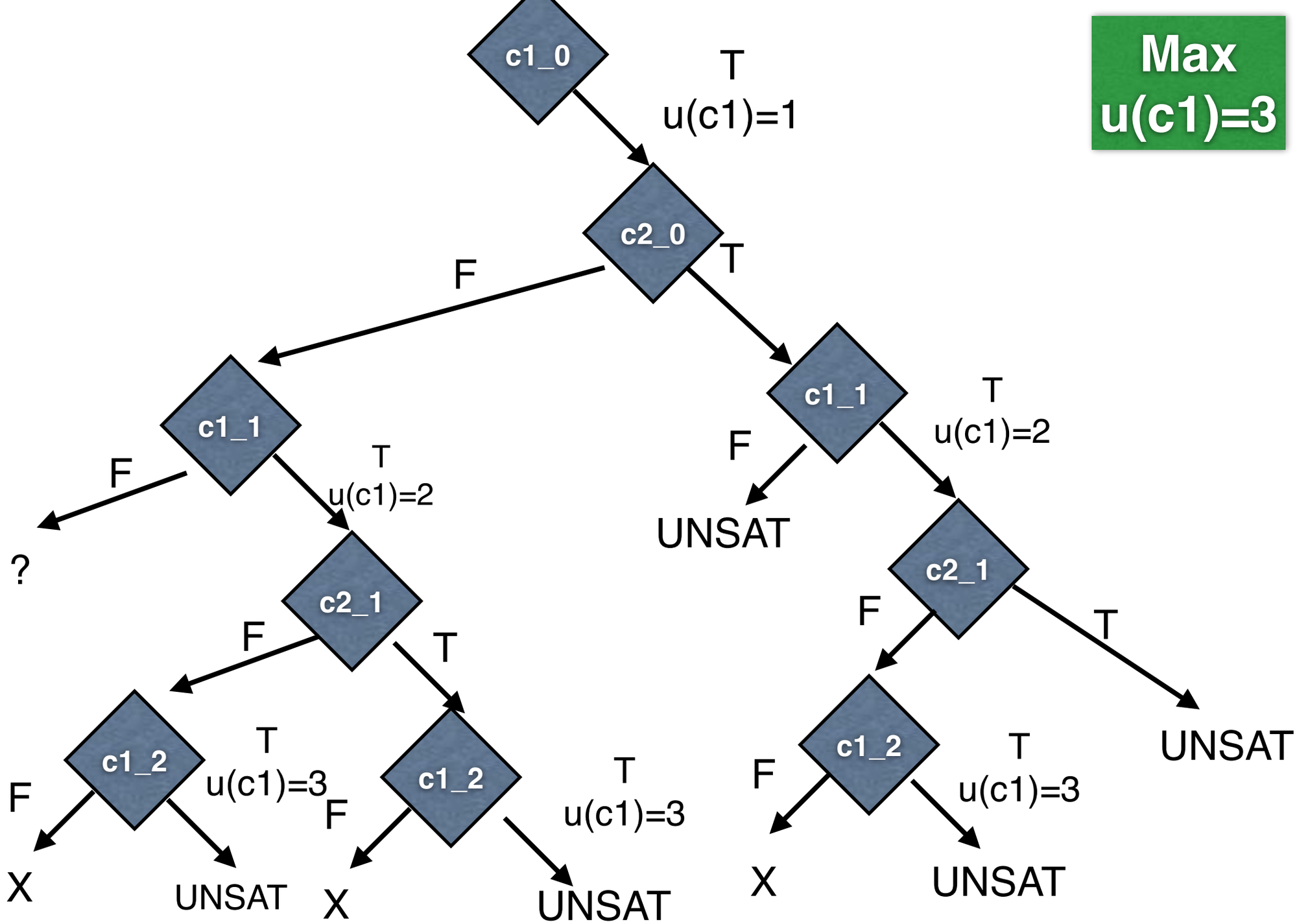
Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	?

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
     if (i==j) { //c2
        r=r+1;
     }
     i=i+1;
  }
  return r;
}
```



Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			?	

```
int test_me(int j) {
  int r=0;
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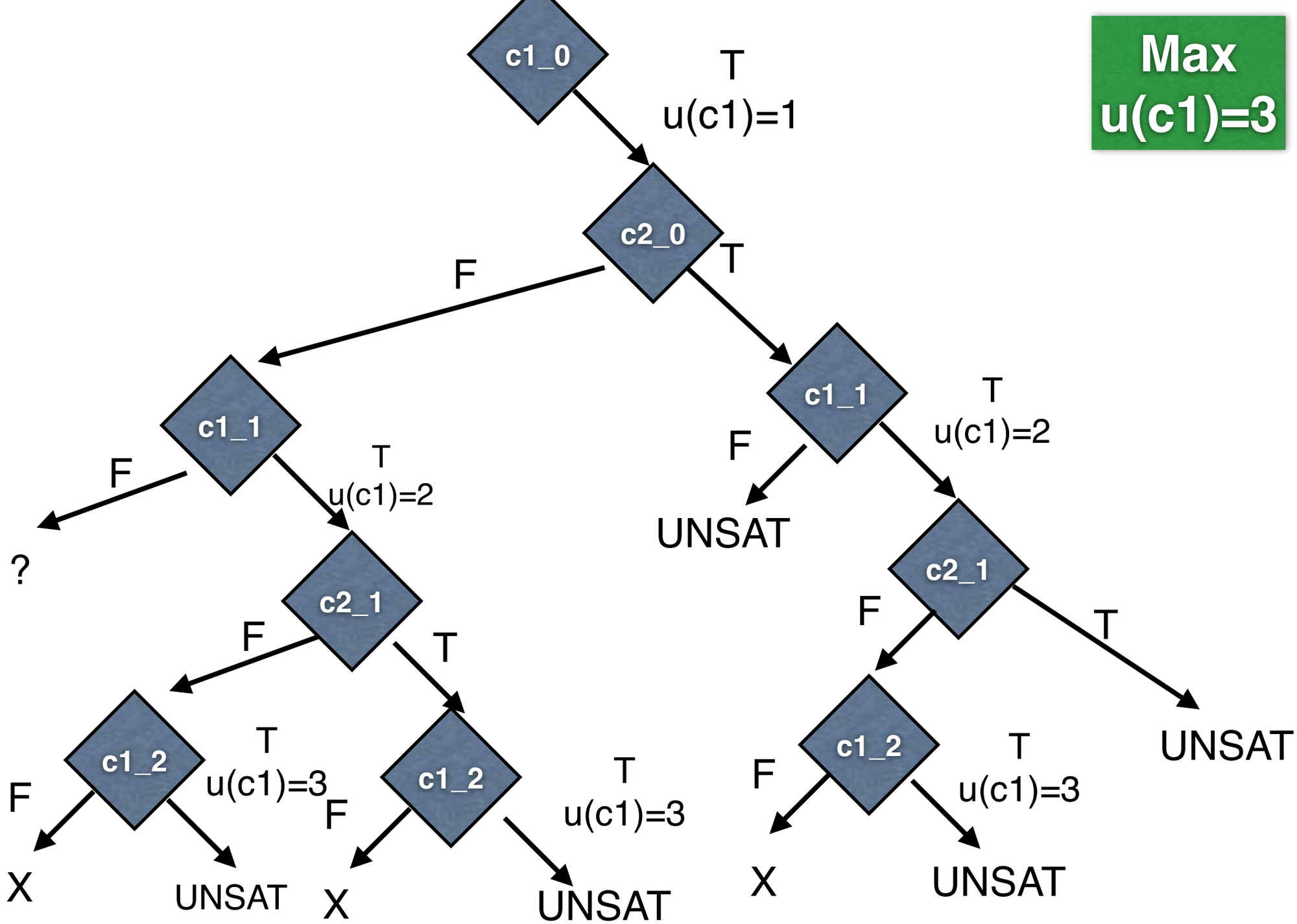
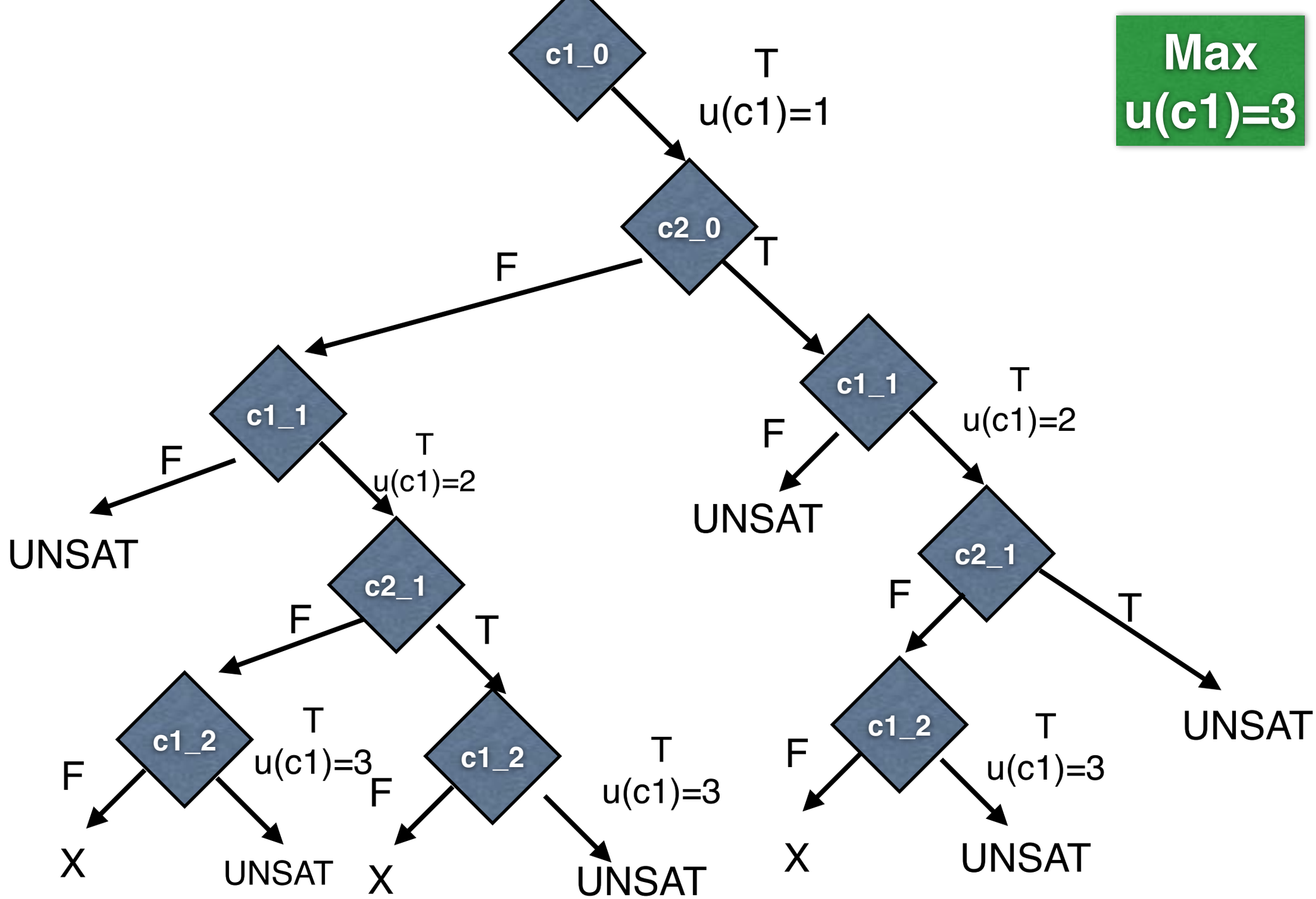
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	?

```
int test_me(int j) {
  int r=0;
  int i=0;
  while (i<2) { //c1
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT

```
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  int r=0;
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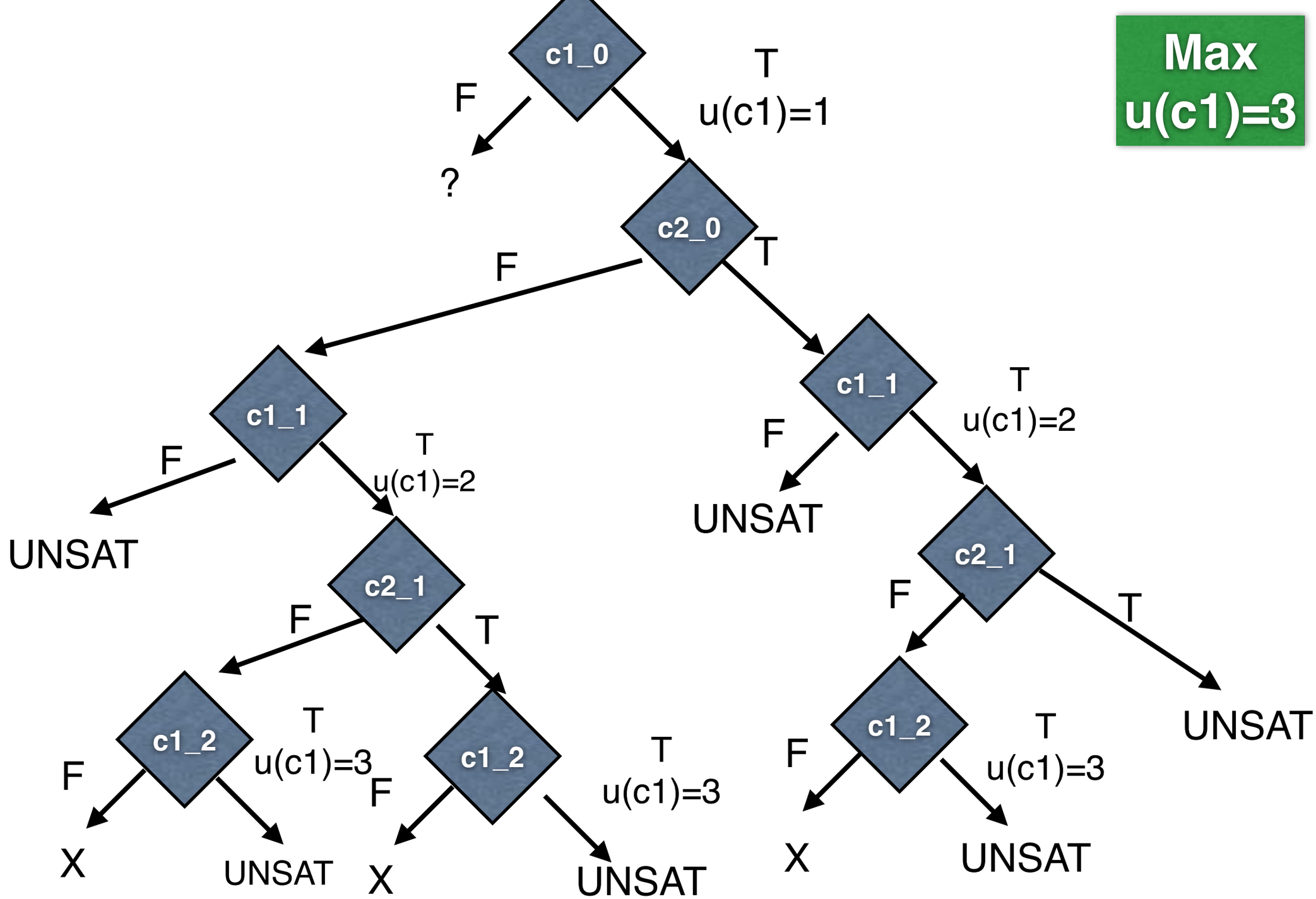
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT
			?	

```
int test_me(int j) {
  int r=0;
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      r=r+1;
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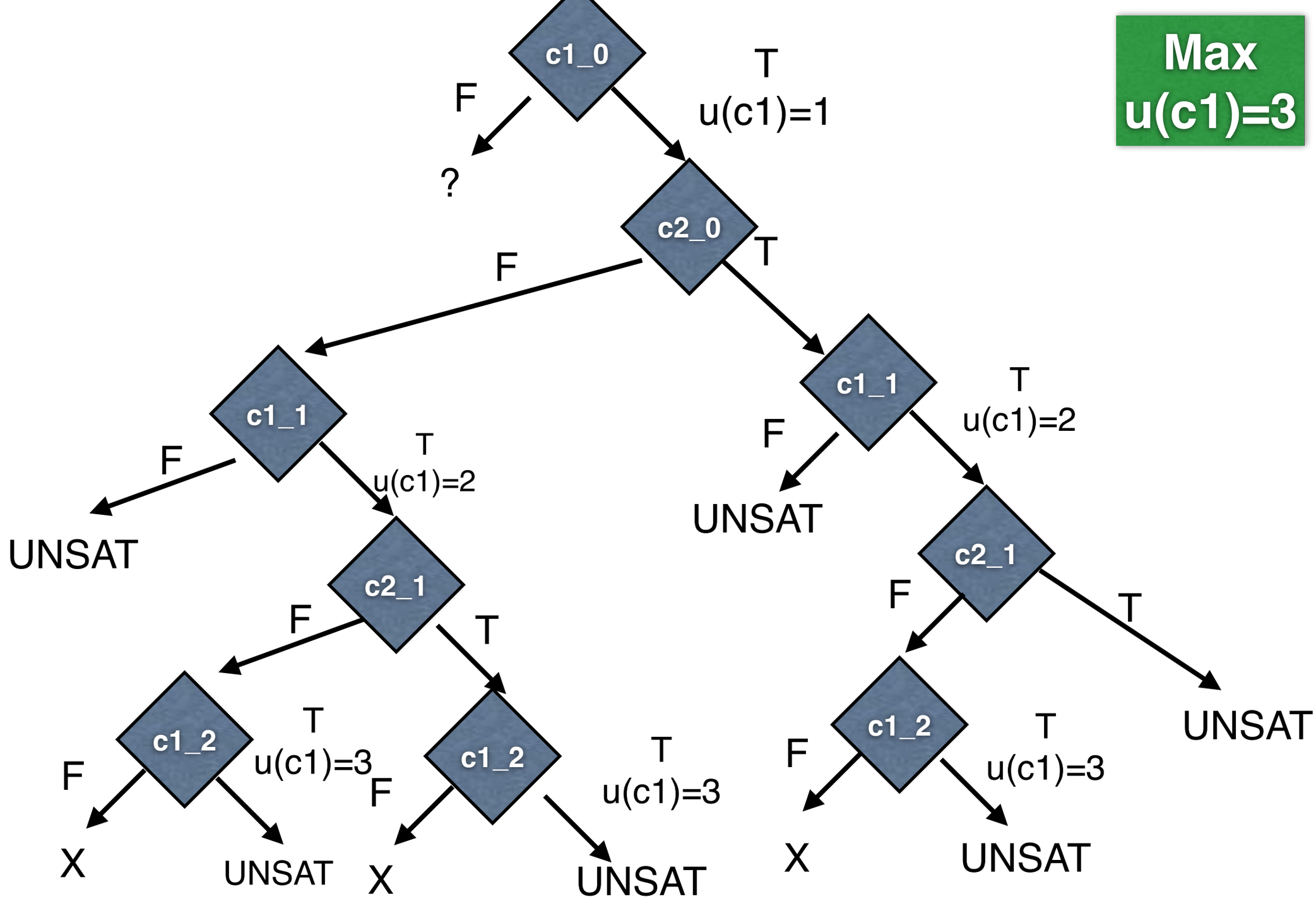

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Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT
			!(0<2)	?

```
int test_me(int j) {
  int r=0;
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  while (i<2) { //c1
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```

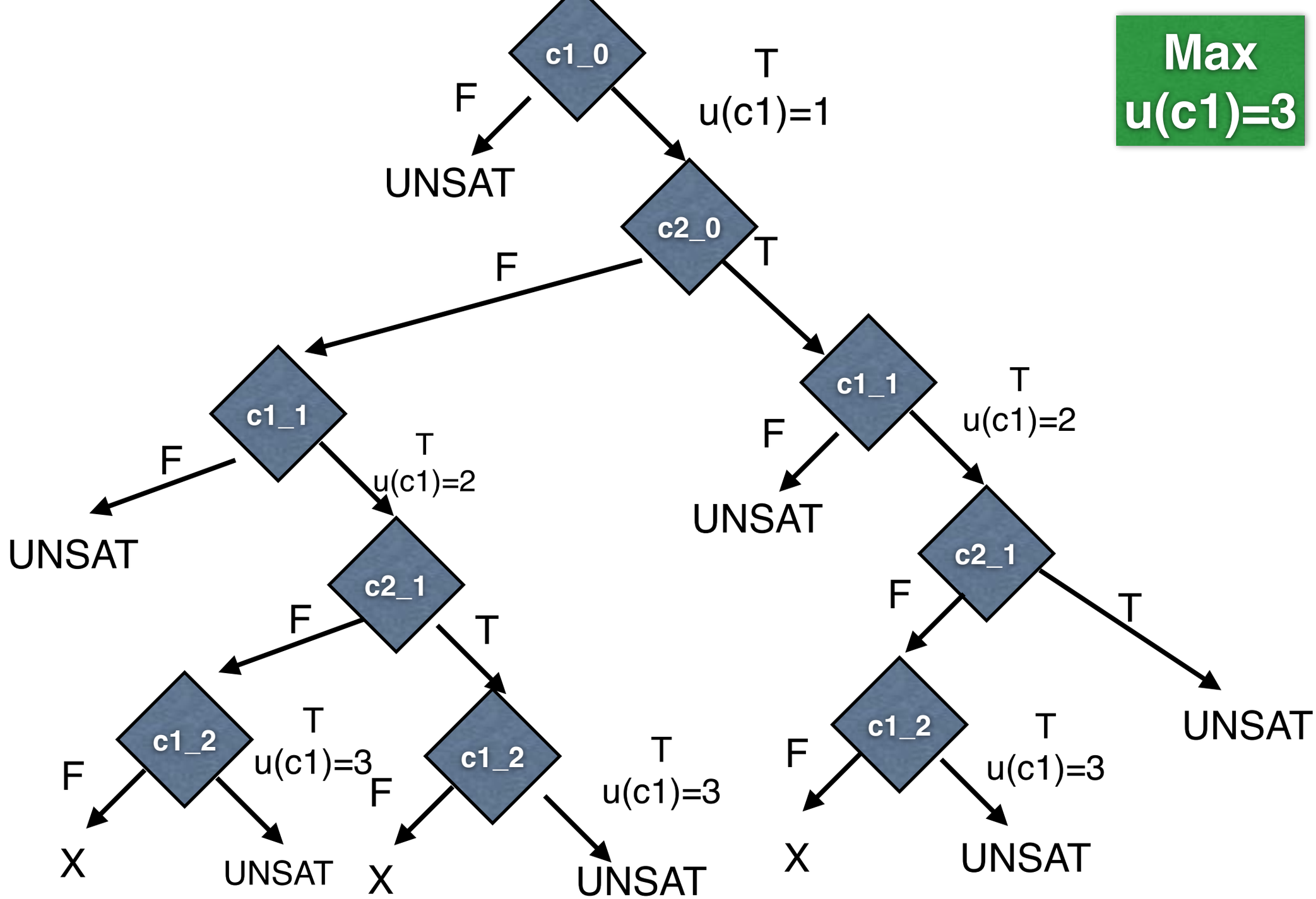

Max u(c1)=3

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3	j=2	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT
			!(0<2)	UNSAT

```
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  int r=0;
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  while (i<2) { //c1
    if (i==j) { //c2
      r=r+1;
    }
    i=i+1;
  }
  return r;
}
```
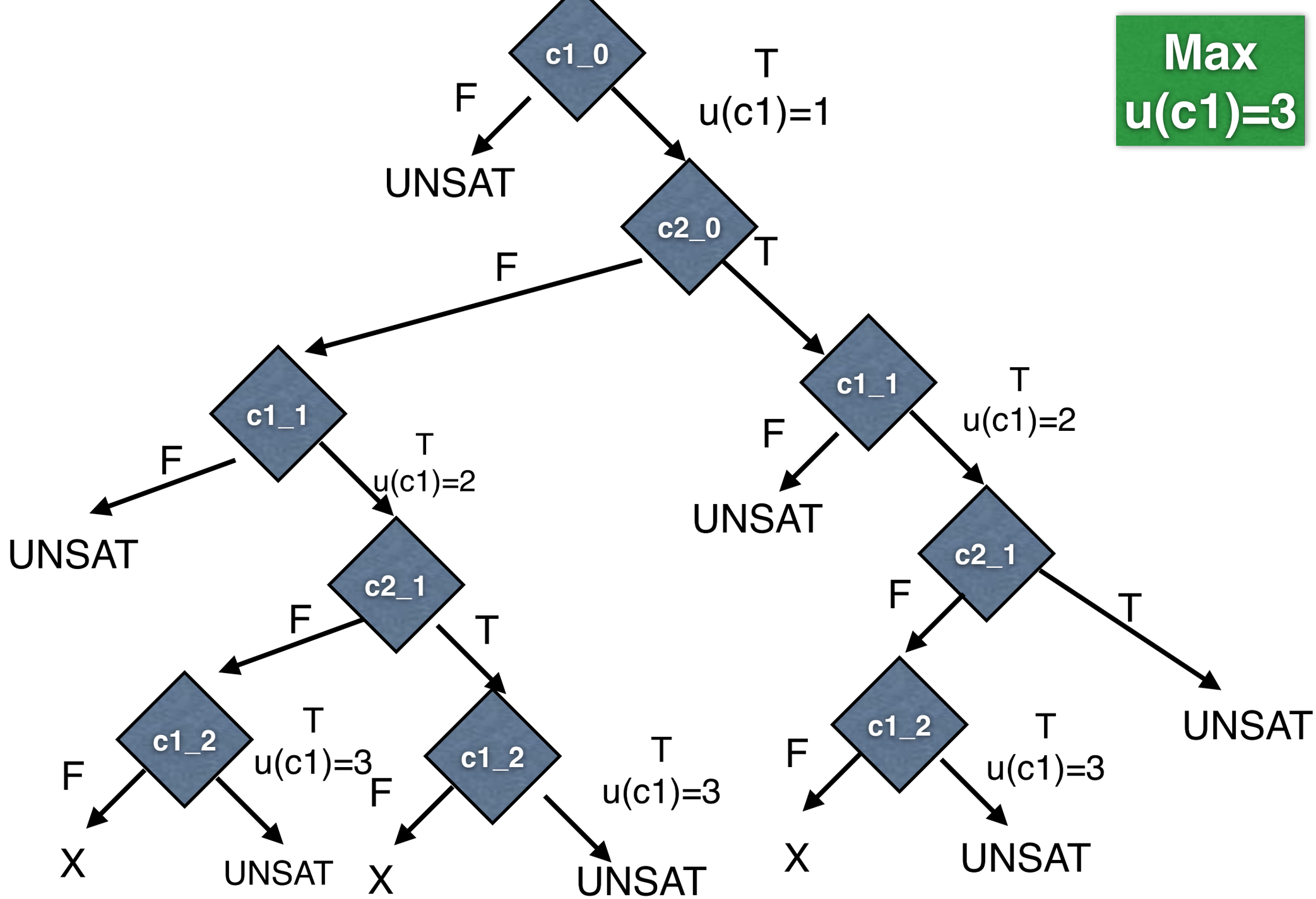
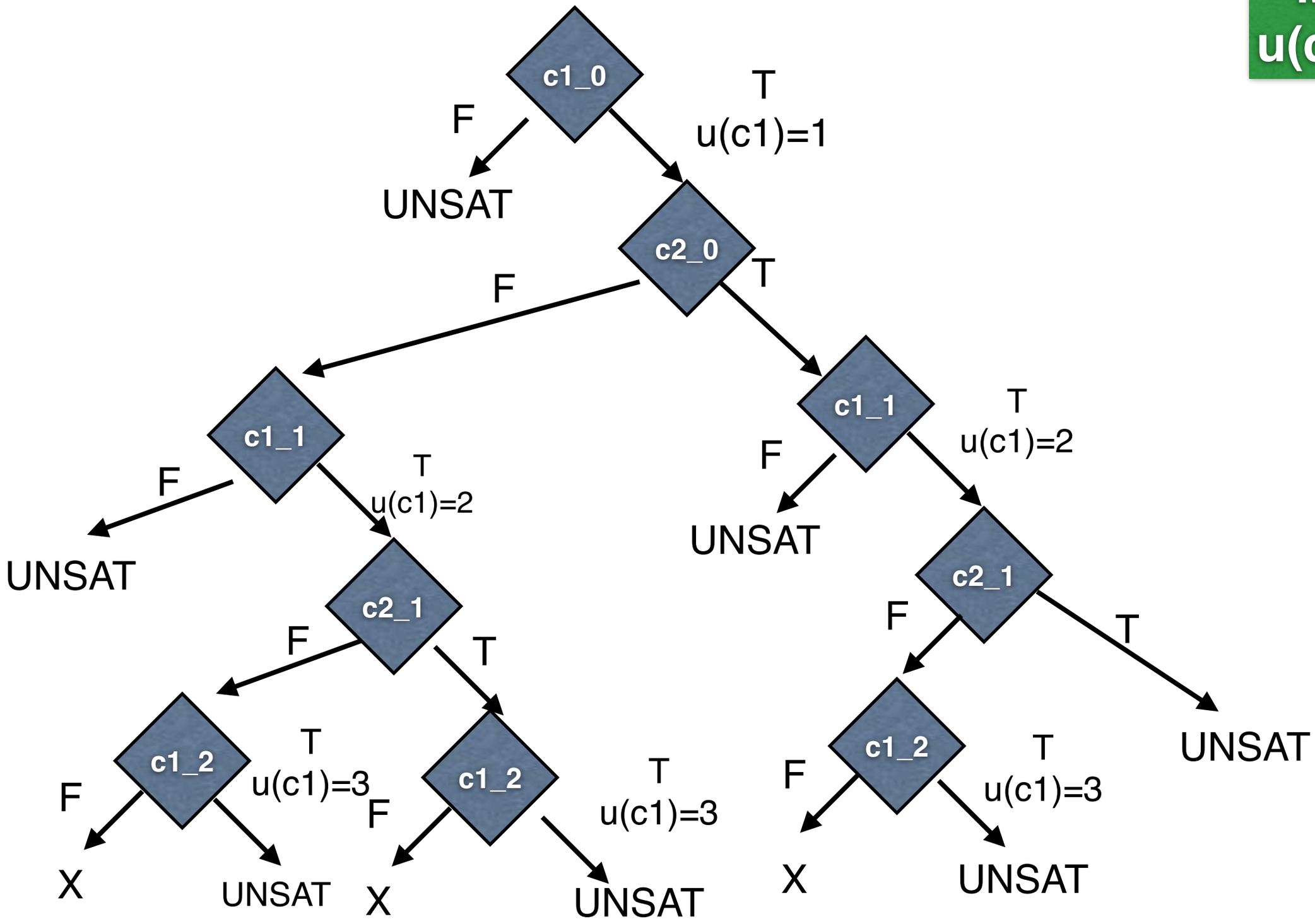



Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=~~0~~ 2	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT
			!(0<2)	UNSAT
			FIN	

Max u(c1)=3



Árbol de Cómputo explorado (i.e., no queda nada por explorar con Max u(c1)=3)

Max u(c1)=3

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
1	j=0	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&!(1<2)	(0<2)&&(0==j0)&&(1<2)&&!(1==j0)&&(1<2)	UNSAT
			(0<2)&&(0==j0)&&(1<2)&&(1==j0)	UNSAT
			(0<2)&&(0==j0)&&!(1<2)	UNSAT
			(0<2)&&!(0==j0)	j0=1

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
2	j=1	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&(1<2)&&!(1==j0)	j0=2

Iter	Input concreto	Condición de Ruta	Fórmula enviada al demostrador	Resultado posible
3	j=~~1~~ 2	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&!(2<2)	(0<2)&&!(0==j0)&&(1<2)&&(1==j0)&&(2<2)	UNSAT
			(0<2)&&!(0==j0)&&!(1<2)	UNSAT
			!(0<2)	UNSAT
			FIN	

Tabla de ejecución simbólica dinámica finalizada

Imprecisión

¿Qué pasa cuando ejecutamos foo con x=567 e y=42 ?

```
int foo(int x, int y) {
   if (x==hash(y)) {
      …
      if (y==10) return -1; // error
   }
   …
}
```

Imprecisión

```
int foo(int x, int y) {
  if (x==hash(y)) {
    …
    if (y==10) return -1; // error
  }
  …
}
```

Input: x=567 and y=42 ⟶ PC: x==567 and y!=10

Solve(x==567 and y=10) ⟶ Input: x=567 and y=10

PERO: x=567, y=10 no alcanza return -1

De hecho, ni siquiera cumple que x==hash(y)

Divergencia entre Ejecución Simbólica vs. Concreta

- Cuando aproximamos un valor simbólico usando un valor concreto corremos el riesgo de introducir **imprecisión**:
  - La solución retornada no recorre el camino esperado
  - Tenemos que considerar este caso y adaptar nuestro algoritmo de ejecución simbólica **en caso de introducir imprecisiones**

Cambios en la Generación si hay Divergencia

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- Si no lo es, entonces comparamos si ya obtuvimos con anterioridad esa path condition

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- Conservamos una lista de todas las path conditions que generamos con ejecución simbólica
- Cada vez que creamos una nueva path condition para resolver, chequeamos que sea un prefijo de la path condition obtenida de ejecutar el nuevo test case
  - Si no lo es, entonces comparamos si ya obtuvimos con anterioridad esa path condition
    - En caso que ya la hayamos explorado, decidimos si vale la pena continuar con el algoritmo de generación

hay que modificar el pseudocódigo p/ verificar que se recorrió el camino esperado (p/ detectar divergencias)

Heap Constraints

- ¿Qué podemos hacer cuando tenemos un PUT que recibe un tipo no primitivo?

```
public void test(MiniStack s, int value) {
  assumeTrue(s!=null);
  assumeFalse(s.isFull());
  s.push(value);
  int rv = s.pop();
  assertEquals(value, rv);
}
```

Heap Constraints

- Muchas veces tenemos constraints que predican sobre el grafo de memoria (heap)
  - Ejemplo: list0.header!=null
- Extendemos el lenguaje de constraints para poder expresar expresiones sobre direcciones de memoria (ie referencias)

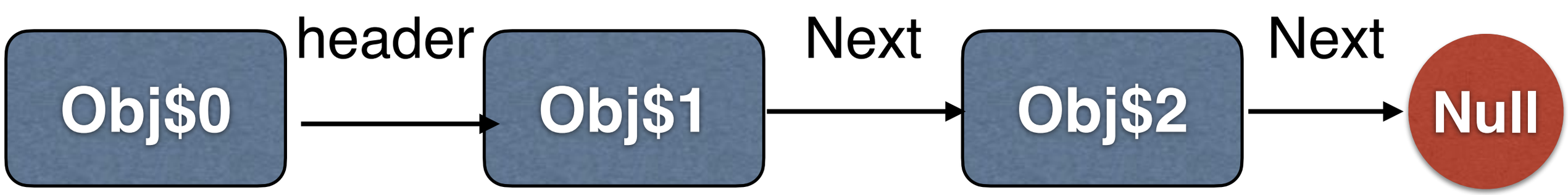
Constraint Language

Referencias a Objetos

(extensión p/ poder manejar objetos)

- Expresiones sobre Referencias:
  - null
  - var0, var1, var
  - E.f
- Constraints:
  - E==E, E!=E

Var0!=null
Var0.header!=Var0
Var0.header!=null
Var0.header.next!=null
Var0.header.next.next==null



Público vs. Privado

```
class MiniStack {
  public int readIndex;
  public Object[] elements;
  …
}
```

Si todos los campos que necesitamos actualizar son de acceso público no hay problema

¿qué pasa cuando hay campos que no son accesibles y necesitamos modificarlos?

```
class MiniStack {
  private int readIndex;
  private Object[] elements;
  …
}
```

Heap Constraints

var0=Obj$1
var0.*header*=Obj$2
var0.*header*.*next*=Obj$3
var1=Obj$2

Heap Constraints

var0=Obj$1
var0.*header*=Obj$2
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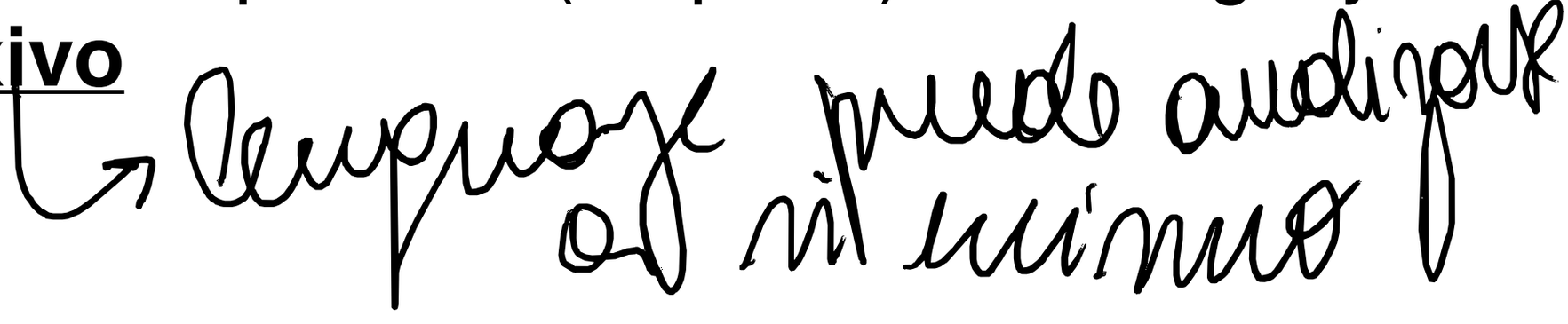
Como *header* y *next* son campos privados, no sabemos como crear esta configuración de la memoria!

Heap Constraints

- Muchas veces tenemos constraints que predican sobre el grafo de memoria (heap)
  - Ejemplo: list0.header!=null
- La solución nos da un grafo posible, pero desconocemos la secuencia de métodos para generarlo si hay métodos privados
  - Podemos reemplazarlo (en parte) si el lenguaje es **reflexivo**



Lenguajes reflexivos

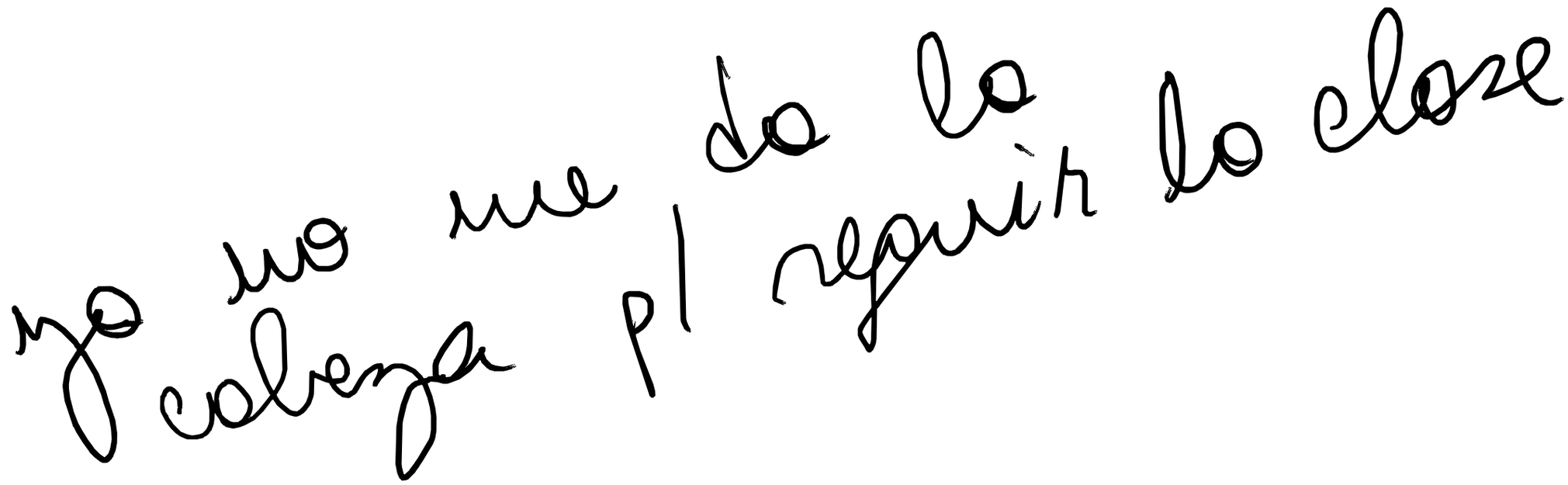
- Nos permiten introspectivamente analizar el mismo programa (ej: Python)
- En Java, podemos:
  - Crear objetos (aunque no haya constructor por defecto)
  - Asignar un valor a campos privados

var0=List$0
var0.*header*=Node$0
var0.*header*.*next*=Node$1
var1=Node$1

```
Object list_0 = createObject(List.class);
Object node_0 = createObject(Node.class);
Object node_1 = createObject(Node.class);
setPrivateField(list_0,”header”,node_0);
setPrivateField(node_0,”next”,node_1);
```

↑ cobertura violenta invocando todos los métodos públicos e interfaces de clases

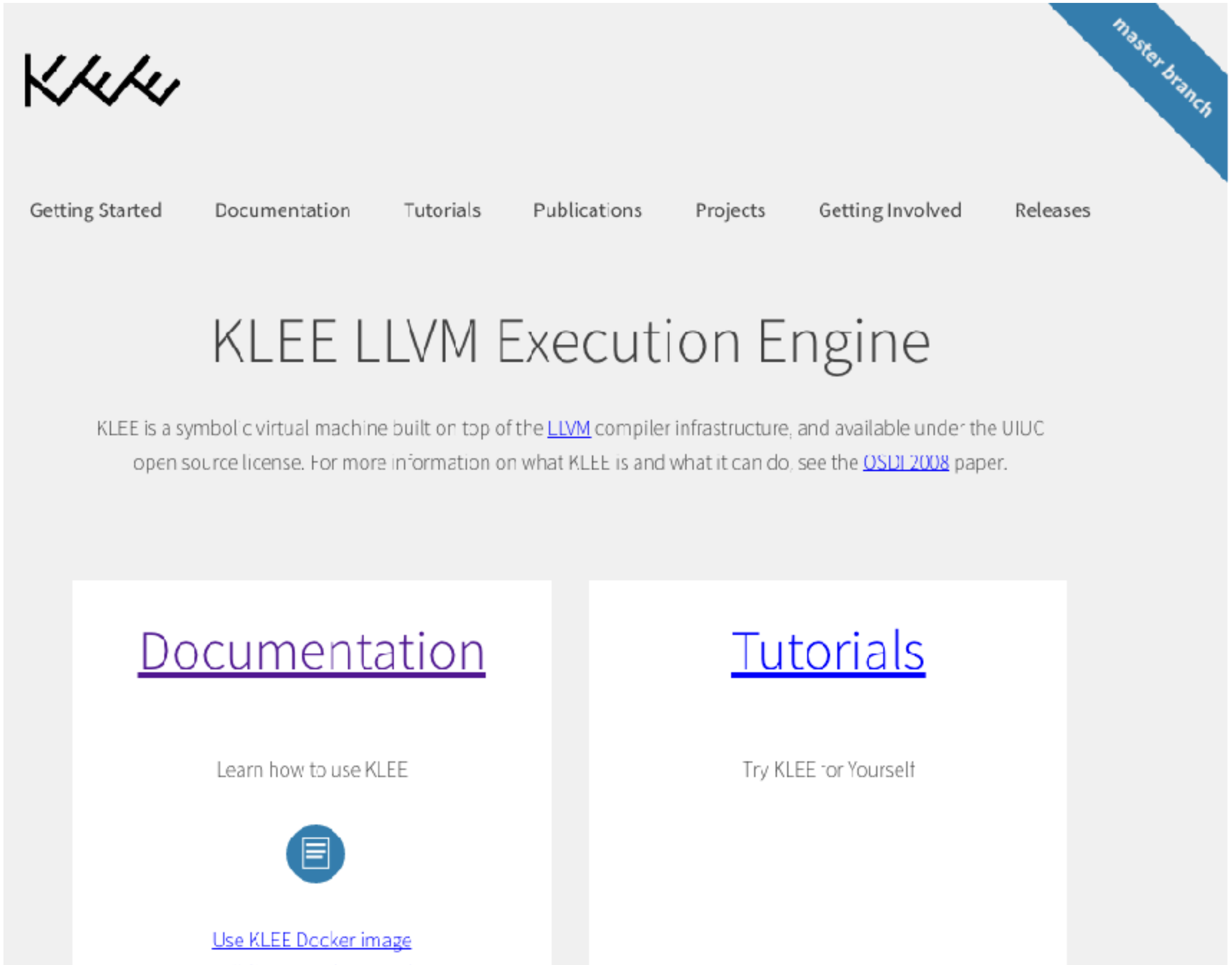
ok



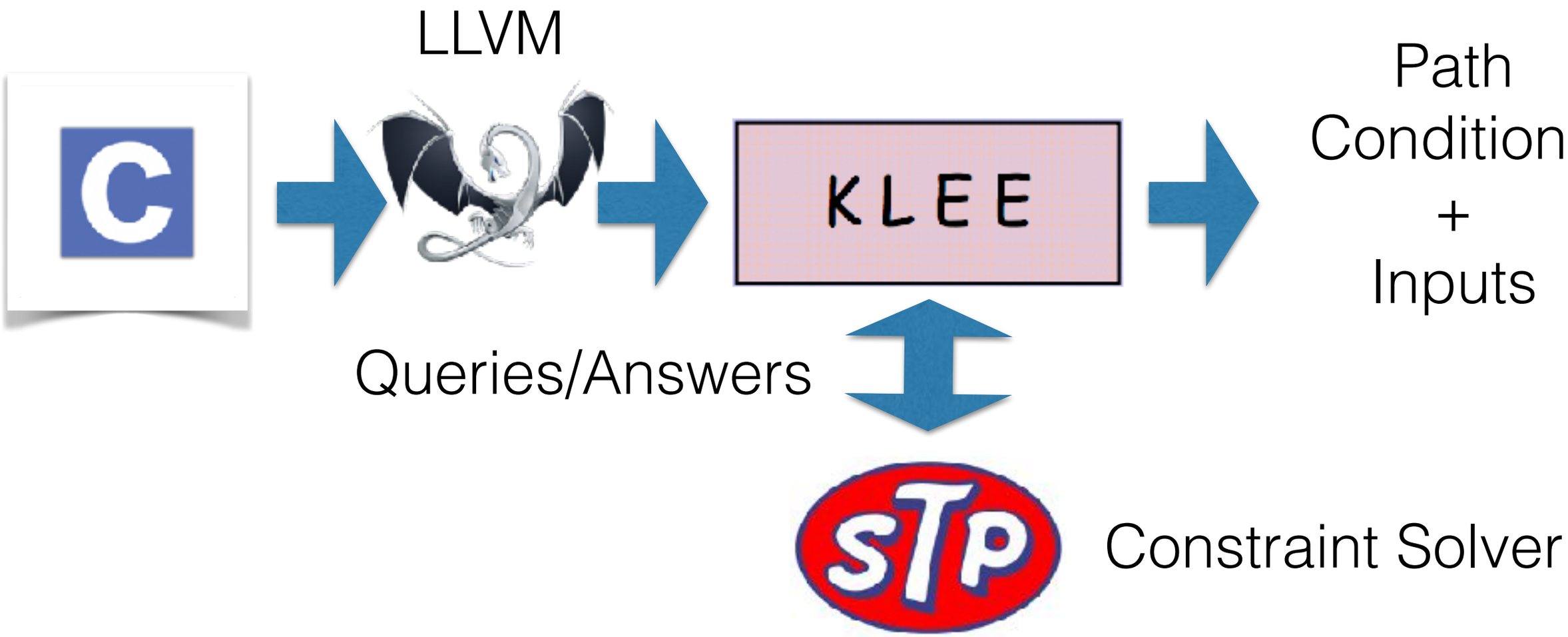
Otros Desafíos Abiertos para ejecución simbólica

- Constraint Solvers:
  - Riqueza del lenguaje para expresar constraints
  - Longitud y complejidad de las path conditions
- Herramienta de Generación:
  - Código no instrumentado, dependencias externas (no accesibles)
  - Complejidad de las entradas (XML, etc)

http://klee.github.io/klee/



KLEE



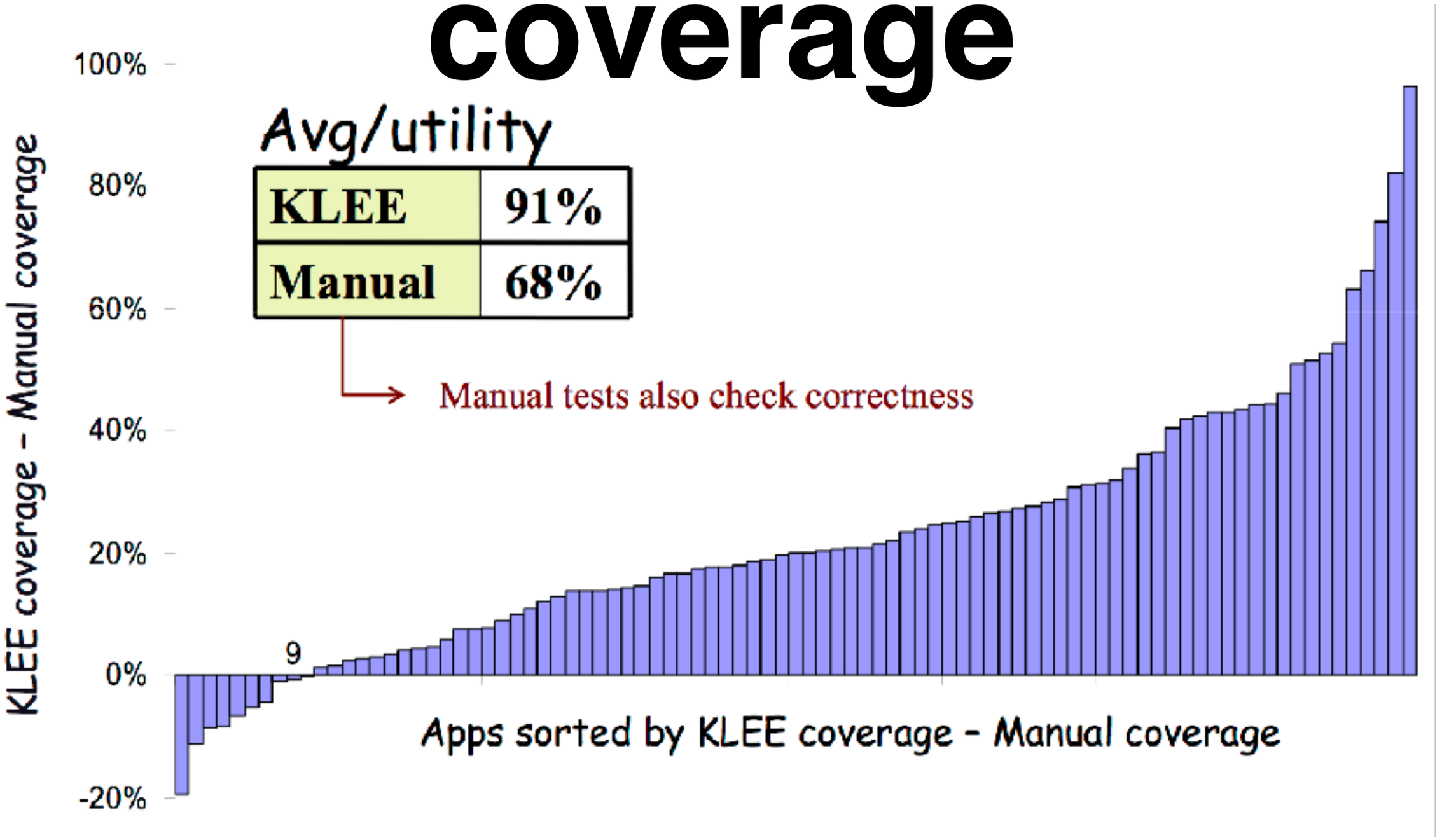
Cristian Cadar, Daniel Dunbar and Dawson Engler, KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs, OSDI 2008

GNU Coreutils application suite

- Core user-level apps installed on UNIX systems (i.e. ls, mkdir, seq, etc.)
- Roughly ~180 KLOC
- Heavily tested, mature code
- Variety of functions, authors, intensive interaction with environment

Cristian Cadar, Daniel Dunbar and Dawson Engler, KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs, OSDI 2008

KLEE: Code coverage



Cristian Cadar, Daniel Dunbar and Dawson Engler, KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs, OSDI 2008

KLEE: Bug finding

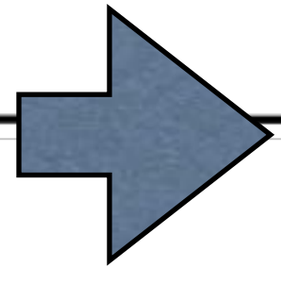
`md5sum -c t1.txt`	`pr -e t2.txt`
`mkdir -Z a b`	`tac -r t3.txt t3.txt`
`mkfifo -Z a b`	`paste -d\\ abcdefghijklmnopqrstuvwxyz`
`mknod -Z a b p`	`ptx -F\\ abcdefghijklmnopqrstuvwxyz`
`seq -f %0 1`	`ptx x t4.txt`

t1.txt: \t \tMD5(

t2.txt: \b\b\b\b\b\b\b\t

t3.txt: \n

t4.txt: A



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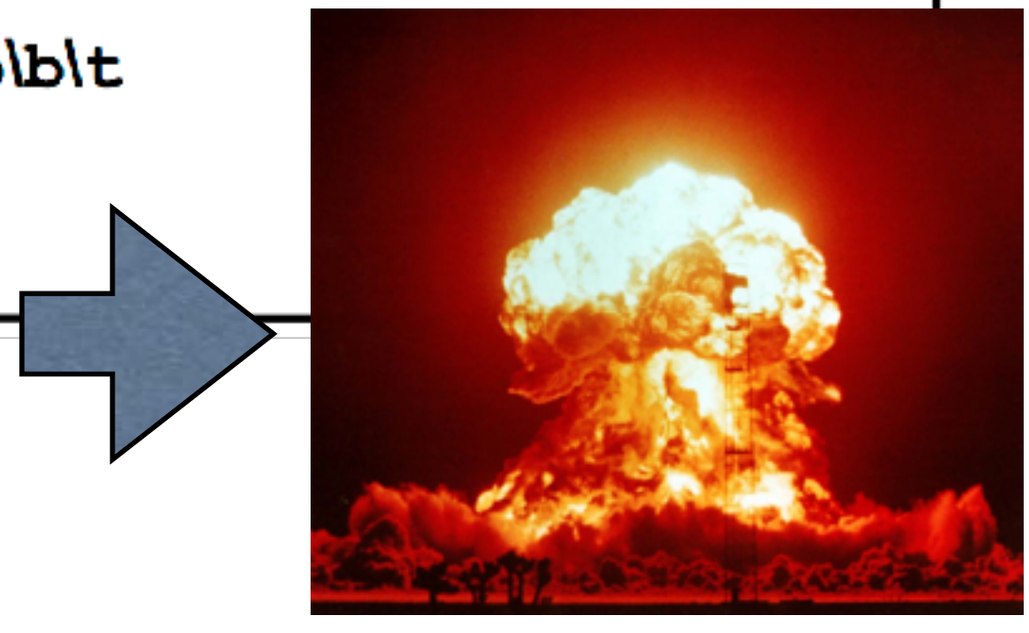
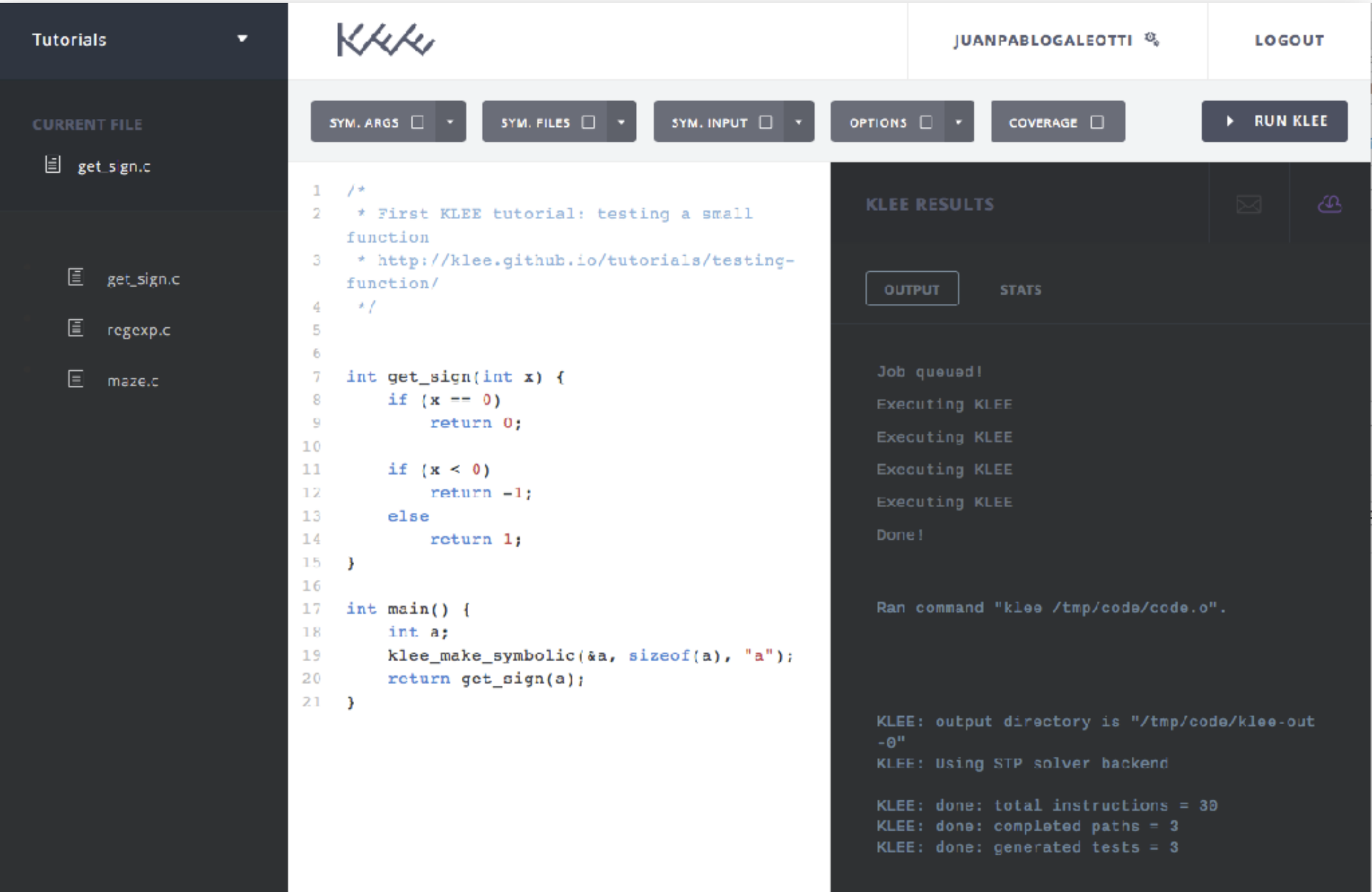
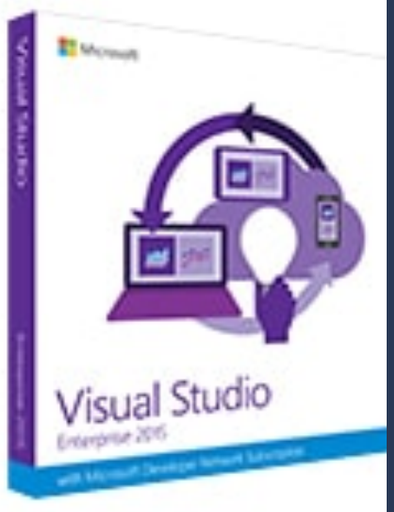
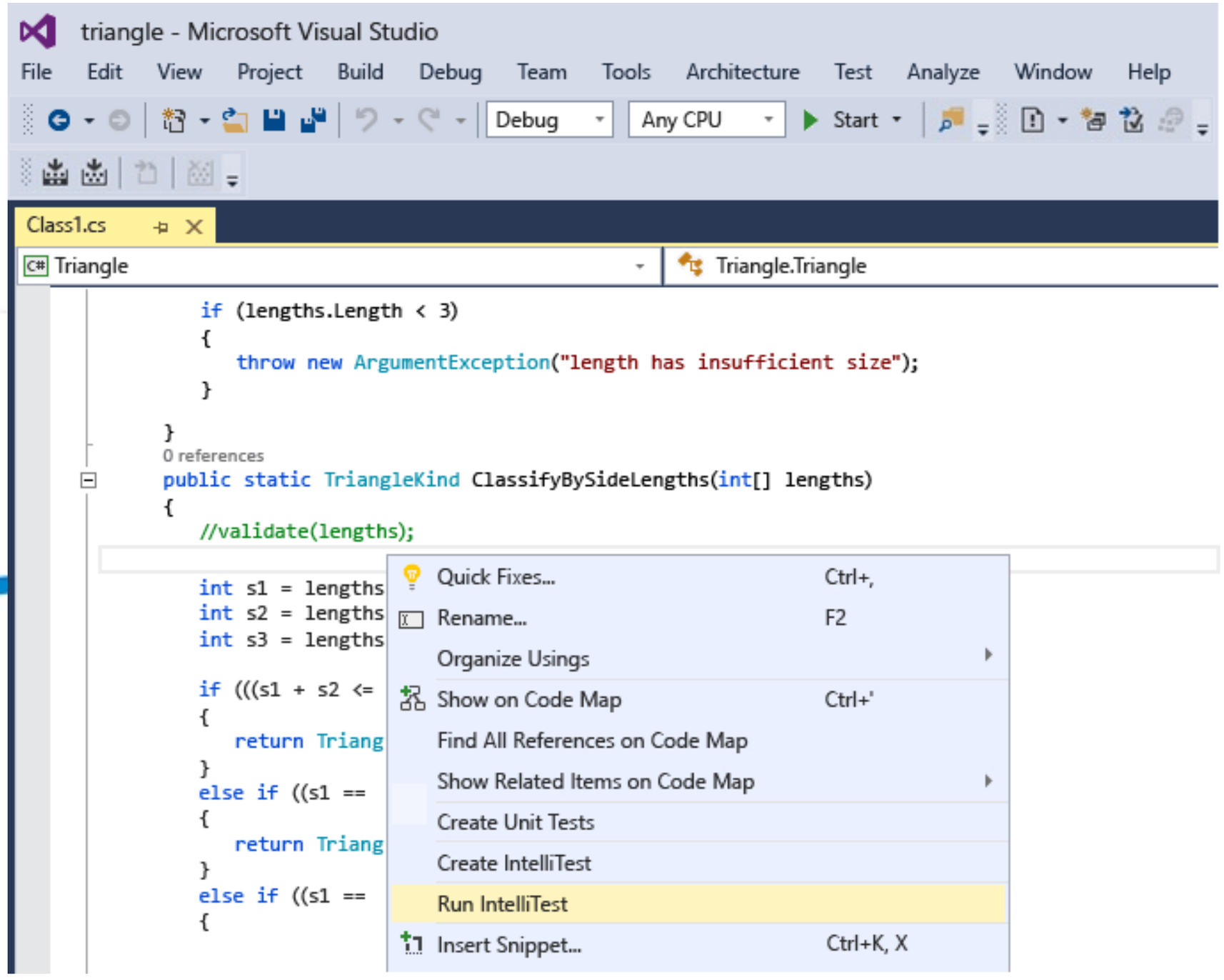


http://klee.doc.ic.ac.uk/



Microsoft Visual Studio 2015 IntelliTest





https://msdn.microsoft.com/en-us/library/dn823749.aspx

Microsoft Visual Studio 2015
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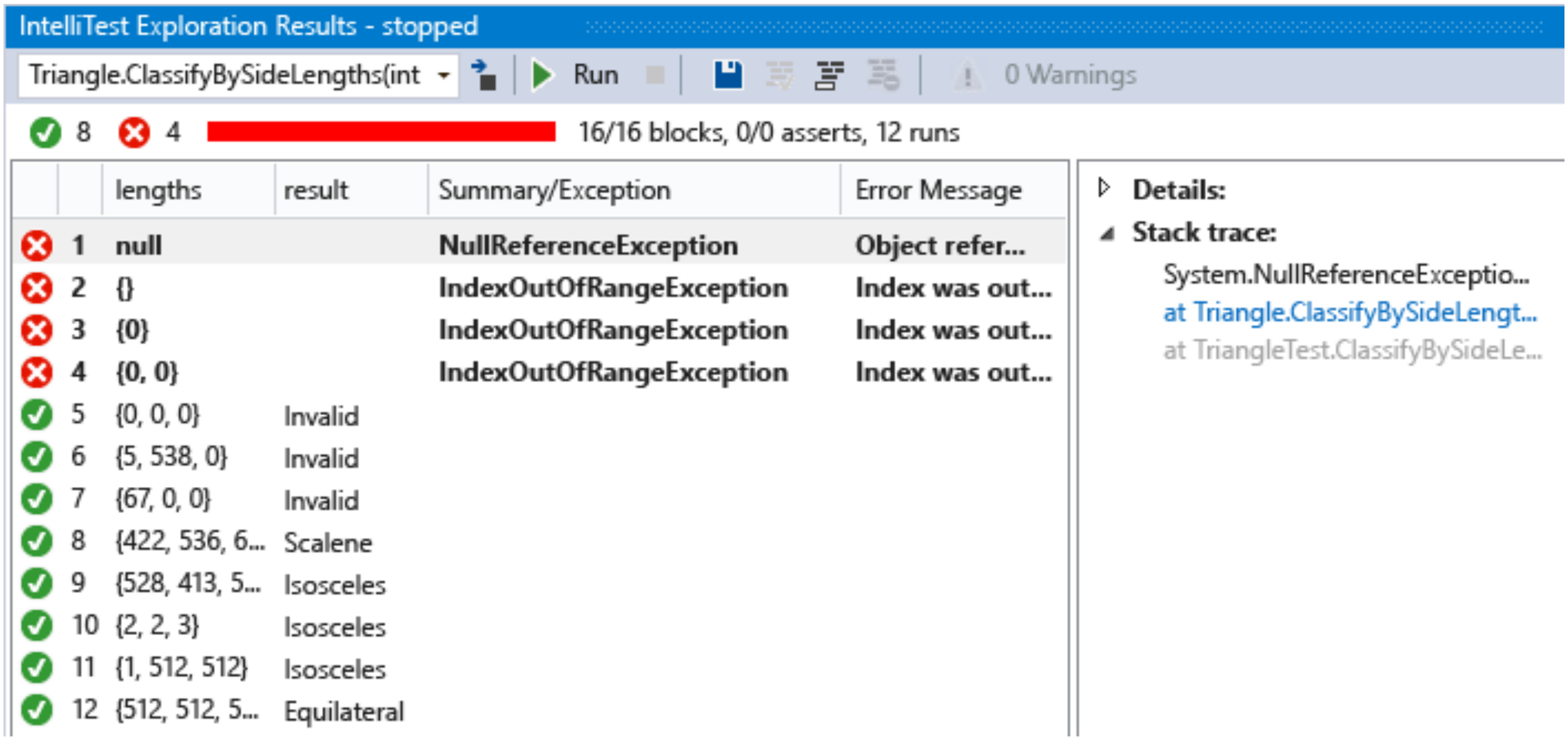


https://msdn.microsoft.com/en-us/library/dn823749.aspx

http://www.codehunt.com

SELECT SECTOR

CHANGE ZONE

00 TRAINING 00/03

01 ARITHMETIC

02 LOOPS

03 LOOPS 2

04 CONDITIONALS

05 CONDITIONALS 2

06 STRINGS

07 STRINGS 2

08 NESTED LOOPS

09 1D ARRAYS

10 JAGGED ARRAYS

11 ARRAYS 2

12 SEARCH SORT

13 CYPHERS

14 PUZZLES

HUNTER STATS

01/15 SECTORS UNLOCKED

00/15 SECTORS COMPLETED

Discover the arithmetic operation applied to 'x'.

CAPTURE CODE

RESET LEVEL

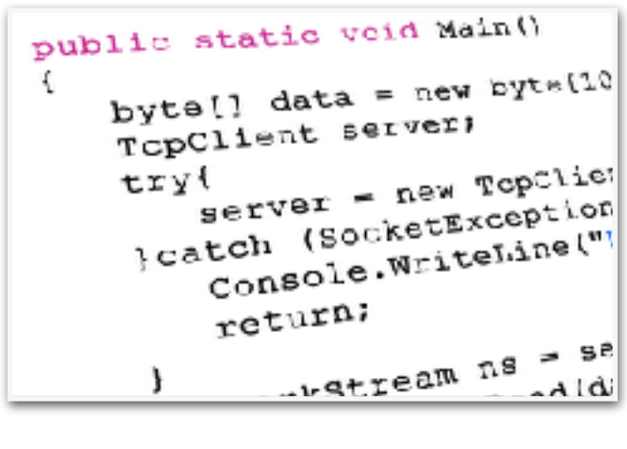
Java

```
1
2 public class Program {
3     public static int Puzzle(int x) {
4         return 0;
5     }
6 }
```

	X	EXPECTED RESULT	YOUR RESULT	DESCRIPTION
✗	0	1	0	Mismatch
✓	-1	0	0	
@	Well done so far. Look at numbers on line 4 to capture the code.			

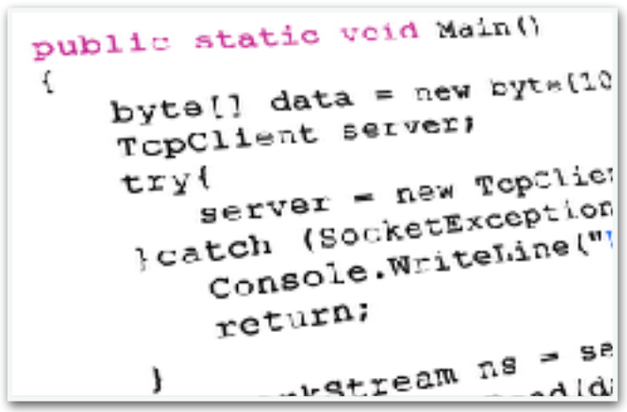
Code Hunt

Code Hunt



secret_Foo(x)

Code Hunt



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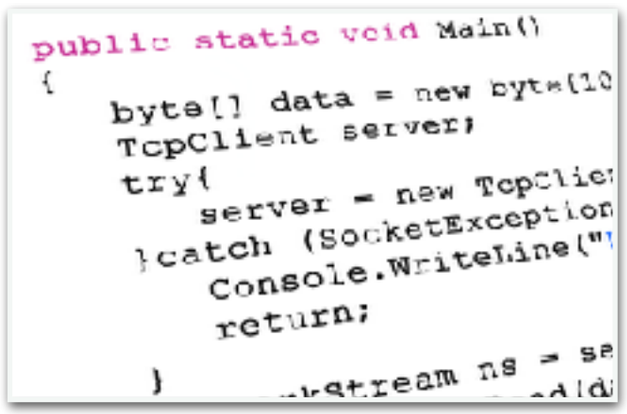
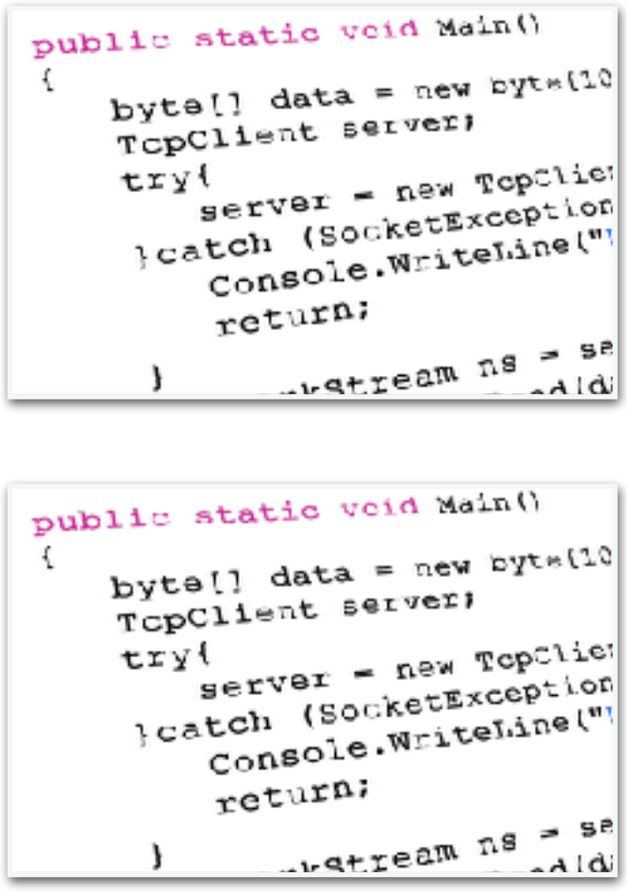


user_Foo(x)

Code Hunt



secret_Foo(x)

user_Foo(x)

```
p_test(x) {
  r0 = secret_Foo(x)
  r1 = user_Foo(x)
  assert r0==r1
}
```

Code Hunt

```
public static void Main()
{
    byte[] data = new byte[10
    TcpClient server;
    try{
        server = new TcpClie
    }catch (SocketException
        Console.WriteLine("
        return;
    }
        NetworkStream ns = se
```

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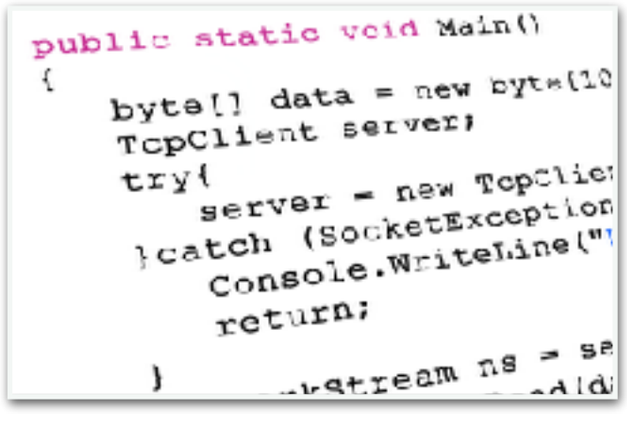
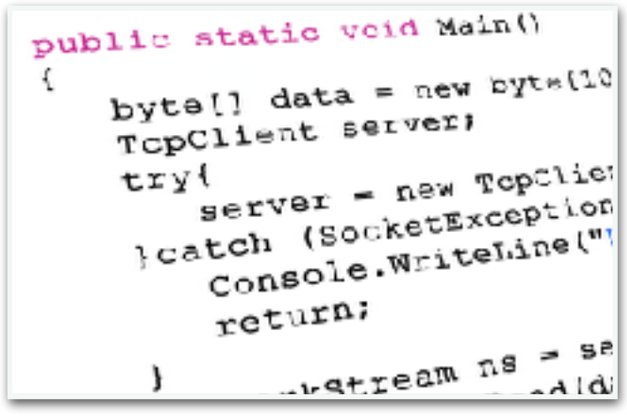
PEX

Code Hunt





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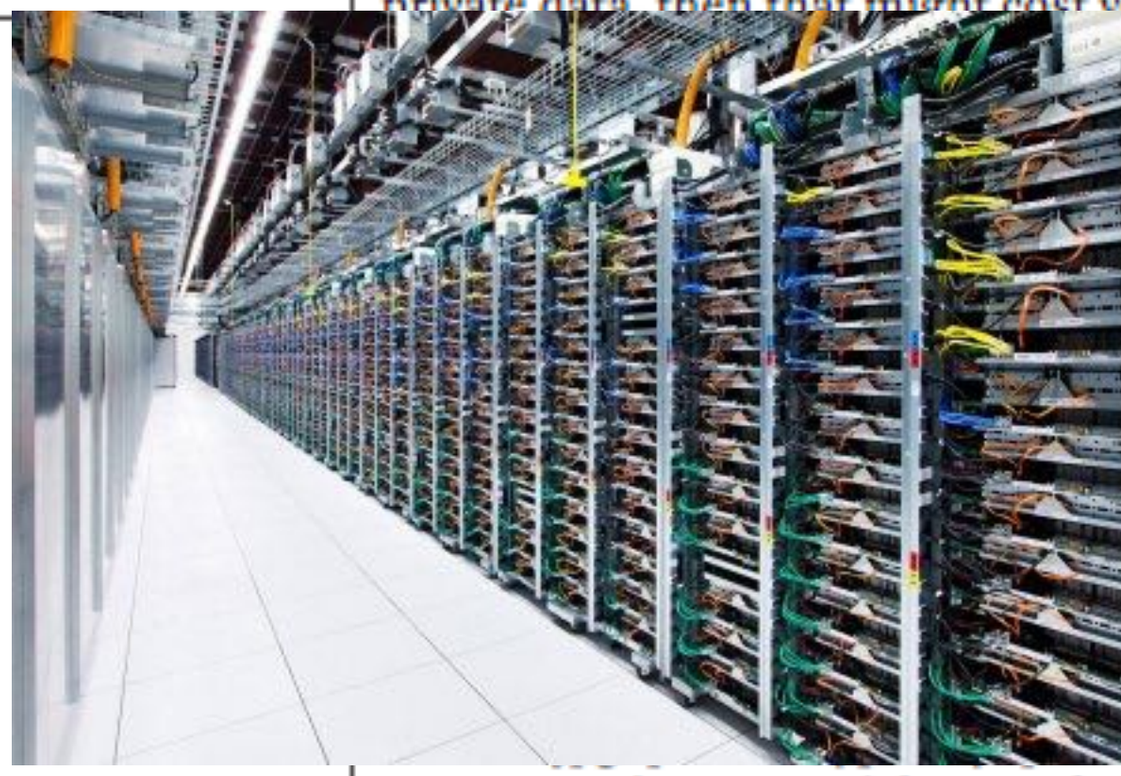
DOI:10.1145/2093548.2093564

Article development led by acmqueue
queue.acm.org

SAGE has had a remarkable impact at Microsoft.

BY PATRICE GODEFROID, MICHAEL Y. LEVIN, AND DAVID MOLNAR

SAGE: Whitebox Fuzzing for Security Testing



and its users millions of dollars. I
monthly security update costs y
$0.001 (one tenth of one cent) in ju
electricity or loss of productivity, th
this number multiplied by one b
lion people is $1 million. Of course
malware were spreading on your m
chine, possibly leaking some of yo
private data, then that might cost y

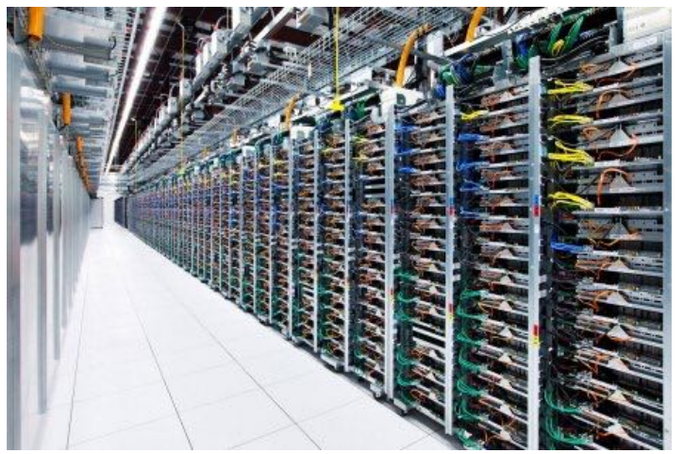
your operating system) has read t
image data, decoded it, created n
data structures with the decoded da
and passed those to the graphics ca
in your computer. If the code imp
menting that jpg parser contains
bug such as a buffer overflow that c
be triggered by a corrupted jpg imag
then the execution of this jpg pars
on your computer could potentially

Scalable Automated Guided Execution

- Primer herramienta en realizar **concolic execution** en binario x86
  - *"what you fuzz is what you ship,"* ya que los compiladores pueden realizar transformaciones que afectan la seguridad.
- Security bugs: los programadores pueden fallar en alocar memoria o manipular buffers apropiadamente, resultando en **vulnerabilidades**.

White-Box Fuzzing con SAGE

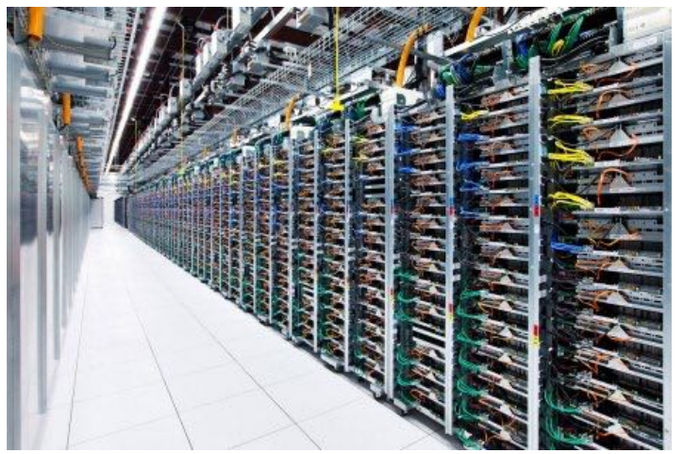
- La exploración de program paths se realiza paralelamente
- Cuanto más diverso y rico el conjunto inicial de inputs (ie seeds o semillas), mayor profundidad se logrará durante el fuzzing
- Utiliza heurísticas para maximizar el cubrimiento de código tan rápido como sea posible, con el objeto de encontrar bugs más rápidamente.
- Las **optimizaciones** son cruciales para manejar el **ENORME** tamaño de las path conditions.



SAGE

Microsoft

- *"Since 2008, SAGE has been running 24/7 on approximately 100-plus machines/cores automatically fuzzing hundreds of applications in Microsoft security testing labs"*



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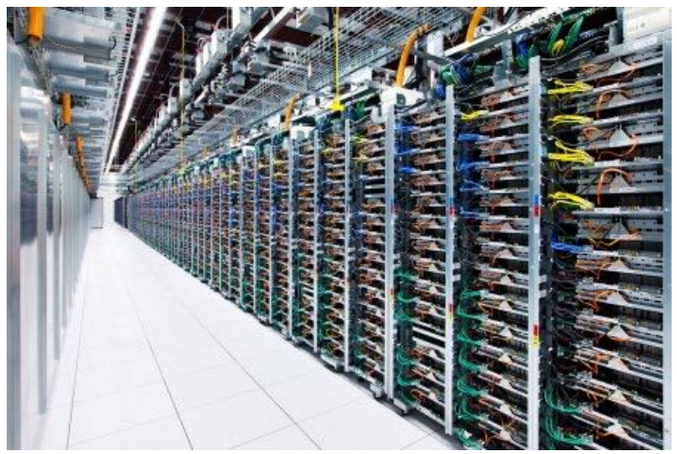

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- *"…has saved Microsoft millions of dollars as well as saved world time and energy, by avoiding expensive security patches to more than one billion PCs."*
- *"The software running on your PC has been affected by SAGE."*

Ejecución Simbólica
Al Rescate!

Necesitamos…

- Recolectar restricciones del código del programa
- Resolver restricciones para crear nuevos inputs

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  - UNSAT
  - UNKNOWN/TIMEOUT
- Si es SAT, da un valor para cada variable

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