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程式動態行為安全分析(2/2)

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摘要

程式的安全分析與軟體品質息息相關，而品質則仰賴於高涵蓋率的測試技術。我們採用自動測試的技術來進行軟體安全分析。傳統上，軟體測試所需成本高達總成本的50%，因此成為軟體發展(Software Development)過程中的主要瓶頸。現今發展軟體系統的趨勢，趨向於藉由輔助工具(Auxiliary Tool)來降低軟體測試(Software Testing)所需的資源，但現有測試系統大多需要使用者自行設定測試環境(Testing Driver)，測試的效能也隨之影響，主要原因是測試分析工具無法有系統地自動產生測試資料，以證明相關輸入資料可到達特定的執行環境(Program State)，這卻是我們用來印證測試效率及品質最直接的方法。本論文中，我們將以程式邏輯推論為出發點，有系統地產生測試資料(Testing Inputs)以執行所有可能路徑(Possible Paths)。我們實作了一個自動測試工具，稱為ALERT，能自動分析程式執行時的邏輯條件(Logic Constraints)，以表示執行的語義(Execution Semantics), 藉此可推論剩下可能執行路徑的測試輸入。我們利用 gcov 來分析 ALERT 的測試效率，所自動產生的測試資料可達 90% 的涵蓋率。藉此高涵蓋率的測試工具，我們可自動產生安全分析的輸入資料，並激發錯誤而有安全疑慮的程式碼。

Abstract

Software security is largely dependent on the code quality and the quality can only be assured by a high coverage testing tool. Testing has become the bottleneck of software development process due to the cost of testing process even attributing to 50% of total cost. The trend of contemporary software development process is toward the use of auxiliary tools to reduce the resource usage of testing process. However, most testing tools require users to manually produce testing drivers which have much to do with testing quality. It is due to the lack of automatic input generation that ensures the existence of the execution path from inputs to the specified program state with rendered testing condition. Nevertheless, it is our intuitive way to prove the testing efficiency and testing quality. In this paper, we analyze program semantics based on program logic reasoning and try to generate testing cases to cover all possible paths. We design and implement an automatic testing tool, called ALERT, which can analyze logic constraints to represent semantics of program executions, and reason testing inputs of remaining paths. We perform coverage test by Gcov [1] to evaluate the testing efficiency of ALERT and reach 90% of coverage rate. With our ALERT tool, we can systematically generate input data to investigate potential software vulnerability and analyze the corresponding program behaviors.

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1. Introduction

In this chapter, we first show the software testing process of modern times and the problem that we are going to solve. An automatic method of testing process is introduced in next section. Finally, we briefly state our motivation and objective.

1.1. Software Testing

Software quality nowadays seems crucially essential. In software engineering, the most significant process to ensure software quality is testing. The key point that how to carry testing process out yet depends on the testing strategies. Figure 1 shows a general type of testing. It consists of three stages: input testing cases, execute programs and compare outputs with correct results.

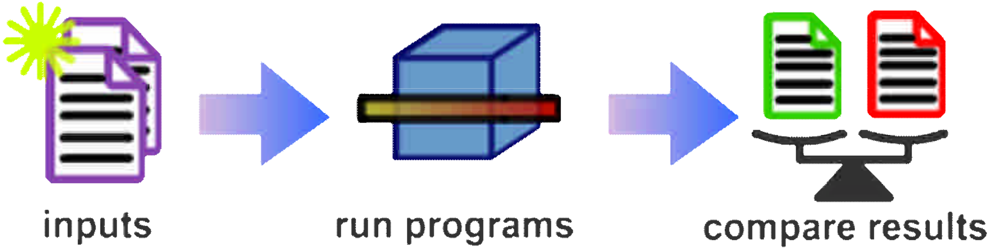


Figure 1, General testing process

In the last stage, we usually perform the comparison of results manually. But it is very expensive to verify the program outputs manually. The Quality Assurance Institute in 1995 proposed a comparison of manual and automatic testing which introduced about 1750 testing cases and 700 defects. Table 1 shows the result about time consumption for testing processes (in hours). The improvement of the test case development, test execution and test result analyses are 55%, 95% and 50%, respectively.

Table 1, Manual vs. automated testing

Test step	Manual testing	Automatic testing	Percent Improvement
Test plan development	32	40	-25%
Test case development	262	117	55%

Test execution	466	23	95%
Test result analyses	117	58	50%
Defect tracking	117	23	80%
Report creation	96	16	83%
Total hours	1090	277	75%

It encouraged us to develop ALERT, an automatic testing tool that automates these test steps including test case development, test execution and test result analyses. In order to generate test cases, ALERT must handle the logic information about program source and static semantics. In addition to generating test cases, the creation of test interface is required to automate test execution. To demonstrate all system functionalities in a direct way, we have to test every component one by one, such a method named unit testing. Finally, due to the automation of the whole test process, we need to generate test case for the remained paths when performing test result analyses, imagining by figure 2.

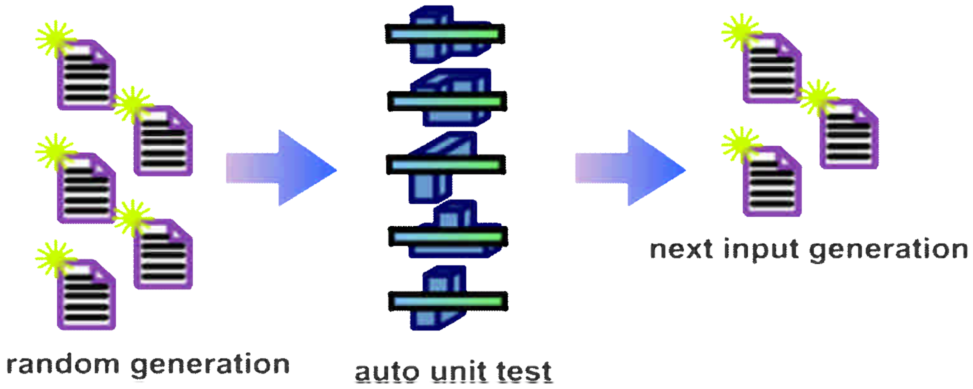


Figure 2, Unit testing with inputs generation

1.2. Test Strategies

Traditionally, test strategies method divided into two classes, static and dynamic analyses, based on the source code and the runtime execution, respectively. Both have been maturely developed in modern times. Static analyses examine program source code or binary image without invoking the programs. It is recommended to apply static analyses to program systems with complex interaction or heavy running overhead. As a consequence, the static method is extensively used in large scale software for inconsistency checking. Yet, the static method could cause large number of false alarms. It is because we can’t verify and perform any feature revealed through static analyses. Static analyses report too many features that the practicability of those features is unknown.

Dynamic analyses involve the execution of programs. We apply the dynamic analysis on programs whose environment can be simply reconstructed and the runtime overheads are tolerable. Obviously, the difficulties of the dynamic method are test input development. Appropriate test inputs enable program states to shift to some specified condition that exactly satisfies the constraints to perform features. The quality of test cases decides the efficiency of testing tools. It is an extremely difficult work to manually generate testing inputs upon thousand of testing runs.

1.3. Motivation

If we can find the input cases for a given code location and environmental content, we are able to eliminate the false positives of static method by examining the feasibility of each reported feature. For dynamic method, with the support of test cases which enable programs to perform the remained paths, we can improve the efficiency of whole analysis process, with better coverage.

With the automatic generation of particular inputs from another running instance, we can easily apply debug method with only failure running instances. It is an advanced integration of testing and debugging that we resolve the program run-time logic and produce special test cases for debugging tools to make decisions more precisely.

1.3.1. Feasible Inputs

We propose a mechanism to automatically generate test cases and ensure feasibility of given paths. Static methods check source code consistency, but if we want to suppress false alarms we must execute programs and check the features reachable. On the other hand, dynamic methods execute programs many times, and require test inputs to go through all branches. In order to generate feasible inputs according to program semantics, we base on program logic to transform programs into special models for of possible test case resolution.

1.4. Objective

Our objective is to extract logic models from execution instances and create test cases that cover as many as possible control branches by checking logic models, as figure 3 shows. We focus on C language, which is one of the most popular imperative languages and present the logic models with rule-based language. Clearly, there is some gap between imperative language and rule-based language, and it is impossible to transform imperative programs into equivalent rule-based models. However, we discover that it is feasible to make a one-way transformation from run-time instances of imperative programs into rule-based ones.

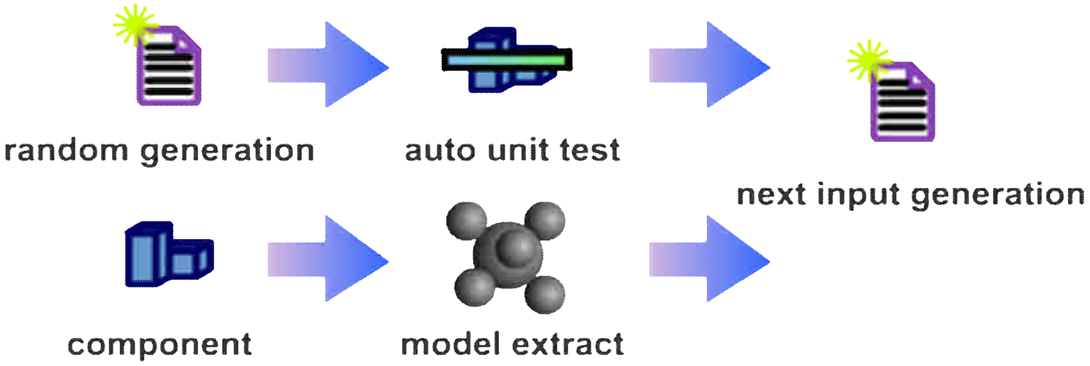


Figure 3, Unit test with model extraction

We perform the test process by reasoning on the program behaviors, similar to manually trace-back of program logic, interleaving with symbolic evaluation and concrete evaluations. Two goals will be fulfilled: logic model extraction and run-time predicates resolution.

1.4.1. Logic constraints extraction

We transform a program running instance view to a list of rules which have the ability to represent the dynamic states upon codes. We are going to build an executable logic model that can be evaluated exactly like the original program running. There is still one difference: an executable model doesn't surround by real program environment. To fix this, the incomplete predicates of logic models would be resolved by symbolic evaluation of runtime traces.

1.4.2. Runtime predicates resolution

What we want to resolve during logic model construction are those variables and date-structures that exist in concrete memory space, including function arguments took by procedures and addresses that pointers refer to. Because logic rules can not express the state transactions of concrete memory space, we mark those predicates as unknown symbols and resolve their value dependencies by symbolic evaluation.

We can evaluate each line of source code, and substitute the symbolic meaning of variables. Of course, the resolving operation is not invertible. We expect to show how the next state comes from according to the current state. It is used to illustrate running instance of program iteration.

1.5. Synopsis

The rest of our report is organized as follows. The related works and state of the art are reviewed in chapter 2. The overview and basic concept of ALERT are discussed in chapter 3. Chapter 4 presents the detail and implementation of ALERT. The result and evaluation of our work is showed in chapter 5. In the last chapter is the conclusion, self evaluation of our project and future work.

2. Related Work

The implementation of program logic resolution spans many topics. Recently researches focus on causes-transaction [2]. This method inspects into a program execution state, e.g. breakpoints, tries to find some clues between each state changing, and extracts a cause effect chain from the blamed site to the faulty site. We are not the first to consider logic representations. Former research like PREFix[3], infers for logic conflicts by treating program expressions as logic constrains and program functions as logic sub-models. We will also introduce other implementations like model extraction[4-7], dynamic instrumentation for tagged memory operations[8], and conditional toggling test method with full path-coverage guarantee[9].

2.1. Data Reconstruction for Cause Effect Chains

Let us denote the memory structure occupied by a program as MStruct(t), where t stands for time. We can conclude that: Zeller’s method [2] automatically creates memory graph MGraph1 and MGraph2 from MStruct(t1) and MStruct(t2) respectively under the debugger. Demskey[10] try to reconstruct data structure representation from MStruct(t) with user-specified constrains and debugging information. Purify[8] searches the whole MStruct(t) for potential dereference. In more general, we propose a logic representation from source code and resolve logic predicates with MStruct(t). Table1 shows advantages and disadvantages of our work and others.

Table 2, Comparison of former data recreation methods

	Zeller[2]	Brian[10]	Purify[8]	ALERT
Advantages	Automatic Memory Graph Extraction and Differentiation	Semi-Automatic Data Structure Construction	Memory Tag Annotation	Automatic Logic Model Extraction and Resolution

Limitations	Require Two Similar MStruct(t)	Require User Specified Constraints	Require Extra Memory Space	Perform Unit Testing for Functions

2.2. Model Checking

The way to model the behavior of programs varies from language properties to checking purposes. Finite state machine checking is easily understood and specified. Most model checking methods use FSM to model program systems. Monica Lam's work [4] creates FSA model representations from Java. They focus on object interactions and method call sequences. Method calls are treated as state transitions. The FSA object obtains a new state when a member function is executed. Metal [6, 7] is a programming language for detecting program contradictions. Users specify a FSA model in Metal to check inconsistence within system codes. The FSA model contains states and transition rules that will match any AST nodes of programs. Metal reports these inconsistent states matched by rules. PREfix[3] have pointed out that programs can be represented in a logic way. They transform each function into a logic model which contains logic-based constraints, guards and results. The entire program model can be built by combination of all sub-models. They search contradictions in program models through logic unification and report contradictions about pointer misuse, dead code, conflicts of conditional statements to users. We make comparisons of each model checking methods and depict in Table2.

Table 3, Comparison of model checking methods

	Monica work[4]	Metal[6, 7]	PREfix[3]	ALERT
Model Properties	Component-based, Object-Oriented	Describing State Transaction with Programming language	Subroutine-based, Top Model Contains Sub-models	Logic-Rules-based, Dependencies between Symbols
Checking Mechanism	Model Extraction for manually testing	Specifying Model for Automatic Checking	Model Construction for Logic Unification	Following Logic Dependencies for Causes

Analysis Type	Static and Dynamic Analysis	Static Analysis	Static Analysis	Static Analysis and Dynamic Resolution

2.3. Techniques of Fault Localizers

There are many fault localization techniques used in debugging tools. Since 1960s these techniques have changed and improved [11]. Our research involves two major conceptual techniques: feasible path generation and logic symbol evaluation. Path generation[12] is an automatic generation of program paths that lead to user-specified outputs by toggling each control branch instances, and uses ESC[13] to check feasibility of toggled paths. Symbolic evaluation [9] is an automatic dependency extraction for unit testing that guarantees full paths coverage. We use path generation and symbolic evaluation to find associates of inputs and conditional control variables, and generate reasonable input to cover all program paths.

2.4. Symbolic Evaluation and Concrete Evaluation

Another tool named DART [9] combines symbolic evaluation with concrete values. It provides an automatic unit testing data and test interface generation for a specified C function, and it can ensure to expand as more program control branches as the variety of testing inputs by evaluation the symbolic expressions of programs and modification of testing data. DART guarantees all the bugs reported have corresponding testing inputs to reveal. It is a very attractive contribution for automatic testing. It also deploys lpsolve [14] to resolve linear symbolic constraints.

CUTE [15], a successive implementation of DART, improves structural testing data generation and pointer arithmetic. CUTE creates logic map for each pointer argument, which mapping to its concrete value of some memory location. During execution, logic map updates all pointer variables with symbolic representations.

3. ALERT overview

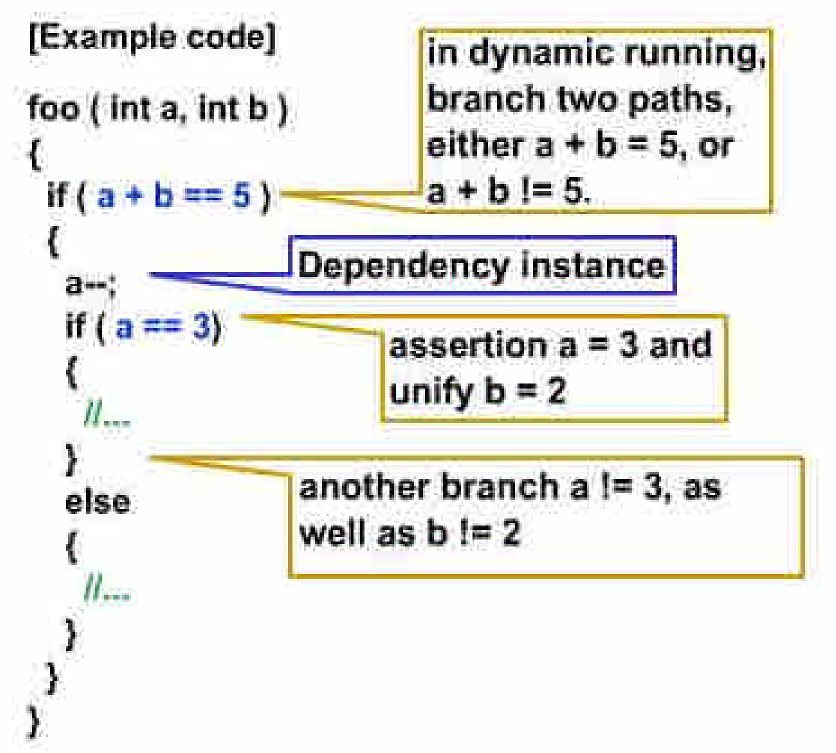
For an example as figure 4, ALERT generate a testing interface and trace the specified function. The result of these trace is to get the suitable input cases that cover all conditional branches. There are two control branches in line 2 and 6. In the first run, x and y input values are randomly created, said -2853 and 416. The program execution path would go through 1, 2, 6, 7, and return. ALERT trap the conditional expressions to show the restrictions of this execution path. In this case, they would be '! (x > 0 && y >1) ' and '(x < 10) ' , as the guard of the if expressions in line 2 and 6. In the next execution turn, the testing case ALERT generated would fulfill the branch alternative restrictions which could be '(x > 0 && y >1) ' or '! (x < 10)'. For ALERT would take the latest restriction, the input data would set x to satisfy "no less than 10" in order to change the execution path to go through line 9 instead line 7.

```
1 int foo( int x, int y ) {               //simple c function
2     if( x > 0 && y > 1) {               //branch condition for x, y
3          /* … */
4          return 0;
5     }
6     if( x <10 )                         // branch condition for x
7          return x;
8     else                                // branch condition (false)
9          return y;
10}
```

Figure 4, ALERT simple example

Here is a more detailed example which illustrates the conditional and dependency constraints extraction and the dynamic logic resolution. In figure 5, there are two control guards along the execution paths: (a + b == 5) and (a == 3), and a dependency instance (a --).

During function execution, the control guards make control thread to branch two paths, one ensures the sum of variable a, b equals 5 and another not. ALERT now can make assurance that if the control thread takes the guard of (a + b == 5) and (a == 3) the value of variable at that moment must be 2. But there is still one thing to took into consideration, the dependency instance (a --) modify the value of variable a, that causes the logic engine misunderstand all following conditional constraints. To modify constraints according to dependencies, we develop an evaluating method over constraint symbols.



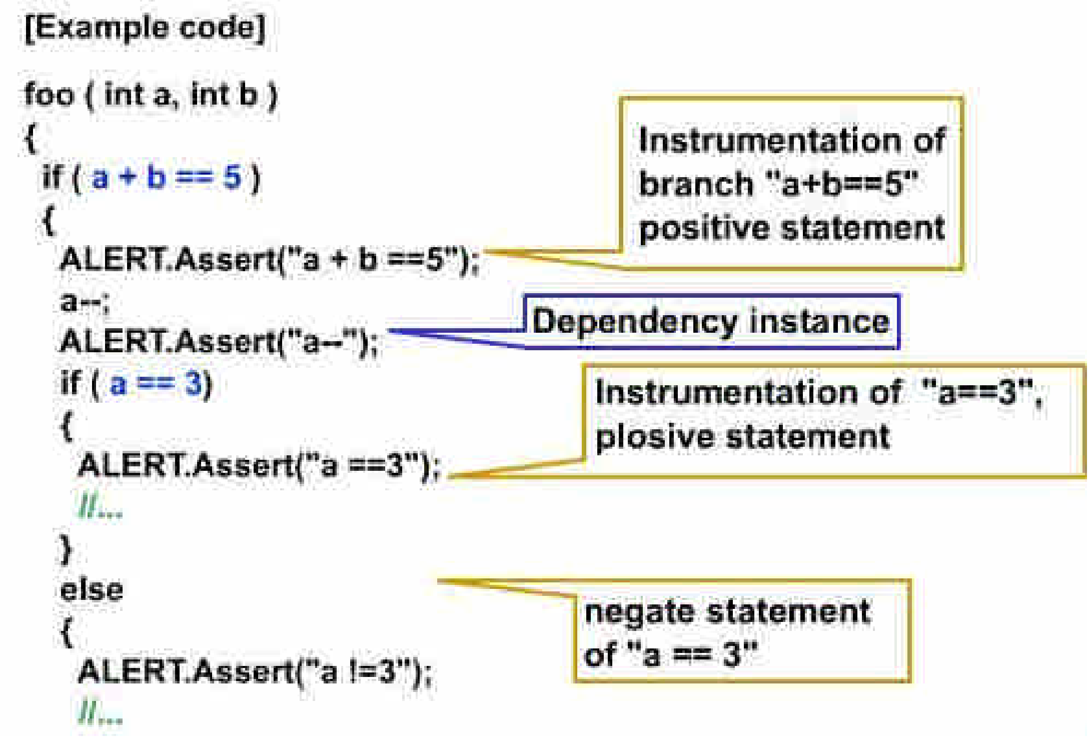
```
[Example code]

foo ( int a, int b )
{
  if ( a + b == 5 )
  {
    a--;
    if ( a == 3)
    {
      //...
    }
    else
    {
      //...
    }
  }
}
```

in dynamic running, branch two paths, either a + b = 5, or a + b != 5.
Dependency instance
assertion a = 3 and unify b = 2
another branch a != 3, as well as b != 2

Figure 5, ALERT constraints example

As figure 6 shows, ALERT traces every conditional and dependency expressions and output as constraint symbols. These constraint symbols are used to forward the modification of dependencies. During runtime interaction, the execution instance outputs a unique set of constraints according to the conditional and dependency expression it reaches. We analyze these constraints to trace back to the initial state of the execution parameters of programs.



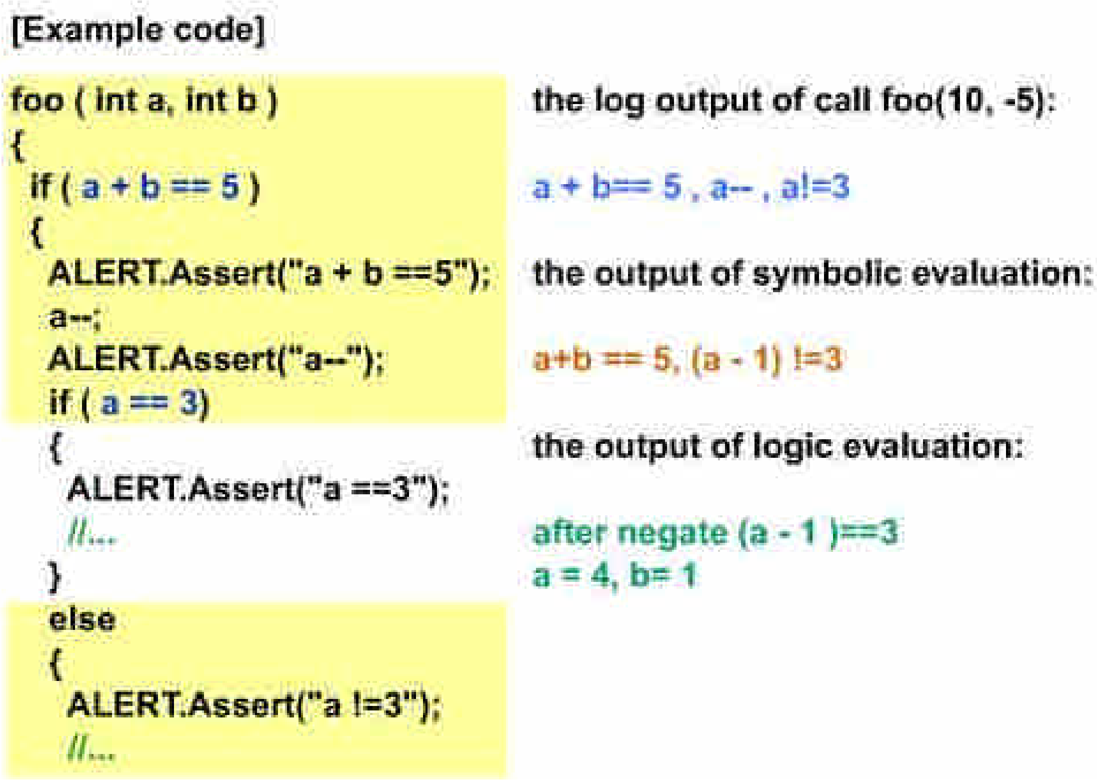
```
[Example code]

foo ( int a, int b )
{
 if ( a + b == 5 )
 {
  ALERT.Assert("a + b ==5");
  a--;
  ALERT.Assert("a--");
  if ( a == 3)
  {
   ALERT.Assert("a ==3");
   //...
  }
  else
  {
   ALERT.Assert("a !=3");
   //...
```

Instrumentation of branch "a+b==5" positive statement
Dependency instance
Instrumentation of "a==3", plosive statement
negate statement of "a == 3"

Figure 6, ALERT constraints example

In the symbolic aspect, we quest for the concrete values of symbols, and in the logic aspect, we just reason a set of solutions to satisfy logic constraints rules. We can easily produce input cases that lead program execution to take different paths by modifying some of those constraints. Theoretically, we can’t claim different constraints lead execution to different paths, but it is true that different paths have different constraints. As figure 7, we produce another input case by negating the last constraint. ALERT maintains a knowledge base to avoid duplicated constraints.



[Example code]

```
foo ( int a, int b )
{
 if ( a + b == 5 )
 {
  ALERT.Assert("a + b ==5");
  a--;
  ALERT.Assert("a--");
  if ( a == 3)
  {
   ALERT.Assert("a ==3");
   //...
  }
  else
  {
   ALERT.Assert("a !=3");
   //...
```

the log output of call foo(10, -5):

a + b== 5 , a-- , a!=3

the output of symbolic evaluation:

a+b == 5, (a - 1) !=3

the output of logic evaluation:

after negate (a - 1)==3
a = 4, b= 1

Figure 7, ALERT traces simulation

The following figures 8, 9, 10, 11 illustrate how ALERT records program execution and handles program outputs. In brief, ALERT has three work stations: instrumenter, symbolic evaluator, and logic resolver. Each station produce input for next the station. Logic resolver generates input cases for next running iteration. The first input case is randomly generated or all zero. Until ALERT can’t resolve inputs to satisfy the constraints after modification anymore, the testing process is terminated.

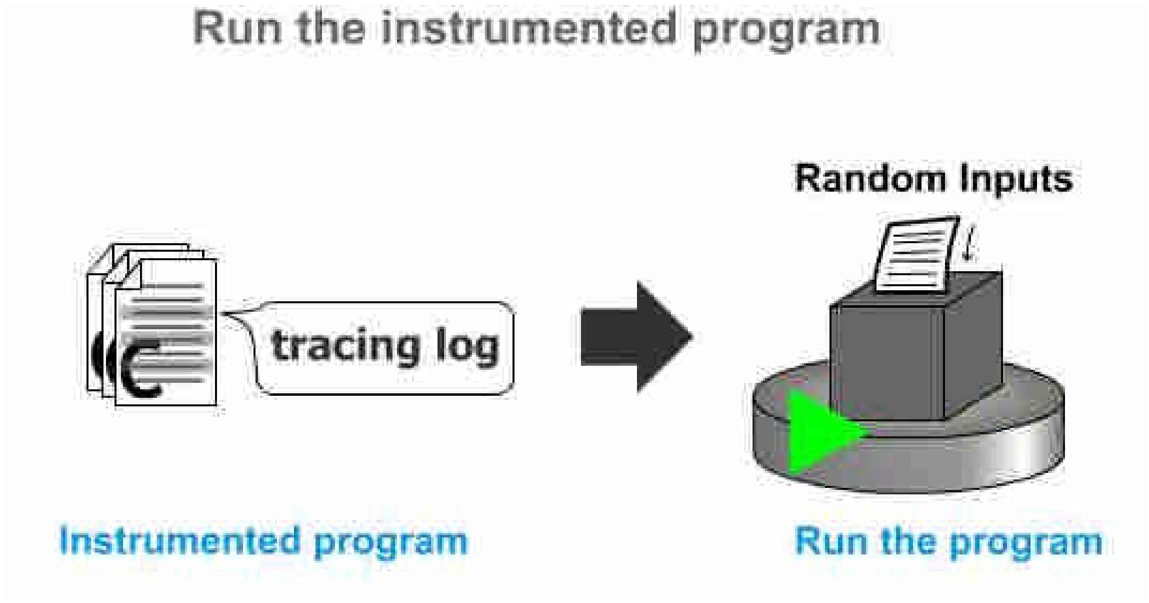
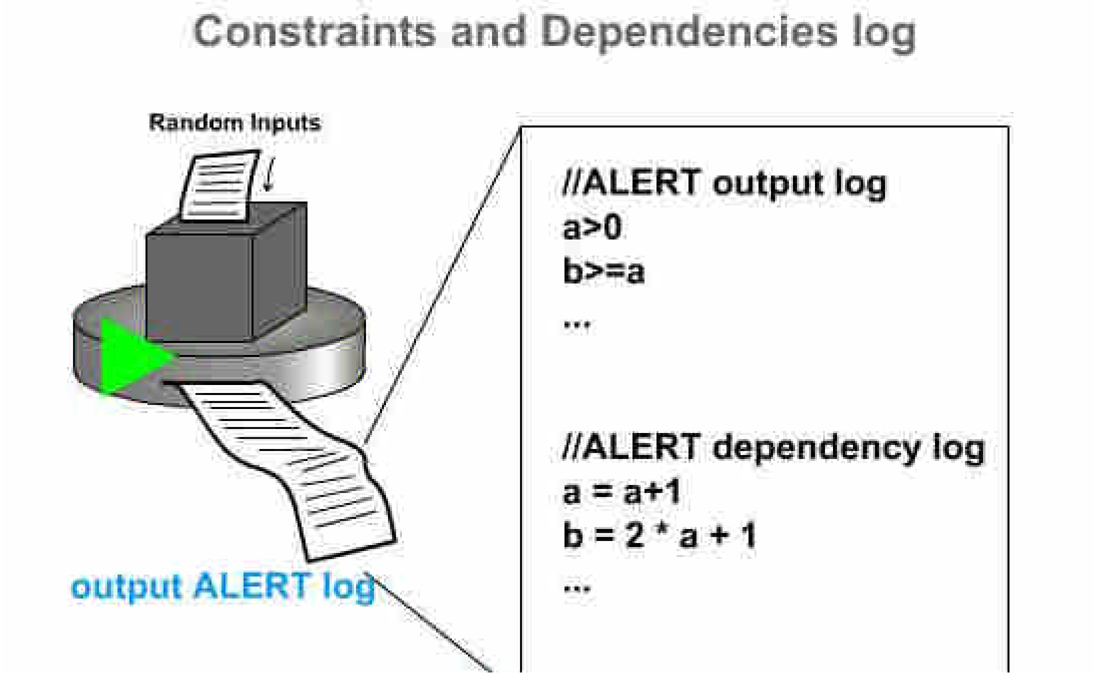


Figure 8, Execute and record logs



```
//ALERT output log
a>0
b>=a
...


//ALERT dependency log
a = a+1
b = 2 * a + 1
...
```

Figure 9, Constraint log and dependency log

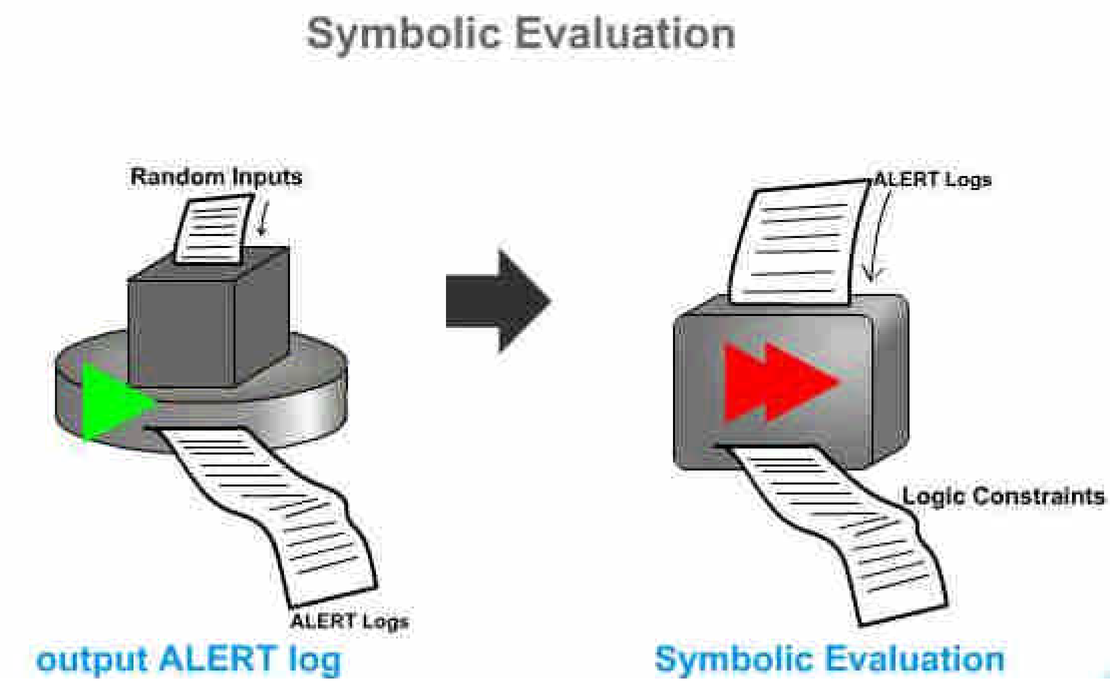


Figure 10, Symbolic evaluate

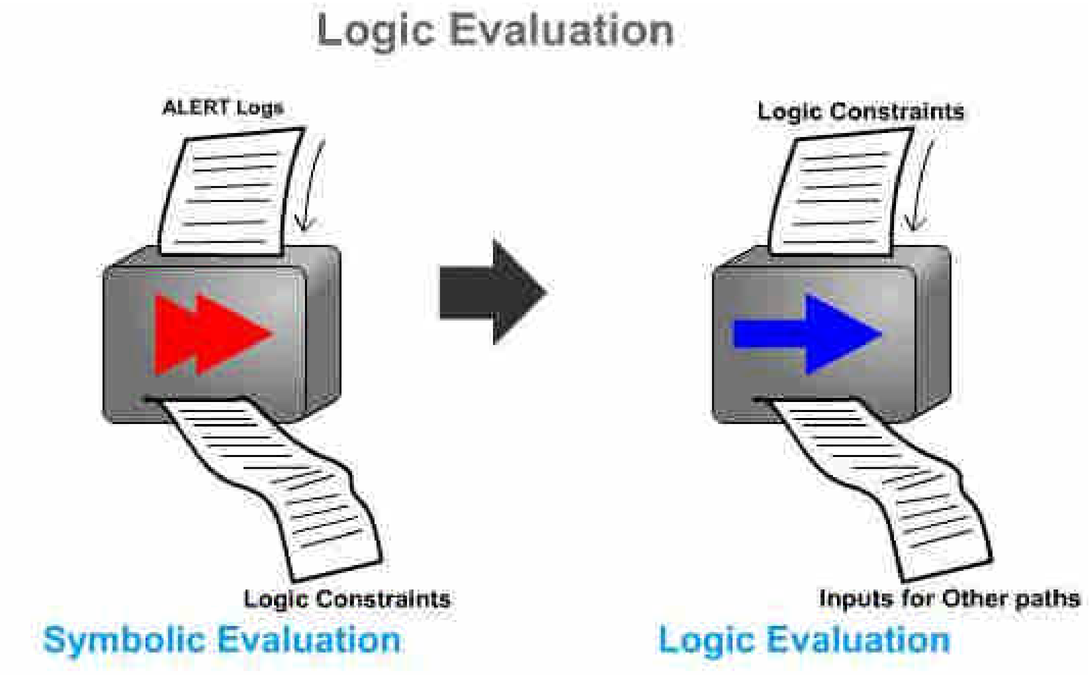


Figure 11, Logic evaluate

The ALERT analysis structure is different from DART and CUTE. We perform a transformation from symbol domain to logic domain which enables us to solve bounded-value constraints. The idea of automatic generation of testing cases and interface is alike DART, which performs symbolic evaluation and concrete evaluation on every program expression, dynamic replacement of variables with symbols, maintenances of branch constraints for full path coverage.

The essential structure of DART is as followed: in the program compilation level, every memory fetch and restore instruction are enclosed by checking functions to ensure every operation over variables is monitored along program progress. At this moment, a testing interface is generated and all possible branch paths are illustrated. DART performs an infinite loop to execute the program until the program abort abnormally or assertion failed. There is a threshold for counting program iterations. One program iteration stands for one program run. DART reports no bug found if a given threshold is broke. The main testing loop begins with randomly generated inputs. In the execution level, each concrete evaluation is coupled with a symbolic evaluation. DART bases on the results of symbolic evaluation to resolve inputs leading another execution path.

ALERT performs instrumentation in the source code level, and enables the program to recode the conditional constraints and variable transactions. Conditional constraints are generated while program evaluates a conditional expression. The purpose of evaluating a conditional expression is to branch or join program control flows. Therefore, ALERT inserts instrumentation code that contains the branched conditions into every spread branch, instead of evaluating the conditional expression to calculate the constraint records. ALERT keeps the runtime constraints of program iterations to avoid the same input data generation.

```
//F is the function to be tested.
Alert(F) :
//S is the set of Symbols.
//I is the input set.
//V is the set of Variables
S <= find-symbols(F).
I <= random();
V <= empty.
do
    //R is the rules generated while execution.
    // Logic-execution throw Exceptions.
    R <= Logic-execution(F,I).
    For-each Rule in R do
        R <= R - Rule.
        If Rule = Assignment-Rule
            Symbolic-evaluation(R,S).
            Trigger-Rules(R,Rule).
        If Rule is Constraints
            If Contradiction(Rule, R-Rule)
                throw Exceptions.
            P <= find-association(Rule).
            Q <= Associate-Rules(Rule, P).
            R <= R∪{Q}.
    Logic-evaluation(S, V).
    I <= map-inputs(V).
```

Figure 12, ALERT pseudo-code

Figure 12 is the algorithm of resolving inputs from symbols and constraints. Conceptually, ALERT does the same things as DART and CUTE. That is to automate testing process according to program execution, but we do trace the logic in the programs, not the actual values in the memory.

3.1. Instrumentation for Runtime Trace

We can't prove the existence of the transformation model from imperative language to rule-based language. But we can model a program execution with rule-based language, because in a program running instance, all variable dependencies have been decided. And also alias naming can be resolved through a running instance interpretation. We never try to transform an imperative language program to a rule-based program; instead, we try to model a dynamic behavior of an imperative language program. In an imperative program, variables are nodes spread entire program, static analysis try to find the links between the nodes during the program execution, but we never ensure the links between variables would really happen. There is a missing portal for a specified link. As a result, we can easily recognize that only tracing in run-time, can we get the exactly linkage between variables, and guarantee feasibility 'cause it is actually running.

3.2. Generation of Runtime Constraints

The information provided by a running program is totally different from the program source code. In running program, all values are ‘active’, which affect each other in a consequence. And such consequences provide us a clear obvious view of how programs run. If we want to understand the control behavior of programs, an intuitive way is to locate every control branches and print the concrete values during execution. It could take overhead to build a concrete memory map from concrete values, because the relationship between values and values is still unknown.

We propose another tracing mechanism that prints the whole branch constraints instead of concrete values. Additionally, we modify the constraints to fit where the program controls reach, that is, we insert the constraints exactly at the end of branch operation, no the beginning. It makes a great reduce on the inspection overhead.

3.3. Symbolic Evaluation Framework

We use symbols to represent variables. If the value of some variable A transfers to another variable B, we can modify the symbolic representation of variable B to A, and A is still A. If after modification B, another operation modifies A to ‘A + 1’; then the representations of both B and A become ‘A + 1’. Initially, we have symbols which represent some variables, constraints that restrict the symbols to some fixed domain, and transaction that refer to a sequence of operations.

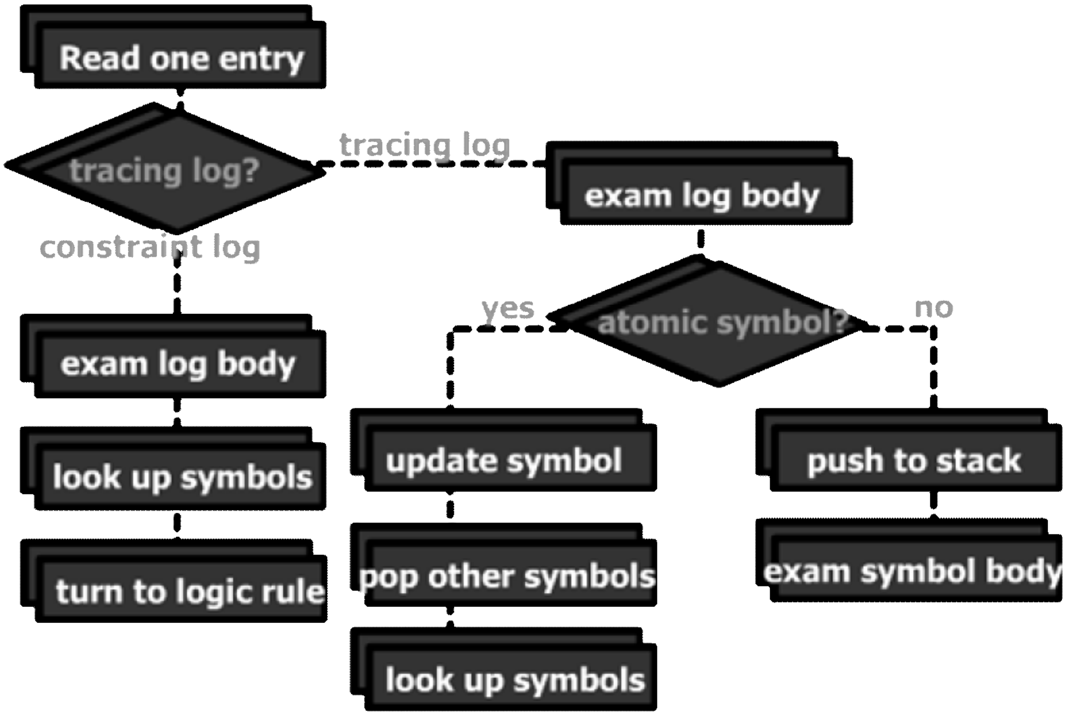


Figure 13, Flow chart of symbolic evaluation

We transfer an execution states into rule-based description. By substitutions between variables and symbols, we found that we can illustrate the whole running path that is composed by every single step of program executions by the accumulation of those steps. For every execution step can be represented by symbolic compositions, we can evaluate the symbols to reduce to the minimal constraints. Figure 13 shows how to replace symbols with representations.

Briefly speaking, the basic concept of ALERT symbolic evaluation is mapping of symbols. Initially, ALERT enforces every variable to map to itself. Every variable is unique before the execution. After any modification expression, ALERT traces the original symbol of the modified variable and combines old symbol with new obtained one. ALERT maintains symbol maps and composite symbol maps used to one-by-one mapping and many-by-one mapping, respectively. Once a symbol is modified to another symbol expression, ALERT evaluates each symbol in the expression and looks up symbol maps for dynamic values. For relative access, like pointer, ALERT uses composite symbols as a key to look up many-by-one maps. In special cases, when some symbol operations require multiple relative accesses, ALERT creates a dummy symbol during the evaluation of relative accesses. For example, ALERT creates dummy symbols for ‘p’, ‘*p’ and ‘**p’ when dealing with ‘***p’ or creates ‘a’, ‘a []’, and ‘a [] []’ when dealing with ‘a[i] [j]’.

Symbolic evaluation terminates if the program reaches a halt state. The main purpose of symbolic evaluation is to aggregate a multi-step program run to a single step. It makes ALERT figure out the execution path in a logic way and obtain other execution paths by inference on logic rules. After all symbols are resolved to their initial references, ALERT sends them as inputs to next stage, logic evaluation.

3.4. Automatic Logic Evaluation

It may be impossible to model programs made by imperative language with logic rules, but it seems to be possible to describe runtime behaviors in logic rules. Because the execution of programs is unpredictable, we can’t reproduce the transaction of volatile program states. But it is possible to reverse the behavior of an executed program. We try to solve the following problem with logic: given rules describing a set of symbols or facts, and rules contain constraints to restrict the binding of variables and symbols, we expect to unify variables to satisfy constraint rules as feasible inputs to specified program conditions.

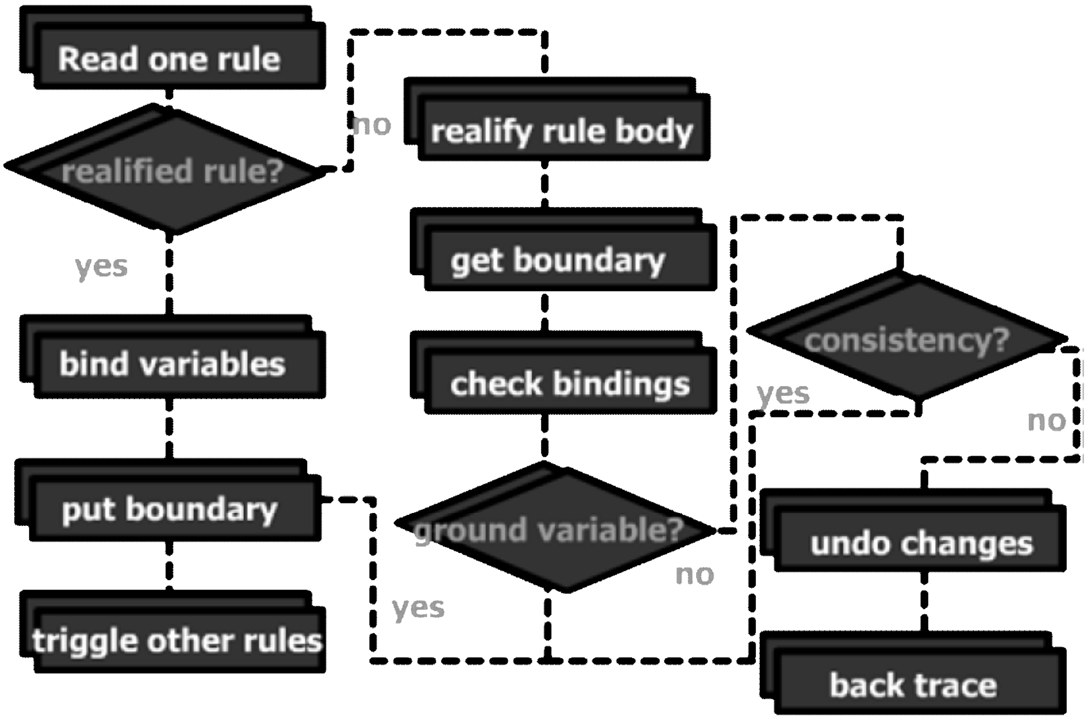


Figure 14, Flow chart of logic resolution

Previous section points out that the transformation from imperative language programs to rule-based programs is possible if the volatile state is revertible. For this reason, we deploy symbolic evaluation before logic evaluation. Symbolic evaluation performs dependency forwarding on symbolic modification, which enables us to trace back the volatile state of imperative language programs.

The main purpose of logic evaluation is to find a feasible input data according to given symbolic constraints. Like figure 14, the evaluation process begins with empty logic variables as input data, initially with bounded range constraints to specify valid domain. For each symbolic constraint, we refine both right-hand-side and left-hand-side to minimal unit, eliminate duplicated constraints, and annotate possible boundary to every logic variables. A series of associated constraints is linked with variables. The associated constraints of that variable are triggered, when the boundary of some variable narrows down. It causes other variables to get more precise boundaries. However, if the unification results are in conflict with the constraints of some variables, the inference process restores the changed bindings and traces back to the nearest alternatives to choose another branch.

4. Implementation

This sector describes the design and architecture of ALERT. ALERT is composed of three blocks: instrumenter, symbolic evaluator, and logic resolver. As Figure 15 shows, they exchange messages through a top module, which is the UI and entry point of ALERT. ALERT takes program source as input and executes the instrumented instance until error occurs or ALERT is unable to generate inputs for a different path.

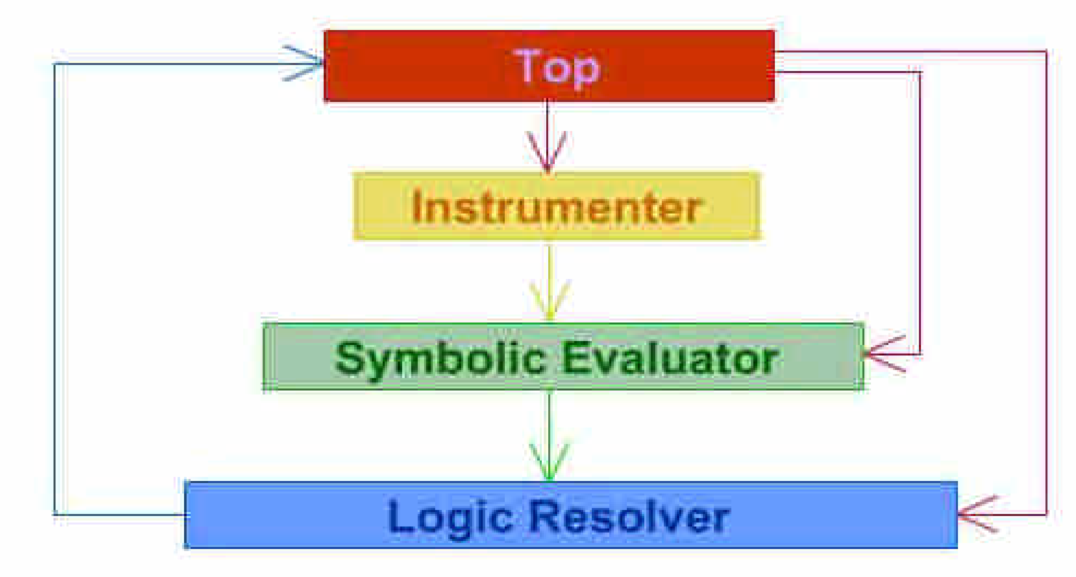


Figure 15, ALERT components

4.1. Instrumenter

The first contact with source code is the instrumenter. It takes program source as inputs and generates testing interface and testing driver for runtime trace. The followings are design feature of instrumenter.

4.1.1. Branch Oriented

The cut point is the program branch. Statically, program branches consist of two parts; one is a conditional statement for checking, and another is some alternative paths to take. It seems that we have two options: put our code before first part or put them after second part.

Both ways influence the same thing in source code. In the option one, the operation of instrumentation includes not only the controlling log but also the evaluation of the condition statement. It is called ‘cut point’. But in the option two, the operation is reduced to only controlling log of the branch choices. It is a tradeoff between time and space. For performance consideration, we insert many log operations in each branch choice instead of one log and evaluation operation in the cut point.

4.1.2. Condition Sensitive

We break composite condition into independent ones. Because different combination of these conditions leads to different program states even they are in the same basic blocks. With the support of different program states, we can resolve the execution logic and generate different path.

4.1.3. Function driven

The smallest unit of program is a function. Based on this, we can analyze each path in the specified function. Each invocation of a function has its unique logic. Parameters of function have different logic meaning when they are passed. ALERT deals with function invocation in the simplest way. With short tags labeling the parameters and local variables we can distinguish variables under different scopes. And by aliasing all passed parameter and return value, we can preserve the consistency of current program state while function invocation.

4.2. Symbolic Evaluator

We discard the concrete values of program executions. We use the composted symbols to explain how the program transfers information by variables. The following are design feature of the symbolic evaluation.

4.2.1. Paired Symbols

ALERT requires two aspects of view of symbols to perform symbolic evaluation:

symbolic appearance and symbolic propagation. An appearance is what the symbol 'looks like' and propagation is how the symbol 'comes from'.

Define *an appearance A of some symbol x is that intuitively x is declared as A.*

Ex:

int a; //a symbol whose symbolic appearance is 'a'.

Define *a propagation P of some symbol x is that the current state of x is propagated from P. P can be composed by any symbol in any ways.*

Ex:

*pi = 3.14159, r =10, area=r*r*pi;*

box[0]=top(table), box[1]=top(box[1]), box[2]=near(box[0]);

Define *a symbol domain S = {A_s, P_s} where A_s is a set of all symbolic appearances, and P_s is a set of all symbolic propagations. The following definitions are under the assumption of S has been constructed.*

Define *a replacement of an appearance A over a propagation X, denoted as* R_a*(A, X), is that for every symbol C in A, if C equals X as propagation symbols, we substitute C with* A_s*[X].*

Ex:

a=3, b=4, c=foo(b, c);

foo(int x, int y){

    *return sqrt(x*x + y*y);*

}//in function foo, R_a *(*A_s *[foo.x,foo.y],[b,c]),* A_s *[foo.x]=*A_s *[a] and* A_s *[foo.y]=*A_s *[b]*

Define *a replacement of a propagation P over a appearance X, denoted as* R_p*(P, X), is that for every symbol C in P, if C equals X as appearance symbols , we substitute C with* P_s*[X].*

Ex:

*pi = 3.14159, r =10, area=r*r*pi;*

//after R_p *(*P_s *[area], r),*P_s *[area]=10*10**P_s *[pi]*

Define *a symbol replacement of an appearance symbol x over symbolic domain S, denotes as* R_a *(S, x), said S' =* R_a *(S, x) and S' = { {a | a in* P_s *and x in* P_s *} , {* R_a *(p,* P_s *[x] | p in* P_s *} }.*

Define *a symbol replacement of a propagation symbol x over symbolic domain S, denotes as* R_p *(S, x), said S' =* R_p *(S, x) and S' = { {a | a in* A_s *and x in* A_s *} , {* R_p *(p,* A_s *[x] | p in* P_s *} }.*

4.2.2. Dependency

The dependency relations between symbols are forwarding and rewriting. It is the fundamental concept of symbolic evaluation. The forwarding is a replacement of the symbol itself. The rewriting is a substitution of the symbol with another symbol.

Ex: x+=y; // after forwarding, P[x] is updated to P[x] + P[y]

fins=stdin; // rewriting the P[fins] as P[stdin]

4.3. Logic Resolver

These logic rules are implemented in SWI-prolog [16]. The followings are design feature of logic resolver.

4.3.1. Variable

Logic variable is an empty container. It could bind to any possible values. The logic variables describe an input of testing initially. And it will finally be assigned a feasible value that satisfies the current constraints. The variables can be mapped to original parameters of testing function. For some structures or array or pointer type, the variables can represent some part of composed-type parameters, for example, a month field of a date structure, the 8th element of an array of real numbers, or the 3rd offset of a pointer. ALERT generates the remaining part without logic variables mapping randomly or zero.

4.3.2. Freezing Expression

Freezing expression is a set of expressions that associates some variables. The expressions will limit value of the associated variable. For example, the freezing expression of a positive odd value is like “freeze(X, [X > 0, X % 2 = 1])”. When the variable is bound, logic engine evaluates its freezing expressions with the binding value. If the result is true, the whole process proceeds and triggers other variable binding, otherwise the engine would trace back to previous decision site and make alternative decision. The logic resolving routine terminates successfully if all variables are bound and their freezing expressions are satisfied.

4.3.3. Domain Range

Domains are used to set the boundary of variables. For variables to have storage type and specified storage bits, we can set up a signed integer X with 2 bytes length like “X indomain(-32768..32767)”. For more advanced application, we can enumerate customized types such as “Color indomain(red, blue, green)”, and it can be extended to display higher order of abstraction of symbolic evaluation.

4.4. Implementation Difficulties

The main problems we encountered during ALERT implementation are to generate testing interface and eliminate program state-transaction into stateless logic rules. The former problem appears in the instrument stage. There are usually various user-defined types associated with testing function. Because we have to generate different testing drivers for different user-defined type automatically, we maintain a stack for registration of structural data-types, a vector for pointers and a list for array type.

The later problem comes from symbolic evaluating stage. It is the key idea for logic evaluating. Because logic engine doesn’t care the order of rules, but program logic does, we make some modification on symbol variables to fix the transaction. We ensure that through symbolic evaluating ALERT can preserve the states and reversibility of program logic.

4.4.1. Generation of User-defined Type Interface

To generate testing interface for automatic execution, we have to create fixed functions that dedicates to input parameters of user specified types. In the beginning, we try to examine the length of specified type and flip the bits to initialize. It can reflect the resolved values, but without field information. The field information tells about the number of sub-elements and their types. It became a problem that we can’t catch the length of sub-elements during bits flipping. We build a type sub-system to get rid of it, according to [9]. We base on fundamental types and construct composed type with point, array, or structure. The inputs function for testing interface and driver can be rendered with recursive type inheritance.

4.4.2. State-sensitive Variable Renaming

In the beginning, we thought that the renaming of variables is simple. It is easy to imagine that as it comes to a state modification, we just store in data pool and change the value of the same symbol variables appear out after the modification. But it is a tough work to decide which the same symbol variable is. A symbol variable could have different names when it is transferred to another scope. The solution is to exchange the appearance of all symbols dynamically during identical symbol selection to prevent symbol variable confusing. It increases execution overhead of symbolic evaluating slightly, about 3%~5%.

5. Experimental Results

We evaluate our work with zlib [17], a well-known compressing library. We apply ALERT on zlib and perform coverage evaluation by conjunction of gcc and gcov [1]. Gcov is a coverage analysis tool that provides coverage statistics include how often each line of code executes, what lines of code are actually executed, and how much computing time each section of code uses.

5.1. Instrumentation and Generation Overhead

The space overhead of ALERT instrumentation is one line-of-code for a significant branch. We insert one line of log trace code into the beginning of a branch block. This results in that our space overhead is in proportion to the conditional statements in programs. The execution overhead of instrumentation is an additional record operation for each conditional evaluating, so one running instance may have extra operations in proportion to the condition statements along the paths.

The testing cases generation overhead is one logic variable for an effective function parameter, but if parameters contain sub-field, logic engine may require more than one logic variable to resolve symbols. We generate one logic script for the next running instance, so the total testing script generation of ALERT application is as many as the found possible paths.

5.2. Expand and Explore

ALERT is worthy to automate the testing process because the ability of alternative path discovery. The discovery algorithm records constraints of previous running instance in database and produces constraints that differ from those in database by negating some of the constraints. In the running instance, the program itself may reach new branch that was not visited before in previous instance. The trace log may contain new constraint entry for negation. ALERT expand the program branches and explore the newly expended node at the same time.

5.3. Similar Path Discovery

The ALERT path discovery algorithm firstly negates the last constraints, resulting in the path of next successful instance which is similar with current paths. The purpose is for generating similar inputs for testing quickly.

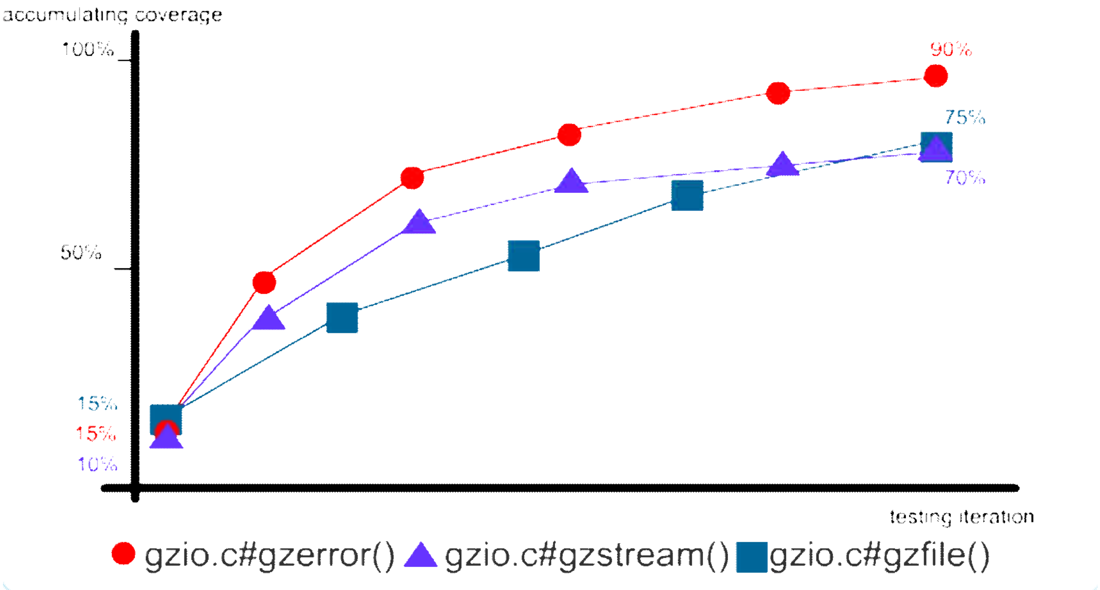


Figure 16, Coverage analysis

Figure 16 shows the accumulating coverage analysis of three zlib programs. The x axis displays the coverage percentage of running iterations accumulatively. The y axis displays the count of successful generated inputs against a program. Initially, the inputs for first running instance are zero, so the coverage percentage is about 10% ~ 15%. It could tell that empty input path contains 15% of LOC. At the end of testing, all program's coverage accumulated about 70% ~ 90%. It is because some conditional ALERT couldn't resolve. Some of them may be pointer arithmetic or array element cross reference. We can deal with pointer arithmetic in symbolic evaluation, by constructing a nameless symbol to represent calculated pointer. But the logic engine can't take any variable without a name to reference, so does array reference. It also a limitation of ALERT, that it can't work in functions take all parameter as pointer or array. This would leave the room for our future improvement initiative.

6. Conclusion

Testing is a time consuming process and hard to automate. Its main purpose is to make sure every functionality works. The simplest suggestion is to “show it wrong or right”. If we do the testing manually, we could lose in the labyrinthine program execution states. To automate the testing processes, it is essentially important to direct the testing program. We divide ALERT into three stages: instrumenter, symbolic evaluator, and logic resolver. Each stage will generate inputs for next stage. A control top module exchanges messages between every stage. It is a better architecture for testing duty.

Program states consist of thousands of variables and their combinations are unpredictable. We know it is impossible to enumerate program states through the values of variables. So we try an alternative way to enumerate program logic. It is much feasible that a program behavioral representation can be considered as the combination of its logic constraints. There are many related work that take advantage of program logic. ALERT is the first application for dynamic analysis.

We discover that program logic is reversible under some circumstances. The reversible states enable ALERT to solve constraints and produce feasible inputs that lead program to perform a different execution path. By recording constraints of each running instance, we can enforce the program to perform all of its possible paths.

6.1. Self Evaluation

In this project, we have implemented a random testing system, called ALERT. It can automatically generate input data to analyze the program behavior and investigate the potential software vulnerabilities. This tool has been applied for a vulnerability finding system and the results reveal several new integer overflow vulnerabilities. It will be published in ICS 2006.

6.2. Future Work

ALERT is just a beginning. For the different testing strategy, such as integration testing, we can enhance ALERT in the component interaction aspect, which enable ALERT to resolve more complicated program logic. In addition to simulating the manual input operation, ALERT could be extended to generate specified environments for exhibitions of security issues by modification of the messages transmitting between the logic resolver and symbolic evaluator layers.

6.2.1. Feasible Input Generation

We desire a tool that tells when and how a defect or fault could occur, especially when we don’t have enough information to prove the existence of the feature. ALERT is just a beginning of that. It automatically resolves specified program logic (or called constraint rules) and produces feasible inputs to render program in the way we want. Not only single function, but integration constrains can be evaluated as a collection of symbols. We look forward to a way of understanding the program semantics automatically. This method would become a new trend in the field of automatic testing to deal with every logic feature in program.

6.2.2. Delta Debugging

In the former software debugging process, we are familiar with getting in the reference between source codes and runtime interaction. To find out what is going wrong behind programs, it would be convenient for programmers to automate the process that traces programs without manual assistance. Delta debugging[2] is a latest debugging method that supports automatic software fault localization. Generally, to report buggy sites, Delta debugging requires the comparison of a failure program run with a successful one. Moreover, the failing program execution characteristics do not actually differ much from the successful program execution. Delta debugging eliminates the common characteristics through comparison of value transaction and cause chain of two runs. Nevertheless, in real cases, we only have program failing runs. That is a tough work to determine the similarity of failing run and successful runs with which we can apply Delta debugging method.

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