Automated Detection of Software Bugs

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Contents

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- Or during runtime (Dynamic program analysis)
- Or in a combination of both.

Problems with Manual Testing

```
int f(int x)
{
        int y = x * 2;
        if(y == 12)fail(); // Crash
        else return y; // OK
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- The number of possible inputs is astronomically large. Infeasible to check every single one.
- Testing every input is a waste of time and computational power since large sets of inputs will follow the same path through the program.
- Test code could have bugs in it since its written by a human. Additional time and energy spent debugging test code.

Real world example: MINIX's tr tool

```
1 : void expand(char *arg, unsigned char *buffer) {          8
2 :   int i, ac;                                             9
3 :   while (*arg) {                                         10*
4 :     if (*arg == '\\') {                                  11*
5 :       arg++;
6 :       i = ac = 0;
7 :       if (*arg >= '0' && *arg <= '7') {
8 :         do {
9 :           ac = (ac << 3) + *arg++ - '0';
10:          i++;
11:        } while (i<4 && *arg>='0' && *arg<='7');
12:        *buffer++ = ac;
13:      } else if (*arg != '\0')
14:        *buffer++ = *arg++;
15:    } else if (*arg == '[') {                             12*
16:      arg++;                                              13
17:      i = *arg++;                                         14
18:      if (*arg++ != '-') {                                15!
19:        *buffer++ = '[';
20:        arg -= 2;
21:        continue;
22:      }
23:      ac = *arg++;
24:      while (i <= ac) *buffer++ = i++;
25:      arg++;      /* Skip ']' */
26:    } else
27:      *buffer++ = *arg++;
28:  }
29: }
30: ...
31: int main(int argc, char* argv[]) {                        1
32:   int index = 1;                                         2
33:   if (argc > 1 && argv[index][0] == '-') {               3*
34:     ...                                                  4
35:   }                                                      5
36:   ...                                                    6
37:   expand(argv[index++], index);                          7
38:   ...
39: }
```

tr(short for translate) is a UNIX tool that converts certain characters in a stream into other characters.

KLEE is a program analysis tool that uses symbolic execution.

When KLEE runs on tr, it finds a buffer overflow error at line 18 in just a few seconds and then produces a concrete input ([""" """) that hits the bug.

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Motivation

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- Automated detection of bugs is preferable as it is **easier, faster, covers more of your code, and avoids bugs in the code doing the testing**.

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- Compiler optimizations such as dead code elimination, constant propagation, common subexpression elimination etc rely on analysis such as control flow analysis, data flow analysis, etc.

Types of Program Analysis

- Static Analysis
  - Control Flow Analysis
  - Data Flow Analysis
  - Model Checking
  - Abstract Interpretation(Symbolic Execution)
  - Type Systems
- Dynamic Analysis
  - Testing
  - Monitoring
  - Program Slicing

Static Program Analysis

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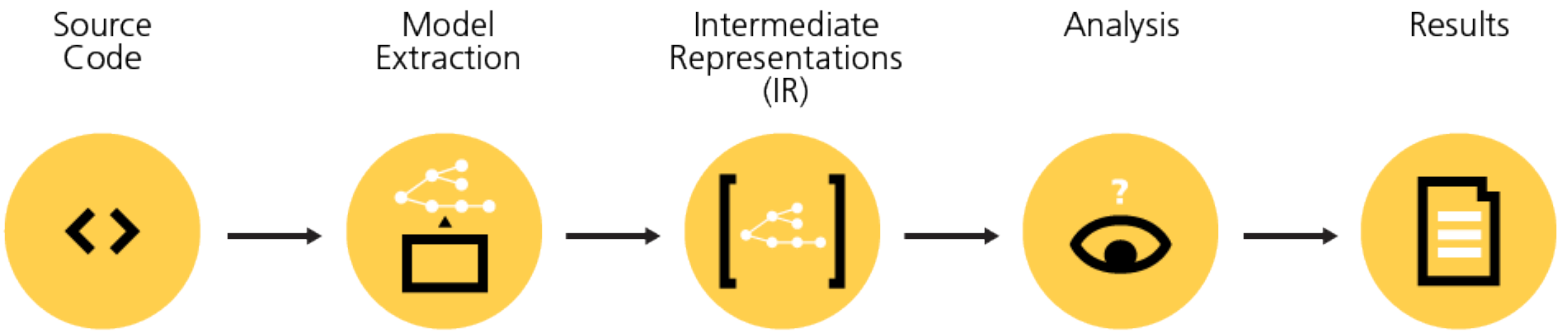
- Usually performed by an automated tool
- When done by a human it is called program understanding, program comprehension, or code review.

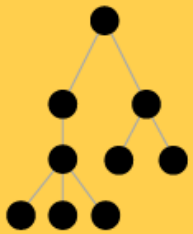
Static Analysis Diagram



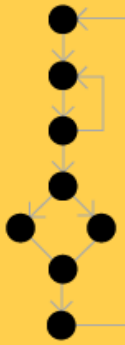
Names Databases/Symbol Table

Name	Kind	Location
copy_item	function	item. c:25
item_cache	variable	itemc:10
color	parameter	pallette.c:23
header.h	file	chapes.c

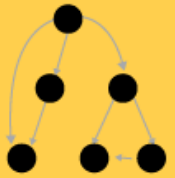
Abstract Syntax Tree (AST)



Control Flow graph (CFG)



Call Graph



Static Analysis Advantages and Disadvantages

Advantages:

- No need to build and execute the program.
- Can detect bugs early in development cycle.
- Cost efficient to correct bugs early.
- Can detect the exact location of bugs in the source code.
- Since it works on source code, it can detect bugs such as unreachable code, boundary value violations, out of bounds memory access etc.

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Disadvantages:

- Time consuming if done manually.
- Automated tools produce false positives and false negatives.
- Does not find vulnerabilities introduced in the runtime environment.

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- Analysis is done on the compiled binary.
- The program is executed within a controlled environment and test inputs are used.
- Instrumentation of the program binary is done to detect memory leaks, unsafe use of user input, monitor performance, etc.
- Capable of exposing a subtle flaw or vulnerability too complicated for static analysis alone to reveal(race conditions, environment specific bugs).

Dynamic Analysis Advantages and Disadvantages

Advantages:

- Can find bugs that are specific to the runtime environment.
- Allows for analysis of applications without access to the source code.
- Can detect subtle bugs such as race conditions, memory leaks, etc that are hard to detect using static analysis.

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- Allows for analysis of applications without access to the source code.
- Can detect subtle bugs such as race conditions, memory leaks, etc that are hard to detect using static analysis.

Disadvantages:

- Need to build and run the program in order to do analysis.
- Cannot guarantee the full test coverage of the source code.
- It is more difficult to trace the vulnerability back to the exact location in the code, taking longer to fix the problem.

Symbolic Execution

Definition: "Symbolic execution (also symbolic evaluation) is a means of analyzing a program to determine what inputs cause each part of a program to execute.

An interpreter follows the program, assuming symbolic values for inputs rather than obtaining actual inputs as normal execution of the program would. It thus arrives at expressions in terms of those symbols for expressions and variables in the program, and constraints in terms of those symbols for the possible outcomes of each conditional branch."

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(eg:- `y = 2 * x; // x = X, y = 2X`)
(eg:- `if(y > 4)x = y; else x = 4 * y;`

$$x = \begin{cases} 2X, & 2X > 4 \\ 8X, & 2X \leq 4 \end{cases}, y = 2X$$

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$$x = \begin{cases} 2X, & 2X > 4 \\ 8X, & 2X \leq 4 \end{cases}, y = 2X$$

)
These constraints allow us to consider ALL possible values those variables can take at the same time.

Standard execution

```
int max(int x, int y)
{
        int t = 0;
        if(x > y)
        {
                t = x;
        }
        else
        {
                t = y;
        }
        return t;
}
```

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        }
        return t;
}
```

```
int max(int x = 2, int y = 4)
{
        int t = 0;
        if(2 > 4) // false
        {
                t = x;
        }
        else
        {
                t = 4;
        }
        return 4;
}
```

Standard execution

```
int max(int x, int y)
{
        int t = 0;
        if(x > y)
        {
                t = x;
        }
        else
        {
                t = y;
        }
        return t;
}
```

```
int max(int x = 4, int y = 2)
{
        int t = 0;
        if(4 > 2) // true
        {
                t = 4;
        }
        else
        {
                t = 2;
        }
        return 4;
}
```

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int max(int x = X, int y = Y)
{
        int t = 0;
        if(X > Y)
        {
                t = X;
        }
        else
        {
                t = Y;
        }
        // now t = T
        return T;
}
```

$$T = \begin{cases} X, & X > Y \\ Y, & X \leq Y \end{cases}$$

Constraints

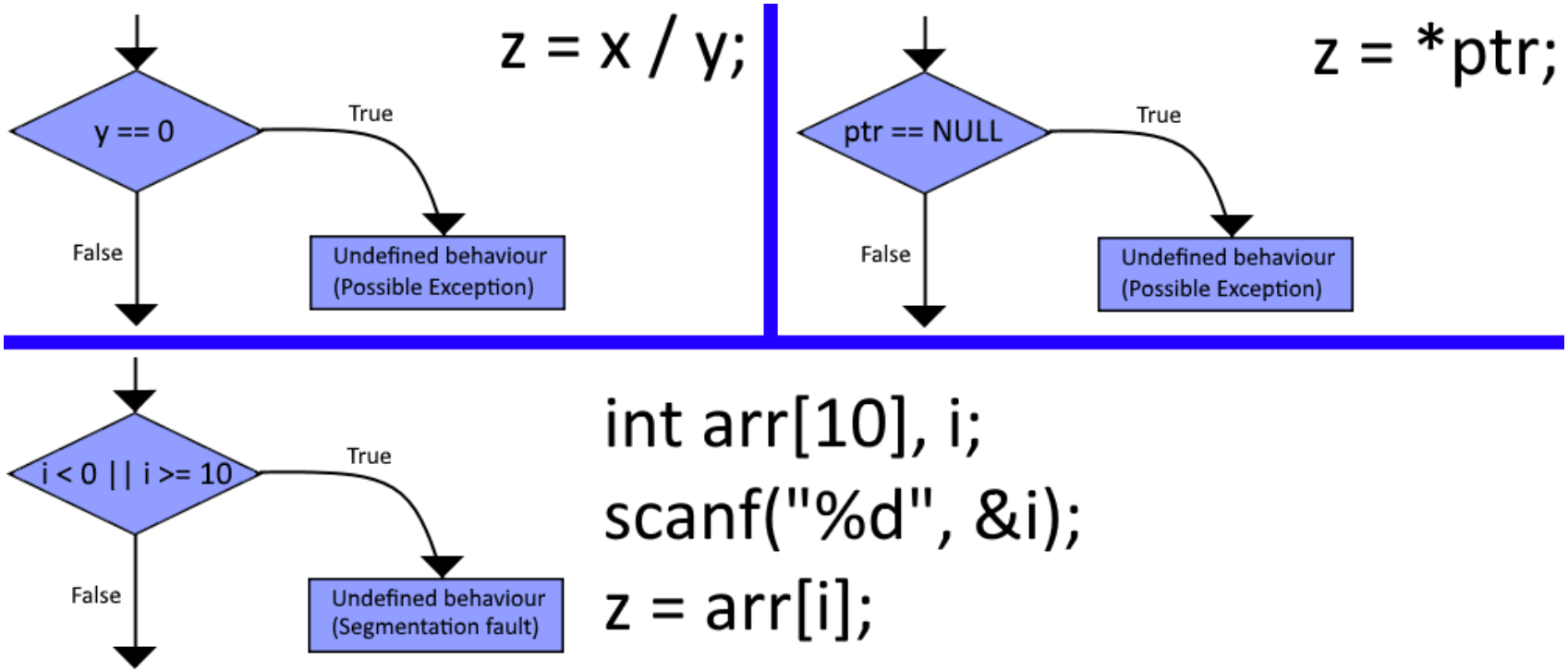
- Constraints generated from symbolic execution
  - $X > Y \implies T = X$
  - $X \leq Y \implies T = Y$
- After symbolic execution finishes, add an additional constraint "$T < X \vee \ T < Y \vee (T \neq X \wedge T \neq Y)$" to check correctness of the function max. This constraint represents a failure state.

$$(X > Y \implies T = X) \wedge$$
$$(X \leq Y \implies T = Y) \wedge$$
$$(T < X \vee \ T < Y \vee (T \neq X \wedge T \neq Y))$$

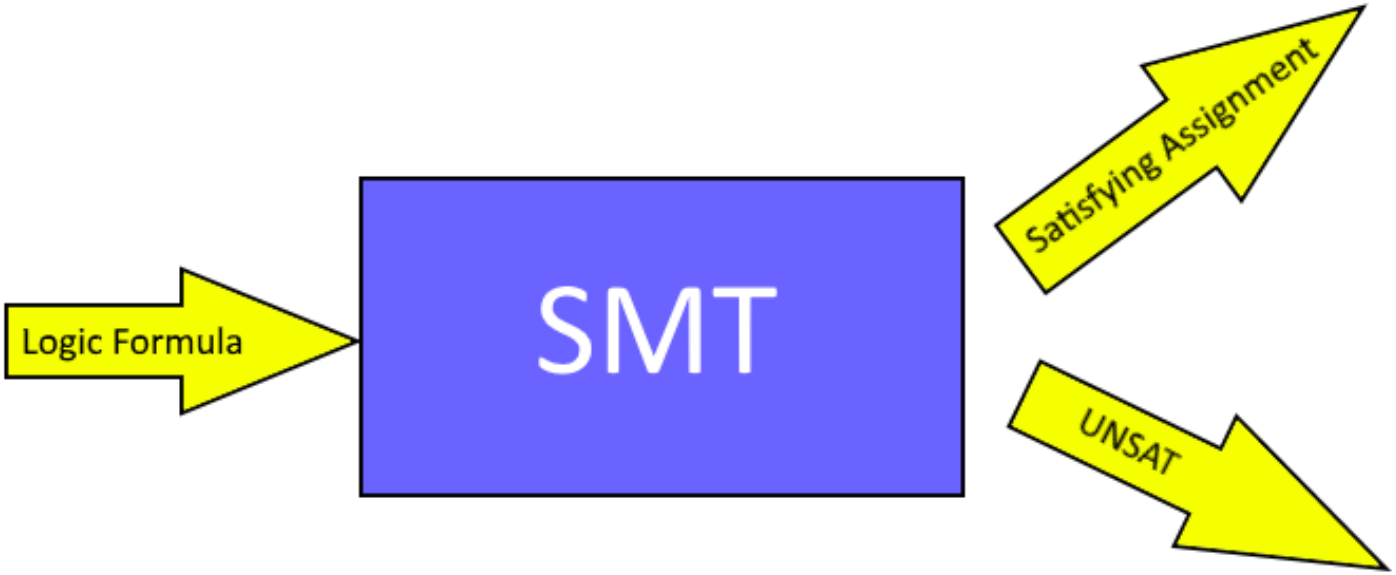
- If all these constraints can be satisfied at the same time then there is a bug. The solution to the constraints is a concrete input that reproduces the bug.
- In this example there is no solution to this set of constraints. Therefore the function is correct.

Branching Statements

"if" conditions are not the only points where execution can branch. Execution also branches when executing any code that could fail such as:



Solving Constraints



What is SMT?

Satisfiability Modulo Theories

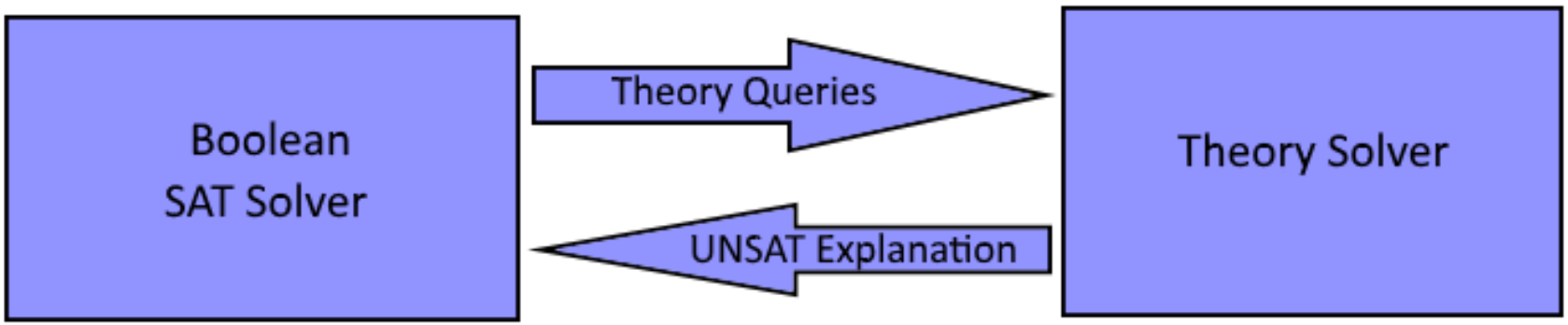
- Boolean SAT + Theories

Common Theories

- Bit Vectors (Fixed Length)
- Theory of Arrays
- Integer Arithmetic (Linear)
- Uninterpreted functions

SMT Working

Constraints: $(X > 5) \wedge (Y < 5) \wedge ((Y > X) \vee (Y > 2))$



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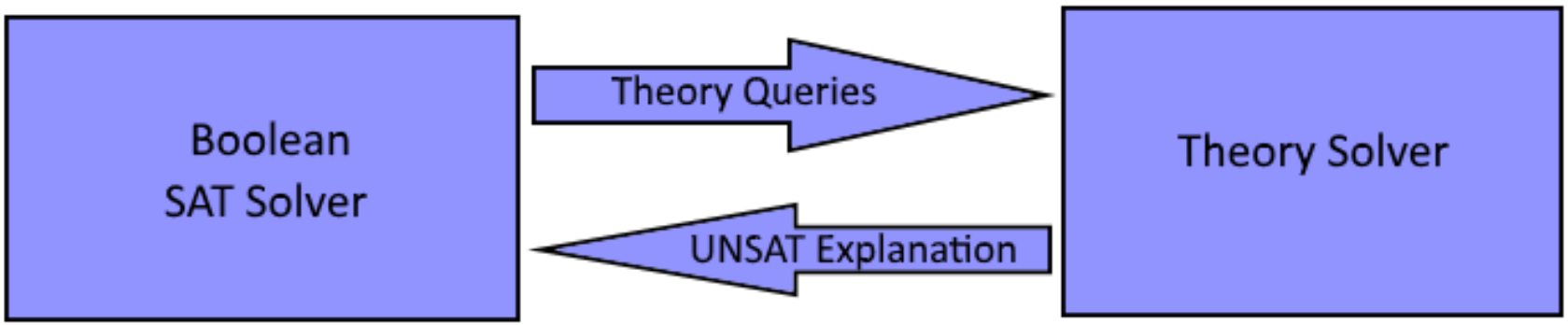
Constraints: $(X > 5) \wedge (Y < 5) \wedge ((Y > X) \vee (Y > 2))$
Simplify: $F1 \quad \wedge \quad F2 \quad \wedge \; (\; F3 \quad \vee \quad F4 \;)$

Give this pure boolean expression to the Boolean SAT solver.



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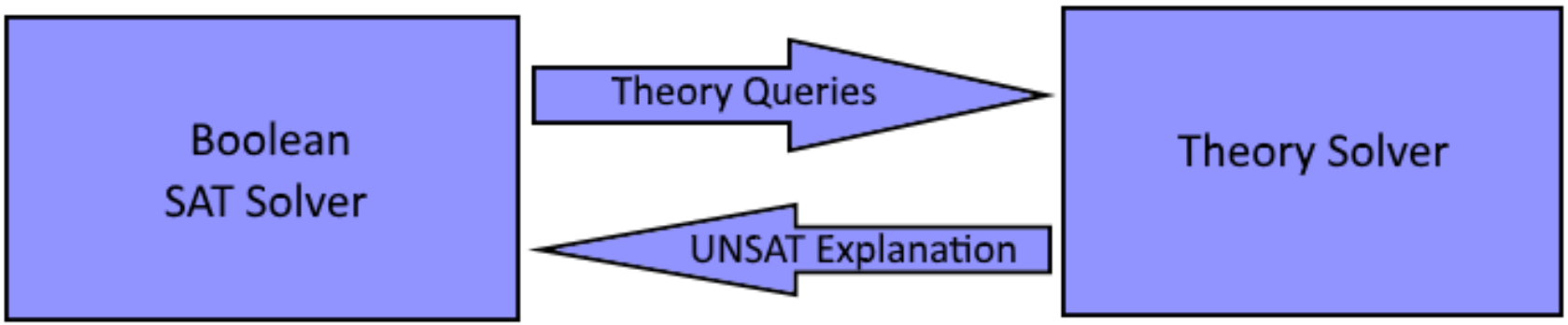
Query 1:

$F1 \wedge F2 \wedge F3 : \; X > 5, Y < 5, Y > X$

Answer:

Unsatisfiable: $\neg(F1 \wedge F2 \wedge F3)$



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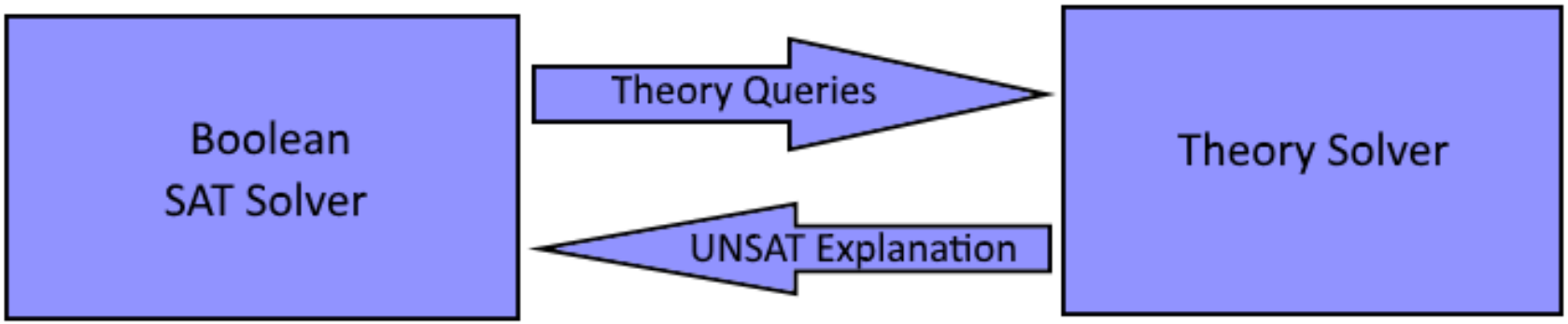
Query 2:

F1 and F2 and F4: $X > 5, Y < 5, Y > 2$

Answer:

Satisfiable: $X = 6, Y = 3$



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This technique reduces the complexity of constraints that are generated since we are not exploring every path at once.

Concolic Execution Example

Program

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    int t = 0;
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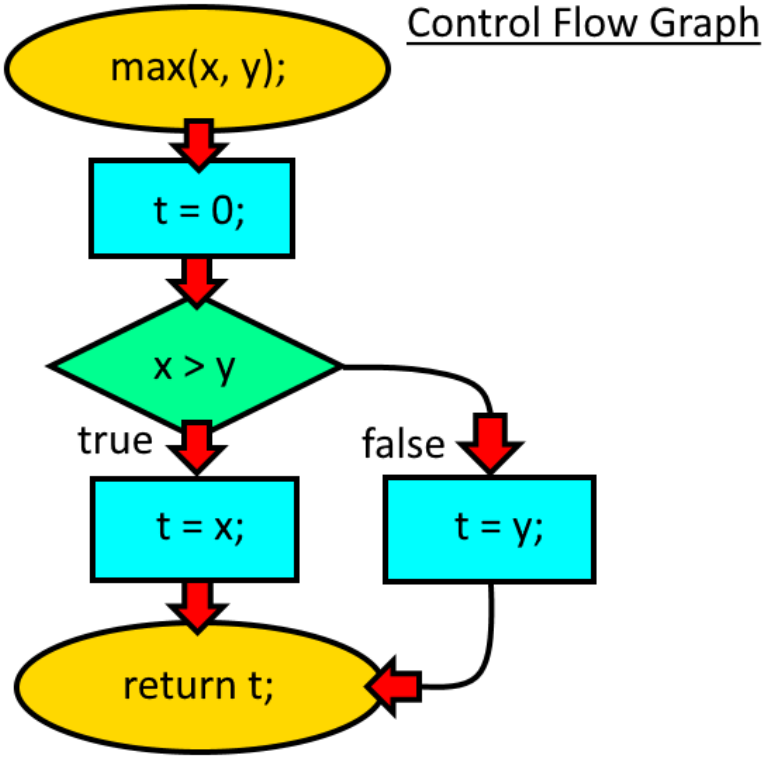
Control Flow Graph



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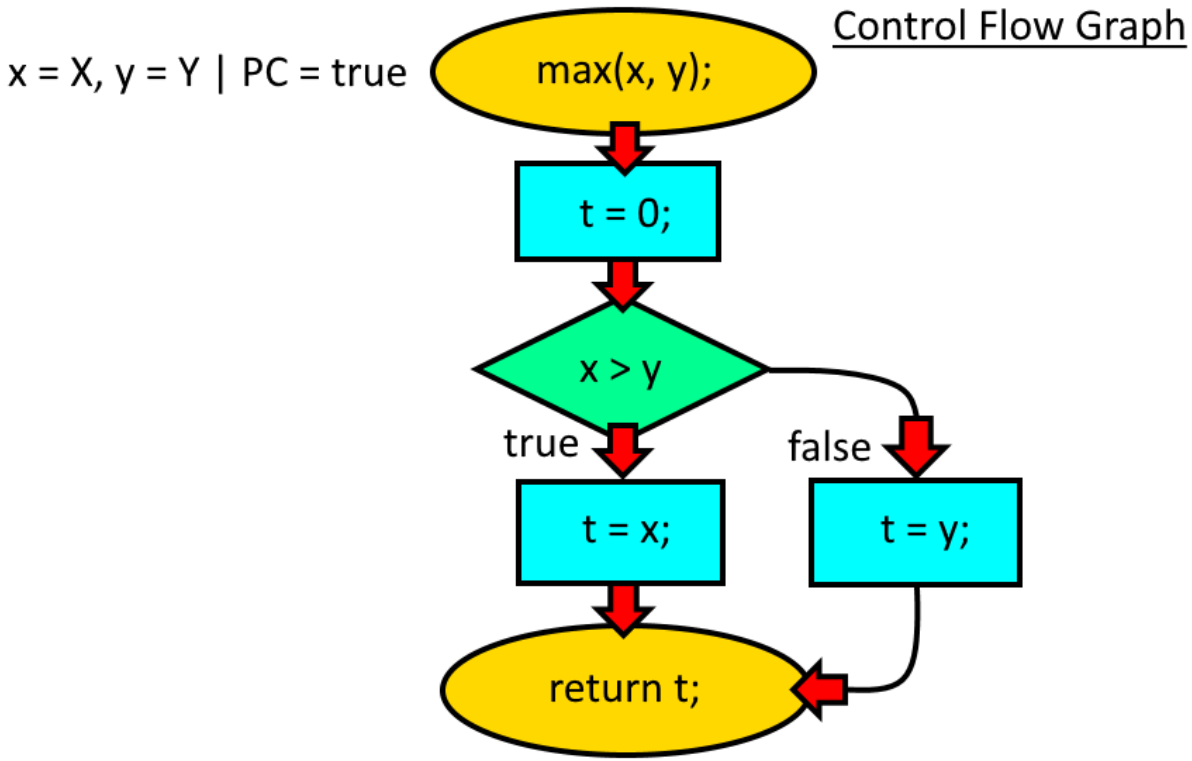

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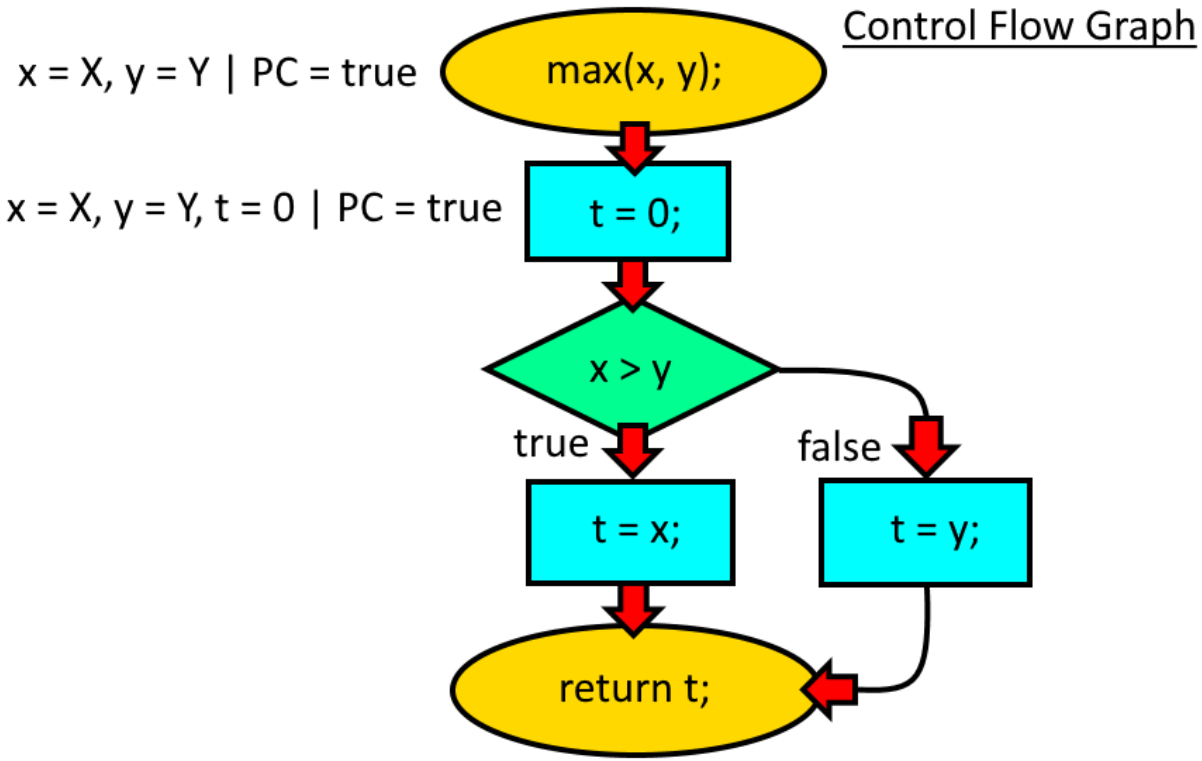

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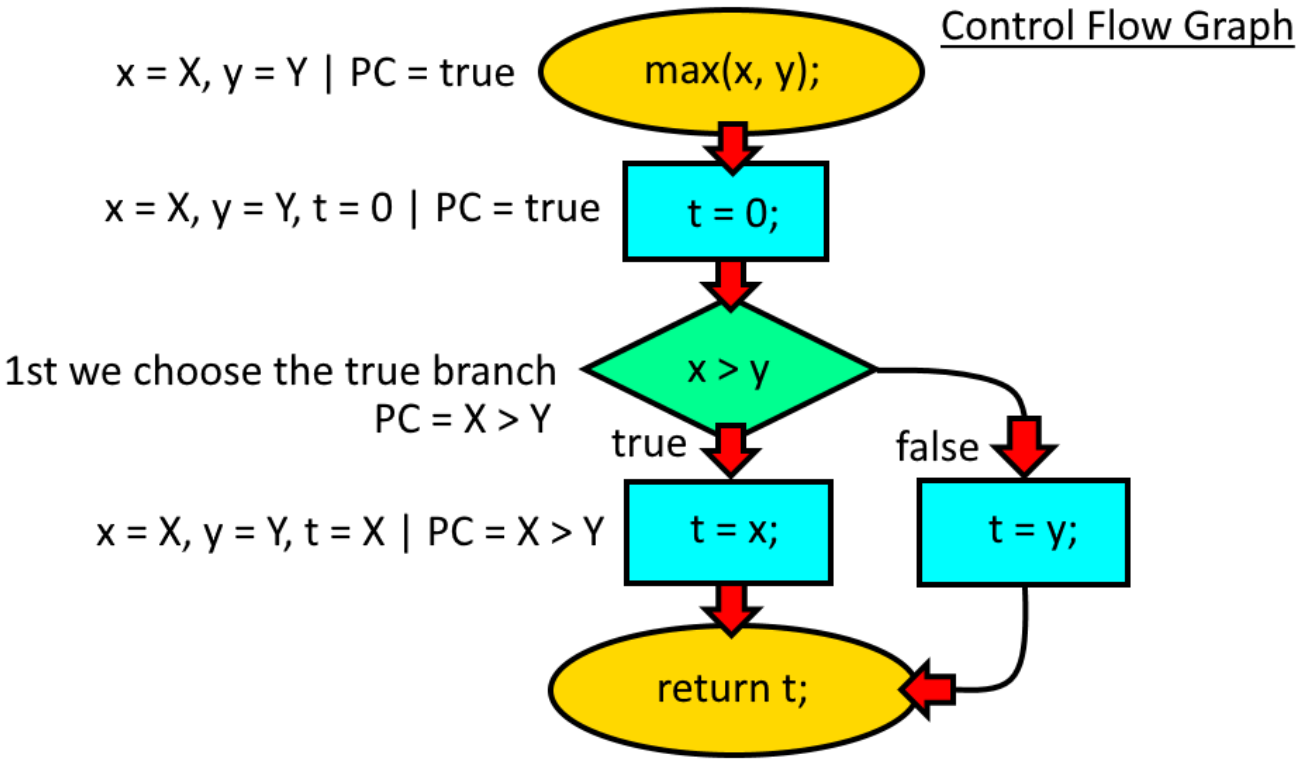

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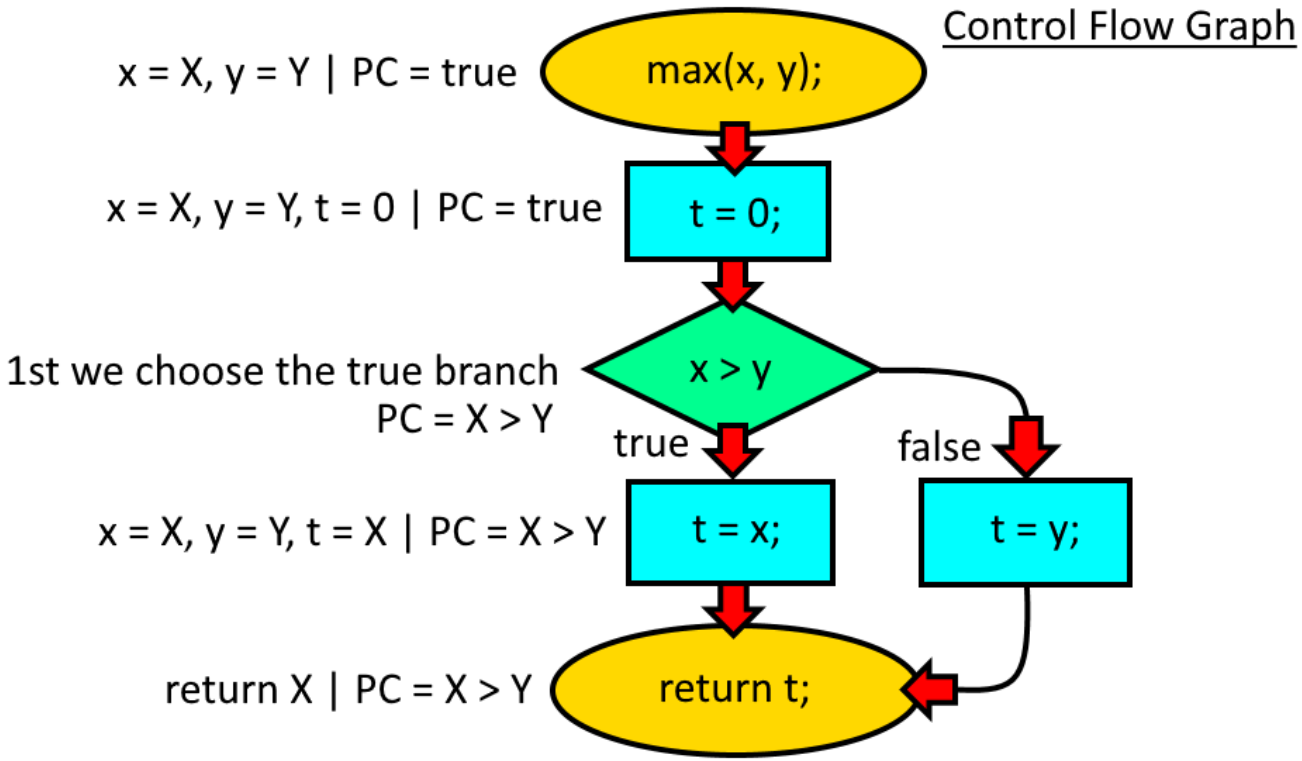

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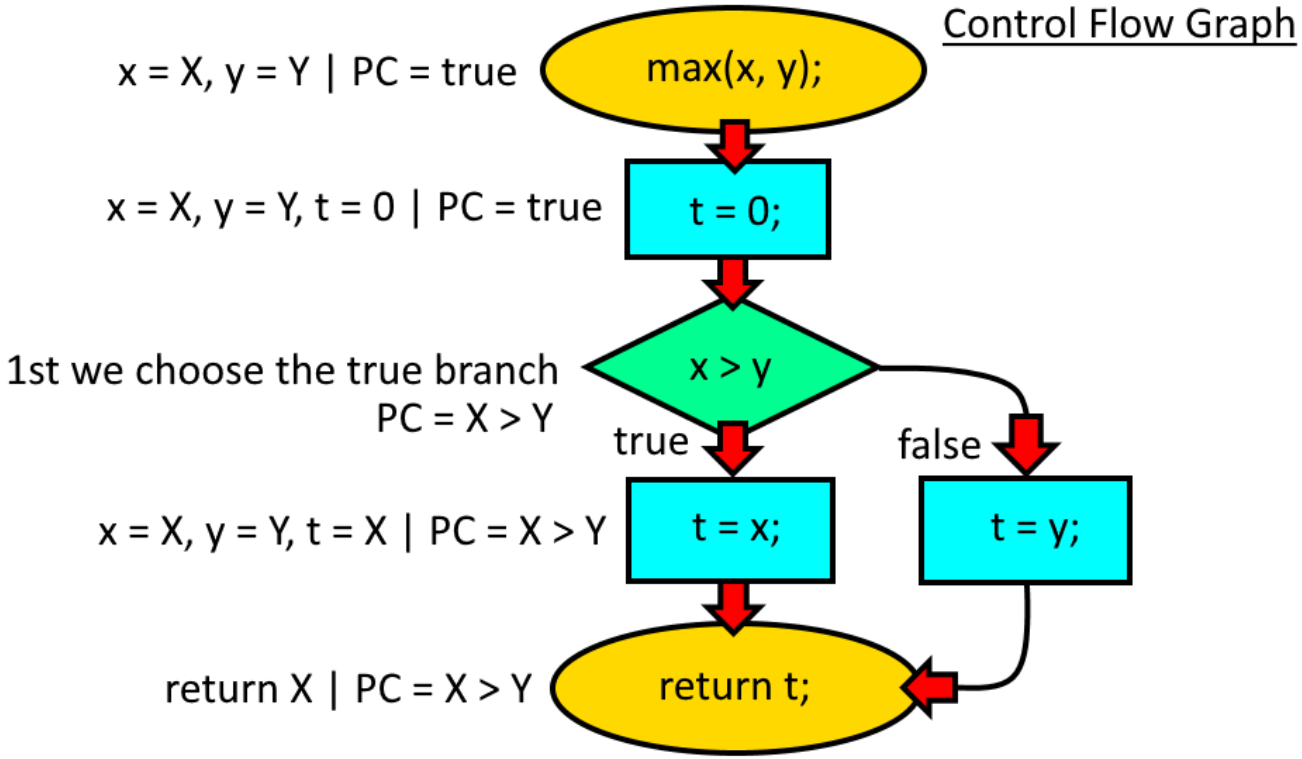
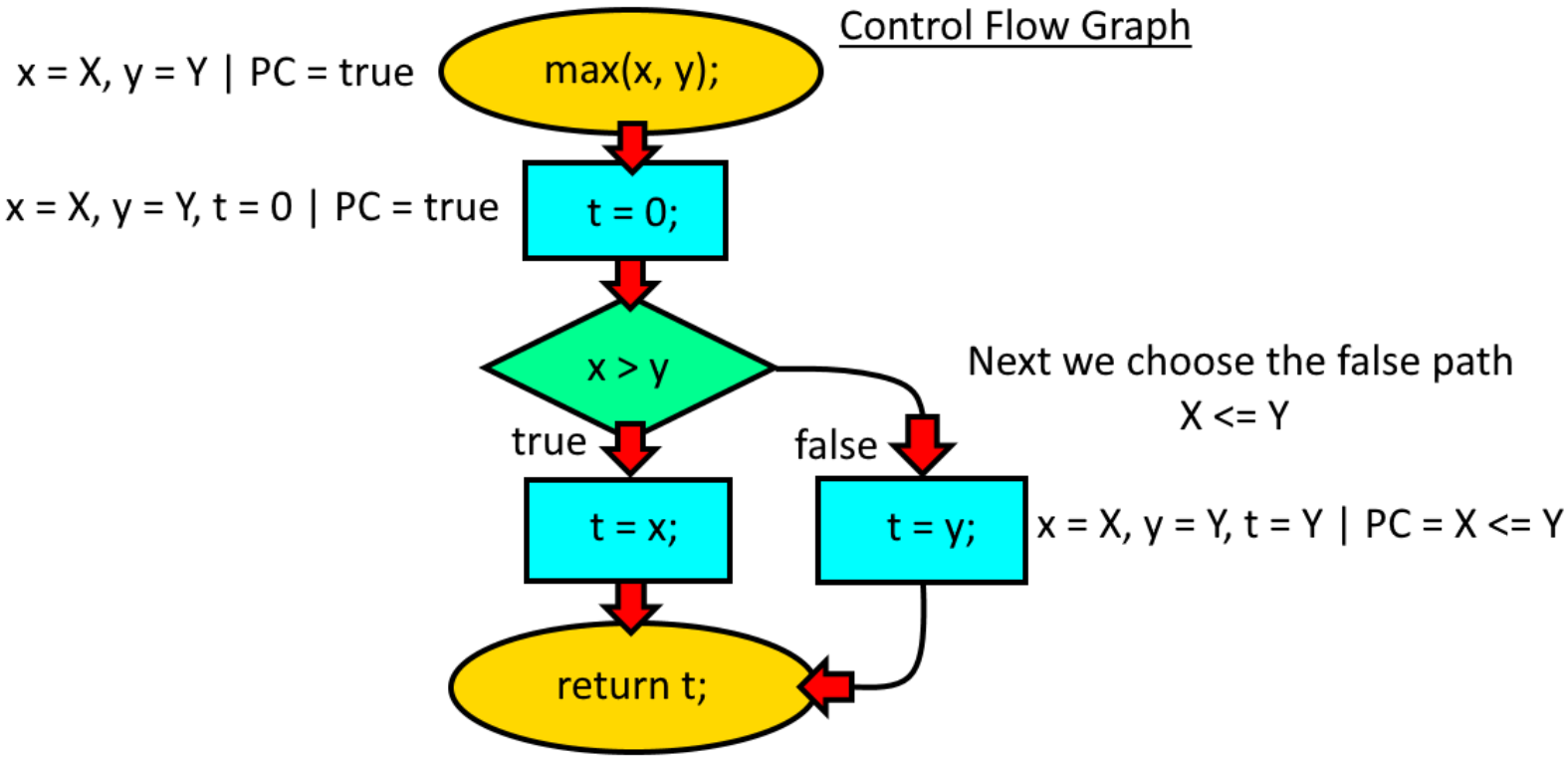


Now we can add the failure condition to the PC to see whether the function can fail:
Final Constraints: (X > Y) and ((t < X) or (t < Y) or (t =/= X and t =/= Y))
= (X > Y) and ((X < X) or (X < Y) or (X =/= X and X =/= Y))
= (X > Y) and ((false) or (X < Y) or (false and X =/= Y))
= (X > Y) and (X < Y)
= false (Unsatisfiable)
So we find that there is no bug along this execution path.

Concolic Execution Example



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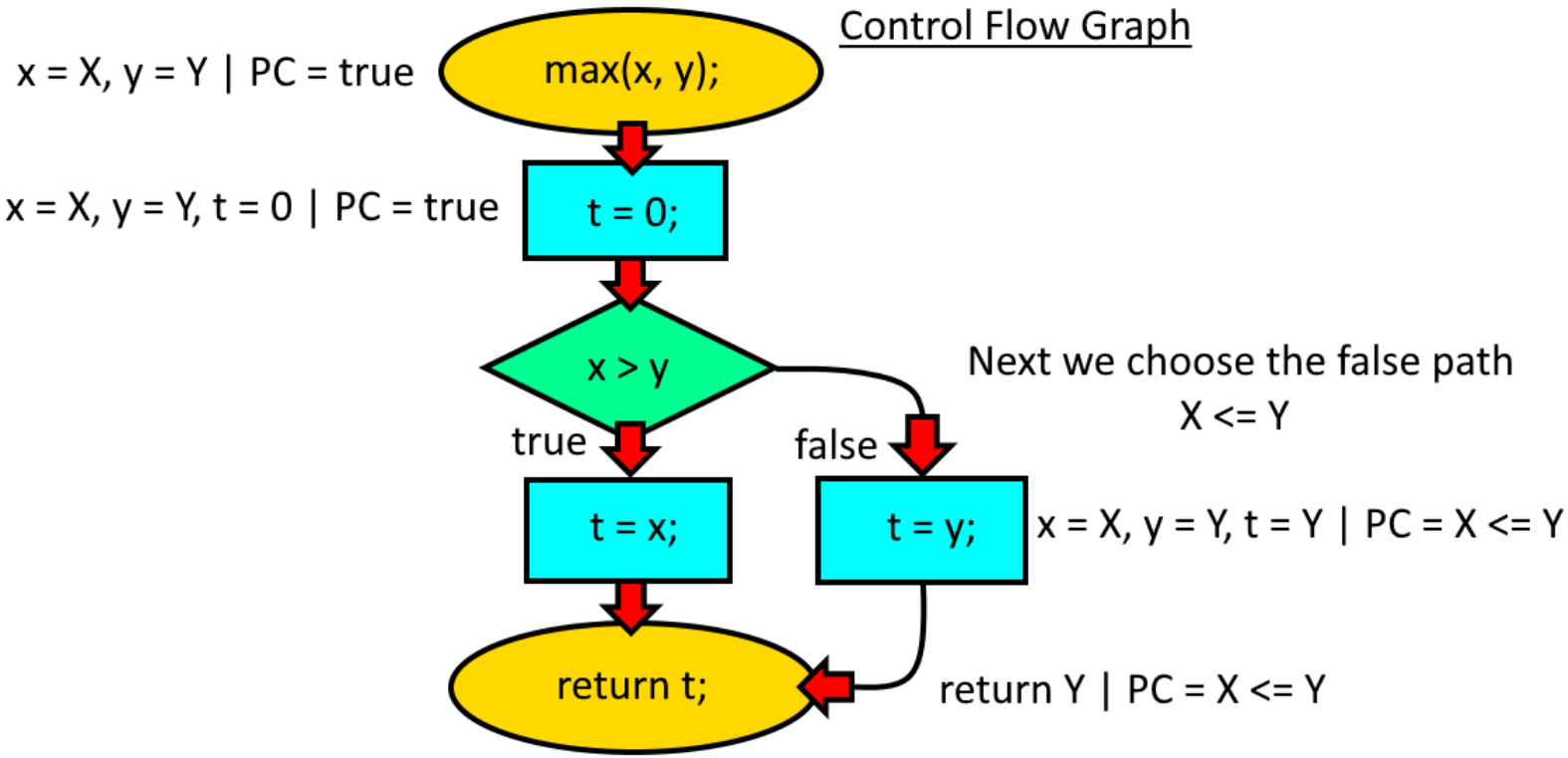

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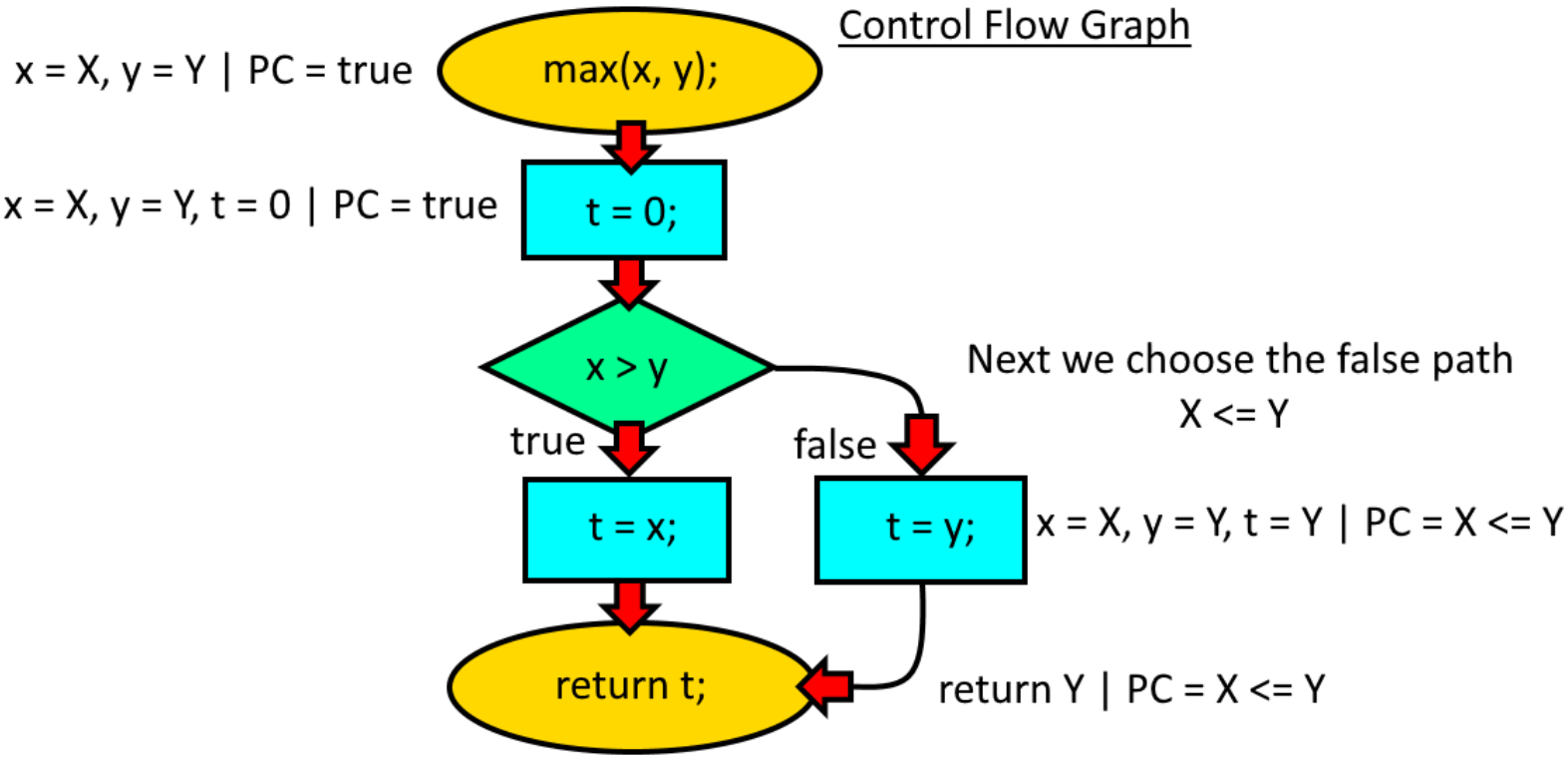

Again we add the failure condition to the PC to see if execution along this path can fail:
Final Constraints: (X <= Y) and ((t < X) or (t < Y) or (t =/= X and t =/= Y))
= (X <= Y) and ((Y < X) or (Y < Y) or (Y =/= X and Y =/= Y))
= (X <= Y) and ((Y < X) or (false) or (Y =/= X and false))
= (X <= Y) and (Y < X)
= false (Unsatisfiable)
So we find that there is no bug along this execution path either.
We have checked every path through the function so the function is correct.

Challenges to Symbolic and Concolic Execution

- *State space explosion* - Number of paths to be executed(and corresponding states) grows exponentially with the number of branches (if statements). Loops also explode the state space.

- *Memory Model* - Any arbitrarily complex object can be regarded as an array of bytes and each byte associated with a distinct symbol. However, when possible, exploiting structural properties of the data may be more convenient.

- *Environment* - Real-world applications constantly interact with the environment (e.g., the file system or the network) through libraries and system calls. These interactions may cause side-effects (such as the creation of a file) that could later affect the execution and must be therefore taken into account.

KLEE LLVM Execution Engine

KLEE is an open source symbolic virtual machine built on top of the LLVM compiler infrastructure.

- Generates tests that achieve high coverage on a diverse set of complex and environmentally-intensive programs.
- KLEE was used to thoroughly check all 89 stand-alone programs in the GNU COREUTILS utility suite.
- Generated tests achieved high line coverage — on average over 90% per tool (median: over 94%) — and beat the coverage of the developers' own hand-written test suites by 16.8%!
- It found ten fatal errors in COREUTILS (including three that had escaped detection for 15 years), which account for more crashing bugs than were reported in 2006, 2007 and 2008 combined.

KLEE Architecture

At a high level, KLEE functions as a hybrid between an operating system for symbolic processes and an interpreter.

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- This loop continues until there are no states remaining, or a user-defined timeout is reached.
- Unlike a normal process, storage locations for a state — registers, stack and heap objects — refer to expressions (trees) instead of raw data values.

KLEE's approach to challenges

- State Explosion - By implementing the heap as an immutable map, portions of the heap can be shared amongst multiple states. Since KLEE tracks all memory objects, it can implement copy-on-write at the object level (rather than page granularity), dramatically reducing per-state memory requirements.

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- Environment Modeling - The environment is handled by redirecting library calls that access it to models that understand the semantics of the desired action well enough to generate the required constraints. Crucially, these models are written in normal C code which the user can readily customize, extend, or even replace without having to understand the internals of KLEE. KLEE has about 2,500 lines of code to define simple models for roughly 40 system calls (e.g., open, read, write, stat, lseek, ftruncate, ioctl, etc).

KLEE's approach to challenges

- Query Optimization - Almost always, the cost of constraint solving dominates everything else — unsurprising, given that KLEE generates complicated queries for an NP-complete logic. A lot of effort is spend on tricks to simplify expressions:
  - Expression Rewriting
  - Constraint Set Simplification
  - Implied Value Concretization
  - These simplify and ideally eliminate queries before they reach the SMT. Simplified queries make solving faster, reduce memory consumption, and increase the query cache's hit rate.

KLEE's approach to challenges

- State scheduling - KLEE selects the state to run at each instruction by interleaving the following two search heuristics:
  - Random Path Selection maintains a binary tree recording the program path followed for all active states. States are selected by traversing this tree from the root and randomly selecting the path to follow at branch points. Therefore, when a branch point is reached, the set of states in each subtree has equal probability of being selected, regardless of the size of their subtrees.
  - Coverage-Optimized Search tries to select states likely to cover new code in the immediate future. It uses heuristics to compute a weight for each state and then randomly selects a state according to these weights. Currently these heuristics take into account the minimum distance to an uncovered instruction, the call stack of the state, and whether the state recently covered new code.

Tools

Other open source tools:

- angr (Python framework supporting x86, x86-64, ARM, AARCH64, MIPS, MIPS64, PPC, and PPC64)
- FuzzBALL for VineIL / Native
- JPF, jCUTE, janala2, JBSE and KeY for Java
- Otter for C
- SymDroid for Dalvik bytecode
- Kite for LLVM bytecode
- SymJS and Jalangi2 for Javascript
- Rubyx for Ruby
- Pex for .NET Framework

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- Fuzzing and Symbolic Execution were the fundamental techniques used to analyze, hack and patch the software.
- Exploits and patches were generated and deployed completely automatically.

DARPA Cyber Grand Challenge at DEFCON 24

- The CGC Final Event (CFE) was held on August 4, 2016 and lasted for 11 hours.
- The winning systems of the Cyber Grand Challenge (CGC) Final Event were:
  - "Mayhem" - developed by David Brumley, ForAllSecure, Carnegie Mellon University of Pittsburgh, Pa. - $2 million
  - "Xandra" - developed by TECHx, GrammaTech Inc., Ithaca, N.Y., and Charlottesville, Va. - $1 million
  - "Mechanical Phish" - developed by Shellphish, UC Santa Barbara, Ca. - $750,000
- The winner was also awarded the opportunity to play against humans in the 24th DEF CON capture the flag competition.
- Full event live stream: `https://youtu.be/n0kn4mDXY6I`

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- Microsoft Sage
  - It is a whitebox fuzzer optimized for long symbolic executions at the x86 binary level.
  - Running continuously since 2008 at the largest fuzzing lab in the world on MS apps such as Word, Office, Powerpoint, etc.
  - Has found 100s of bugs in 100s of apps which were missed by other program analyses and blackbox testing techniques. For instance, revealed nearly one third of the bugs discovered during the development of Windows 7.
  - Bug fixes shipped quietly (no MSRCs) to 1 Billion+ PCs.

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- KLEE (Has found severe bugs in open source software).
- S^2E - Virtual machine augmented with symbolic execution and modular path analyzers. It runs unmodified x86, x86-64, or ARM software stacks, including programs, libraries, the kernel, and drivers.

What I plan to do

- Replace the heuristics used for path selection in concolic execution with a machine learning algorithm.
- Augment the constraint solvers used with a machine learning based solver specifically aimed at solving non linear constraints.

Literature Survey

Randomized Coordinate Shrinking(RaCoS) algorithm from "Derivative-Free Optimization via Classification" research paper. Has been used to solve non linear constraints in concolic execution in another research paper("Symbolic Execution of Complex Program Driven by Machine Learning Based Constraint Solving").

- It is a machine learning based optimization algorithm.
- Can minimize non linear functions that are not differentiable, hence "derivative free optimization".
- Efficient for certain classes of functions(Polynomial time convergence). Has a strong theoretical foundation.
- Simple algorithm which is easy to implement and analyze.

Fuzzing

Fuzzing or fuzz testing is an automated software testing technique that involves providing invalid, unexpected, or random data as inputs to a computer program.

- The program is then monitored for exceptions such as crashes, or failing built-in code assertions or for finding potential memory leaks.
- Typically, fuzzers are used to test programs that take structured inputs.
- This structure is specified, e.g., in a file format or protocol and distinguishes valid from invalid input.
- An effective fuzzer generates semi-valid inputs that are "valid enough" in that they are not directly rejected by the parser, but do create unexpected behaviors deeper in the program and are "invalid enough" to expose corner cases that have not been properly dealt with.

Fuzzing Example

```
int main(void)
{
        char name[100];

        printf("Enter your name:");
        scanf("%s", name);
        printf("Hello %s!!", name);

        return 0;
}
```

- This program reads a string as user input and displays it back to the user.
- If we enter a string less than 100 characters(Ex: "World") we will get the desired output("Hello World!!").
- However since the user input is read into a fixed length 100 byte buffer using scanf(which does no bounds checking), it is easy to overflow the buffer and rewrite the stack memory.

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        char name[100];

        printf("Enter your name:");
        scanf("%s", name);
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```

- A fuzzer when given a valid input (like "World") will generate 1000s of new inputs that are variations of the input.
  Ex: "$Worl#d"", "W01234RLD",
  "WWWWWWWWWWWWWWWWWWWWWWWWORLD",
  etc
- Eventually it will generate an input that is longer than 100 bytes and overflow the buffer and crash the program. It will then report this as a bug and provide the crashing input.

Driller: Combining Symbolic Execution and Fuzzing

Driller is a hybrid vulnerability excavation tool which leverages fuzzing and selective concolic execution in a complementary manner, to find deeper bugs in programs.

- There are two different categories of user input:
  - General input, which has a wide range of valid values (e.g., the name of a user) and
  - Specific input, which has a limited set of valid values (e.g., the hash of the aforementioned name).
- Checks for particular values of specific input effectively split an application into compartments, separated by such checks.

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- Fuzzing is efficient when exploring possible values of general input, inside a compartment, but struggles to identify the precise values needed to satisfy checks on specific input and drive execution flow between compartments.
- On the other hand, Concolic Execution is efficient at determining the values that such specific checks require, but the path explosion problem makes it inefficient for pushing execution inside a compartment.

Example of combining the 2 approaches

```
int main(int argc, char** argv)
{
   int cmd, input1, input3;
   float input2;

   if(argc < 2)return -1;
   else if(strcmp(argv[1], "echo") == 0)
   {
      cmd = 1;
      input1 = atoi(argv[2]);
   }
   else if(strcmp(argv[1], "add") == 0)
   {
      cmd = 2;
      input1 = atoi(argv[2]);
      input2 = atof(argv[3]);
   }
   else if(strcmp(argv[1], "exec") == 0)
   {
      cmd = 3;
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   /*
   Complicated parameter parsing and command execution code
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Compares the 1st argument to different commands and initializes some variables

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Otherwise does some complicated parsing and execution of the command.

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These specific checks separate the program into compartments.

Compartments (area between checks)
- **Easy to fuzz**
- **Hard to do concolic exec**

Specific checks (separates compartments)
- **Difficult to fuzz**
- **Easy to solve with concolic exec**

Driller: Results on Cyber Grande Challenge Binaries

Experiments were done on a cluster of modern AMD64 processors.
Each binary had four dedicated fuzzer nodes and 64 concolic execution nodes, shared among all binaries.
Each concolic execution job had max 4GB RAM. Analyzed each binary until either a crash was found or 24 hours had passed.

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- The symbolic execution baseline experiment faired poorly on this dataset. Out of the 126 applications, symbolic execution discovered vulnerabilities in only 16.
- Fuzzing proved to be sufficient to discover crashes in 68.
- In Driller's run, Driller's concolic execution was able to generate a total of 101 new inputs for 13 of these applications. Using these extra inputs, AFL was able to discover an additional 9 crashes, for a total of 77, meaning that Driller achieves a 12% improvement over baseline fuzzing in relation to discovered vulnerabilities.

Conclusion

Symbolic Execution is a extremely useful technique to find software bugs. It can be used at both the source code and binary level. It can check practically infinite number of inputs at once, as opposed to traditional testing techniques which checks 1 input at a time. It can also check all possible paths of execution through the program thus achieving 100% code coverage. This makes Symbolic Execution both Sound (No false positives, generated test cases lead to actual bugs) and Complete (Finds all buggy inputs).

While there are still several challenges involved in scaling symbolic execution to large programs, significant research is going on in this area and as machines get faster and more powerful, it is sure to become more and more feasible in the future.

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