Software Architecture and Engineering

Automatic Test Case Generation

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Chair of Programming Methodology

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9. Automatic Test Case Generation

Test Case Generation

```
int foo( boolean a, boolean b ) {
  int x = 1;
  int y = 1;
  if( a )
    x = 0;
  else
    y = 0;
  if( b )
    return 5 / x;
  else
    return 5 / y;
}
```

```
[ Test ]
public void TestFoo(
       boolean a,
       boolean b )
{
  int res = foo( a, b );
  Assert.IsTrue( res == 5 );
}
```

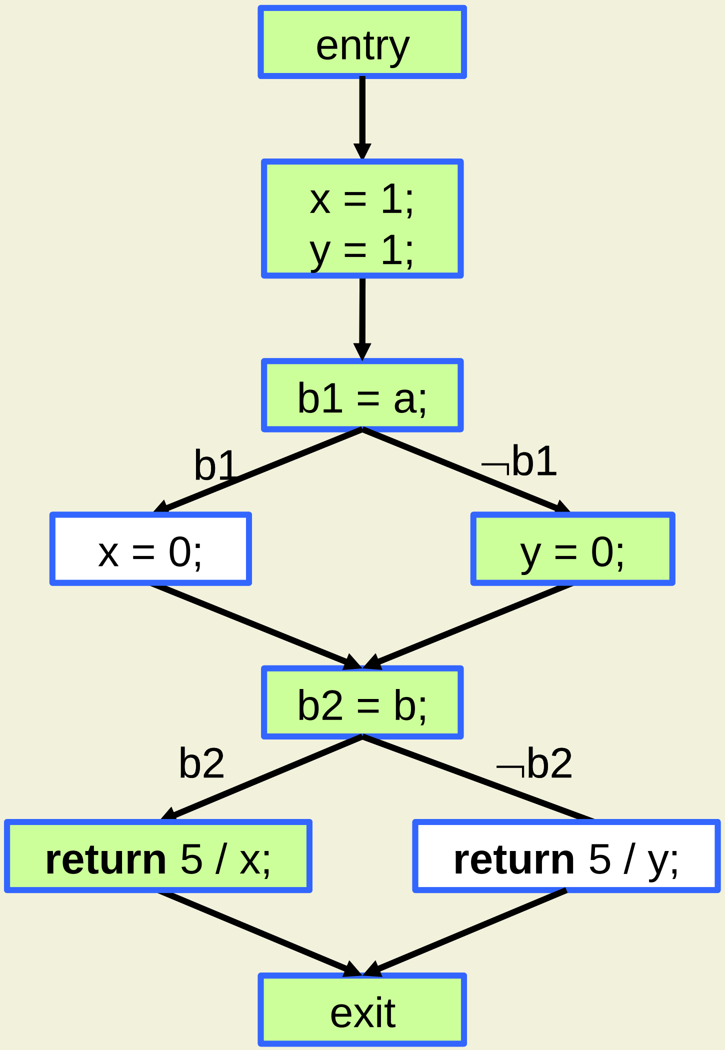
Challenge:
how to determine
test data?

Test driver is
straightforward

Specify test oracle via
parameterized unit test
or assertion

Determining Test Data

- **Choose path** to be tested
  - Based on coverage goals
- **Derive constraints** on inputs from conditions and statements on chosen path
- **Solve constraints** to obtain test inputs



9. Automatic Test Case Generation

9.1 Symbolic Execution

9.2 Concolic Testing

Symbolic Execution

- Symbolic execution **simulates the execution** of a program statically, using **symbolic** rather than concrete **values**
  - Introduce symbolic variables to represent inputs

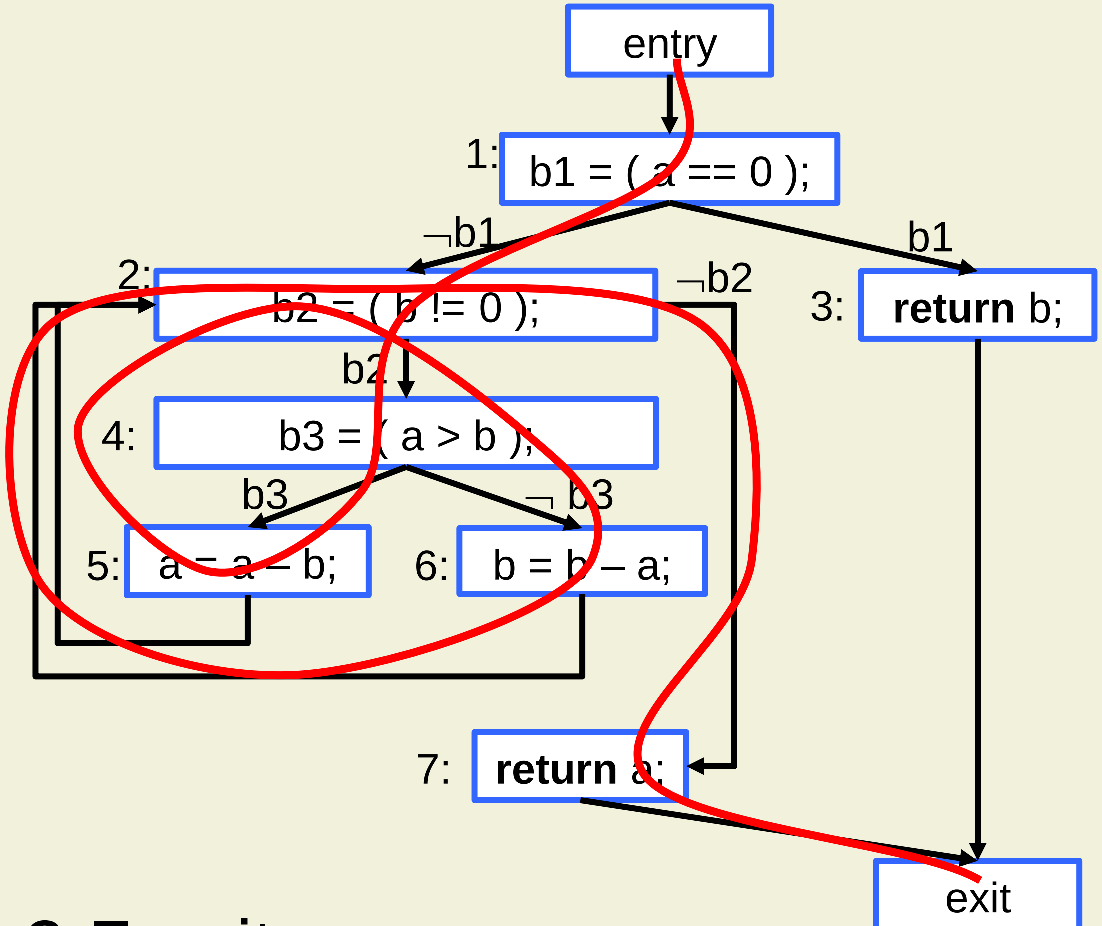
- Symbolic state consists of
  - A prefix of a **path** in the CFG
  - A **symbolic state**, which maps each variable of the program to an **expression over the symbolic variables**
  - A **path condition** (a constraint over the symbolic variables), which holds if and only if the execution takes the current path

Symbolic Execution Algorithm

- Symbolic execution can be described by an operational semantics that operates on symbolic states
- Key operations
  - Expressions: Evaluation yields **an expression**
  - Branches: Add label of target basic block to path prefix and conjoin branching-condition to path condition
  - Assignments: Update the symbolic state
- We look at heap data structures later

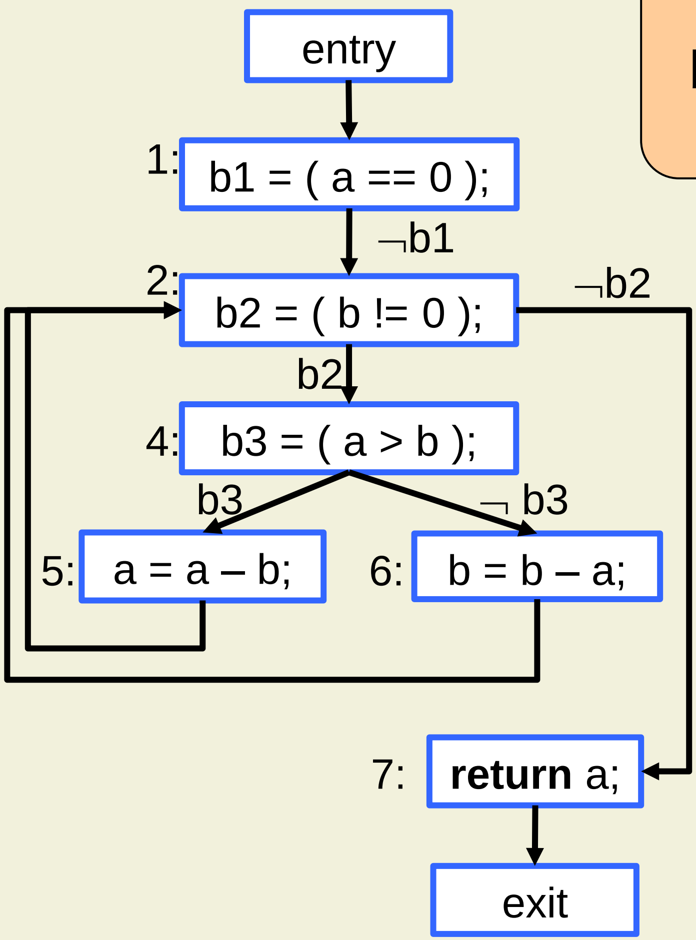
Example

```
int gcd( int a, int b ) {
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```



- Test the path entry-1-2-4-5-2-4-6-2-7-exit

Example: Constraint Generation



Next basic block to be executed

State changes

Additional conditions (conjuncts)

Path	State	Path Condition
1	a→A, b→B	true
2	b1→(A = 0)	A ≠ 0
4	b2→(B ≠ 0)	B ≠ 0
5	b3→(A > B)	A > B
2	a→(A – B)	true
4	b2→(B ≠ 0)	B ≠ 0
6	b3→(A – B > B)	¬(A – B > B)
2	b→(B – (A – B))	true
7	b2→(B – (A – B) ≠ 0)	¬(B – (A – B) ≠ 0)

Example: Constraint Solution

Path Condition
true
$A \neq 0$
$B \neq 0$
$A > B$
true
$B \neq 0$
$\neg(A - B > B)$
true
$\neg(B - (A - B) \neq 0)$

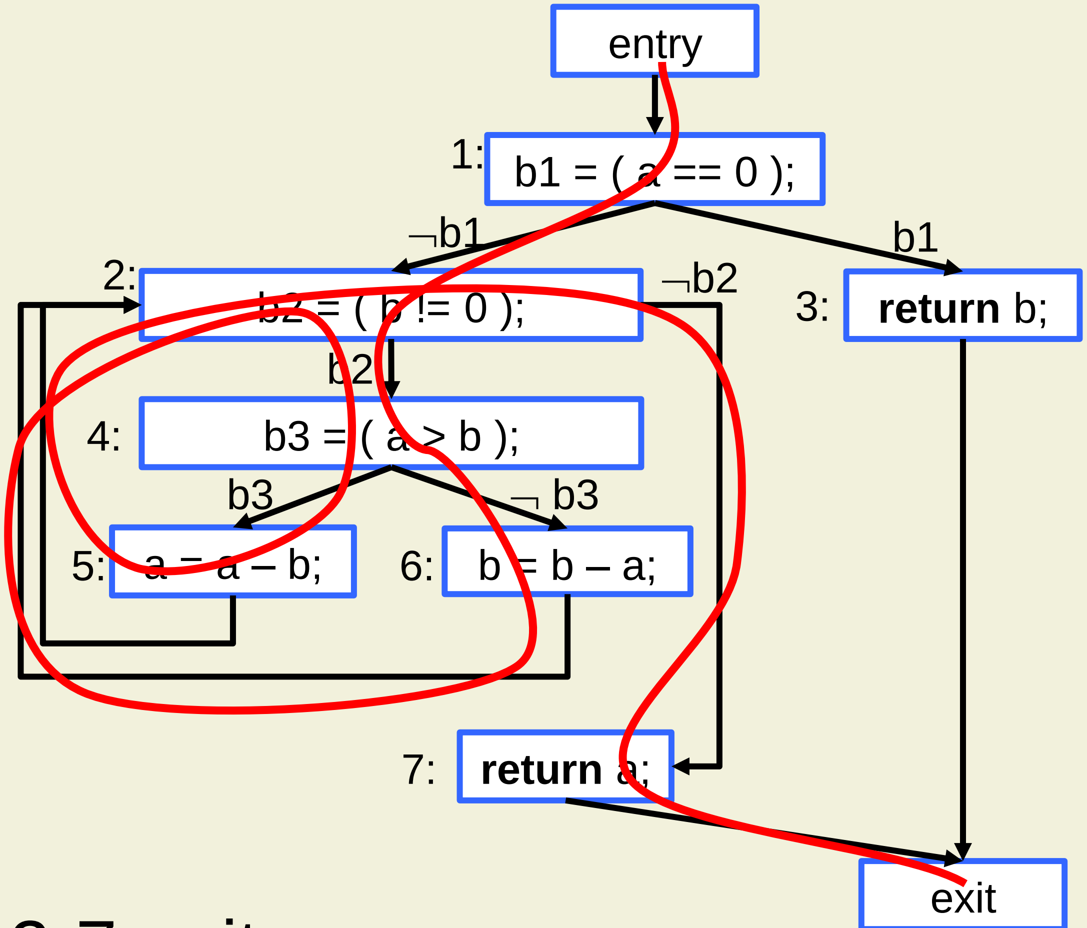
- Simplifying the path condition yields:
  $A \neq 0 \land B \neq 0 \land A > B \land A = 2 \times B$

- Possible solutions are for instance
  - $A = 2, B = 1$
  - $A = 4, B = 2$
- All solutions test the chosen path

```
int gcd( int a, int b ) {
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

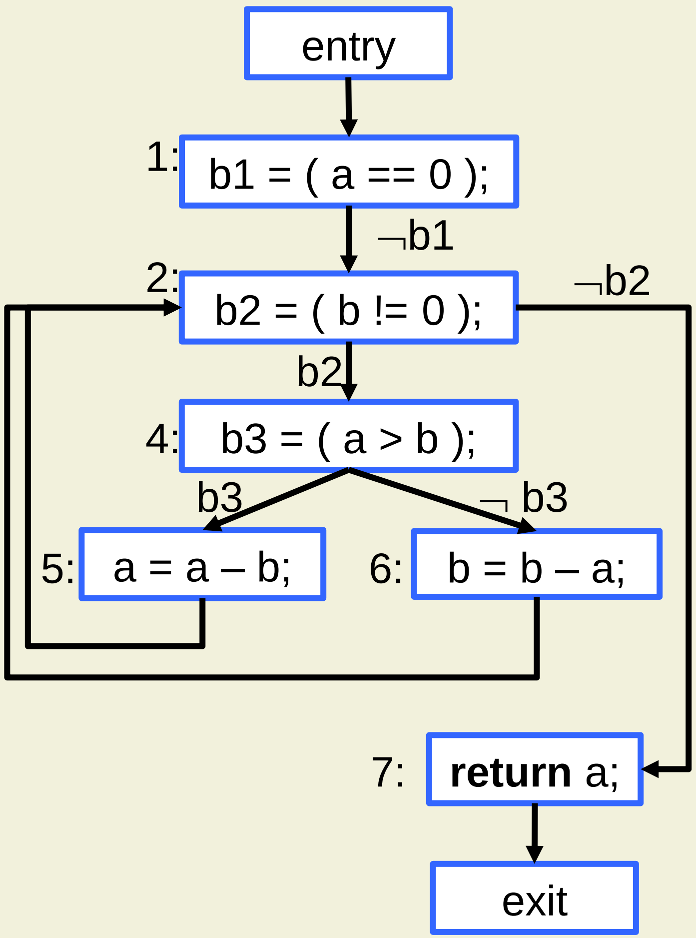
Example: Another Path

```
int gcd( int a, int b ) {
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```



- Test the path
  entry-1-2-4-6-2-4-5-2-7-exit

Example: Constraint Generation



Path	State	Path Condition
1	a→A, b→B	true
2	b1→(A = 0)	A ≠ 0
4	b2→(B ≠ 0)	B ≠ 0
6	b3→(A > B)	¬(A > B)
2	b→(B – A)	true
4	b2→(B – A ≠ 0)	B – A ≠ 0
5	b3→(A > B – A)	A > B – A
2	a→(A – (B – A))	true
7	b2→((B – A) ≠ 0)	¬((B – A) ≠ 0)

Example: Constraint Solution

Path Condition
true
$A \neq 0$
$B \neq 0$
$\neg(A > B)$
true
$B - A \neq 0$
$A > B - A$
true
$\neg((B - A) \neq 0)$

- The path condition is unsatisfiable: $B - A \neq 0 \wedge \neg((B - A) \neq 0)$
- The chosen path is not feasible
  - There is no input that will execute this path
- Infeasible paths do not necessarily indicate dead code

```
int gcd( int a, int b ) {
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

Constraints

- Constraints can be classified according to the **domain of the variables** and the **relations between the variables**
- Common domains
  - Booleans, bounded integers, integers, rationals, set, sequences, functions, etc.
- Common relations
  - Linear constraints, polynomial constraints, etc.
- Generated constraints depend on the programming language and the UUT

Constraint Solving

- For many of the interesting constraints, constraint solving is **NP-complete**
  - E.g., linear constraints over bounded integers
- For some classes, constraint solving is **undecidable**
  - E.g., Non-linear constraints over rationals
- Nevertheless, useful tools with **powerful heuristics** exist
  - E.g., SMT (Satisfiability Modulo Theories) solvers

Applications of Symbolic Execution

- Enumerate all paths to achieve a **given coverage**
  - E.g., branch and loop coverage
  - Generate inputs for each path

- Enumerate paths until a **timeout** is reached
  - Limits in particular the number of loop iterations

- **Active bug searching**
  - Attempt to create inputs that trigger an error

Bug Searching: Example

```
boolean isPalindrome( int[ ] a ) {
  int j;
  if( a == null ) throw new NullPointerException( );
  j = a.length – 1;
  for( int i = 0; i < j; i++ ) {
    if( a == null ) throw new NullPointerException( );
    if( i < 0 || a.length <= i ) throw new IndexOutOfBoundsException( );
    if( j < 0 || a.length <= j ) throw new IndexOutOfBoundsException( );
    if( a[ i ] != a[ j ] )
      return false;
    j--;
  }
  return true;
}
```

Attempt to generate inputs that execute exceptional paths

If the exceptional path is not feasible then the error cannot occur

Bug Searching and Oracles

```
int abs( int x ) {
  if( x < 0 )     return –x;
  else            return x;
}
```

```
[ Test ]
public void TestAbs( int x ) {
  int res = abs( x );
  Assert.IsTrue( 0 <= res );
}
```

- CFG contains two paths with path conditions x < 0 and 0 <= x
- Covering both paths does not necessarily detect the bug

Bug Searching and Oracles (cont’d)

```
[ Test ]
public void TestAbs( int x ) {
  int res = abs( x );
  Assert.IsTrue( 0 <= res );
}
```

```
int abs( int x )
  ensures 0 <= res;
{
  if( x < 0 )     return –x;
  else            return x;
}
```

```
int abs( int x ) {
  if ( x < 0 )
    if ( 0 <= –x )
      return –x;
    else
      throw new ContractException( … );
  else
    if ( 0 <= x )
      return x;
    else
      throw new ContractException( … );
}
```

Bug Searching and Oracles (cont'd)

```
int abs( int x ) {
  if ( x < 0 )
    if ( 0 <= –x )
      return –x;
    else
      throw new ContractException( … );
  else
    if ( 0 <= x )
      return x;
    else
      throw new ContractException( … );
}
```

- Instrumented method contains four paths
- Constraints
  - $x < 0 \wedge 0 <= -x$: correct
  - $x < 0 \wedge \neg 0 <= -x$: error
  - $\neg x < 0 \wedge 0 <= x$: correct
  - $\neg x < 0 \wedge \neg 0 <= x$: infeasible
- Instrumentation causes symbolic execution to actively attempt to violate the test oracle

Undesired Test Cases

```
class SavingsAccount {
  int balance;
  // invariant: 0 <= balance
  void deposit( int a )
  {
    balance = balance + a;
    assert 0 <= balance;
  }
}
```

Check invariant as part of the oracle

```
class SavingsAccount {
  int balance;
  // invariant: 0 <= balance
  void deposit( int a )
  {
    balance = balance + a;
    if( ! ( 0 <= balance ) )
      throw new Exception( );
  }
}
```

- Symbolic execution will find test cases that violate the assertion

balance	a
0	-5
-5	0
Integer.MAX_VALUE	1

Assume Statements

- Assume statements introduce constraints that are trusted by the symbolic execution
- Useful for
  - Preconditions
  - Invariants
  - Properties of called methods
  - Information about the environment

```
class SavingsAccount {
  int balance;
  // invariant: 0 <= balance
  void deposit( int a )
  {
    assume 0 <= balance;
    assume 0 <= a;
    balance = balance + a;
    assume 0 <= balance;
    if( ! ( 0 <= balance ) )
      throw new Exceptio
  }
}
```

Invariant

Precondition

No overflow

Assert vs. Assume

Assert

- Checked at run time
- Checked by symbolic execution (bug search)
- Confirm that condition holds

```
int div( int p ) {
  int x = p – 1;
  assert x != 0;
  return 5 / x;
}
```

Assume

- Checked at run time
- Trusted by symbolic execution
- Express properties that are justified elsewhere

```
int div( int p ) {
  int x = p – 1;
  assume x != 0;
  return 5 / x;
}
```

Symbolic Execution with Assumptions

- We encode path conditions as sequences of elements of the form
  - brn(P) for a **branching condition** P (if, while, etc.)
  - asm(P) for an **assumption** P
  - During symbolic execution, branching statements and assume statements **append an element** to the sequence
- The path condition encoded by a sequence s is

$$\bigwedge_{(\, brn(\, P\,) \in s \,\wedge\, asm(\, P\,) \in s\,)} P$$

  - brn(P) and asm(P) are treated identically in the path condition, but we will use them differently later

SE with Assumptions: Example

```
int div( int p ) {
  int x = p – 1;
  if( x == 0 )
    throw new Exception( );
  return 5 / x;
}
```

- Symbolic execution produces [brn(P–1=0)]
  - Path condition is $P-1=0$
  - Test fails for p=1

```
int div( int p ) {
  int x = p – 1;
  assume x != 0;
  if( x == 0 )
    throw new Exception( );
  return 5 / x;
}
```

- Symbolic execution produces [asm(P–1≠0), brn(P–1=0)]
  - Path condition is $P-1 \neq 0 \wedge P-1=0$
  - Path is infeasible

Heaps Data Structures

- Conditions and oracles may depend on heap values
- Symbolic states must track values of heap locations
- Path conditions may include constraints over heap locations

```
class Account {
  int balance;
  void transfer( Account to, int a )
    requires to != null;
    ensures this.balance ==
              old( this.balance ) – a;
  {
    this.balance = this.balance – a;
    to.balance = to.balance + a;
  }
}
```

Symbolic Heaps

- The heap memory can be modeled as an updatable map per field f
  - $Heap_f$: Reference $\rightarrow$ Value
- Heap operations
  - Field read:
    select: Heap $\times$ Reference $\rightarrow$ Value
  - Field update:
    store: Heap $\times$ Reference $\times$ Value $\rightarrow$ Heap
- Axioms
  - $\forall$H,r,v.select(store(H, r, v), r) = v
  - $\forall$H,r,r',v.r $\neq$ r' $\Rightarrow$ select(store(H, r, v), r') = select(H, r')

Symbolic Heaps: Example

Symolic state:
this→T0, to→T1, a→A, heap→H0

Symbolic heap: heap→H1
H1≡store(H0, T0, select(H0, T0) – A)

Symbolic heap: heap→H2
H2≡store(H1, T1, select(H1, T1) + A)

```
class Account {
  int balance;
  void transfer( Account to, int a)
    requires to != null;
    ensures this.balance ==
              old( this.balance ) – a;
  {
    this.balance = this.balance – a;
    to.balance = to.balance + a;
  }
}
```

- Path condition for postcondition includes select(H2, T0) = select(H0, T0) – A

Limitations: Method Calls

- Results of method calls may be
  - Assigned to variables: how to update symbolic state?
  - Used as conditions: how to record path condition?

```
Seq prefix( Seq s, int n ) {
  if ( s.length( ) < n )  return s;
  else                    …
}
```

```
void transfer( Account to, int a) {
  checkAvailability( a );
  this.balance = this.balance – a;
  to.balance = to.balance + a;
}
```

- Methods may have side effects
  - How to update the symbolic heap?

- Perform interprocedural symbolic execution
  - Issues: scalability, modularity

Limitations: Constraint Solving

```
void roots( double a, double b, double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    double r = Math.sqrt( q );
    x1 = (-b + r) / (2 * a);
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    x1 = -b / (2 * a);
  } else {
    numRoots = 0;
  }
}
```

- Nonlinear constraint $b^2 - 4ac > 0 \wedge a \neq 0$ over reals is difficult to solve
- Without a solution, no test data will be provided
  - Neither for the other branches

9. Automatic Test Case Generation

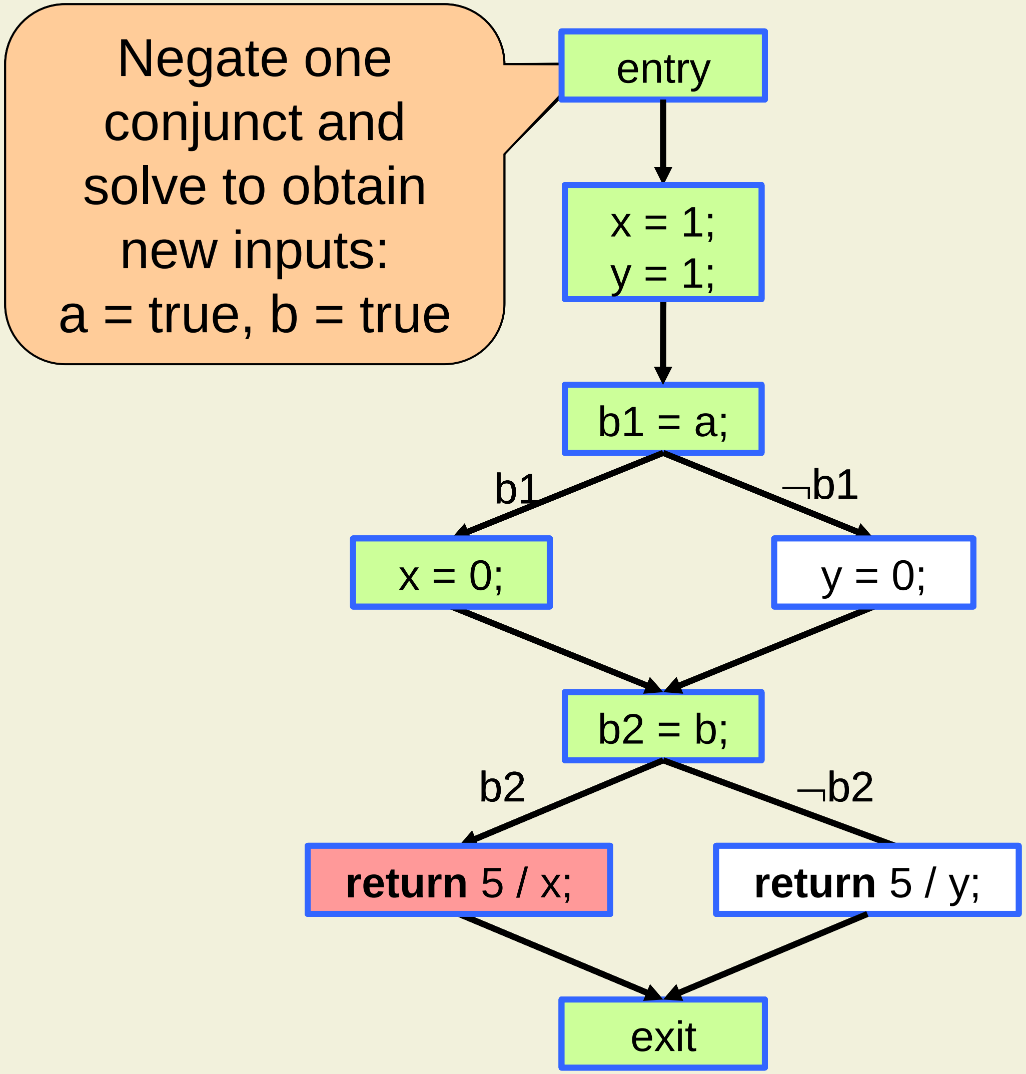
9.1 Symbolic Execution

9.2 Concolic Testing

Approach

- Combine concrete program executions with symbolic execution

- Use values from concrete executions when constraint solving fails



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(Simplified) Procedure

- Attempt to explore all paths whose path condition starts with a given prefix

```
procedure explore( Seq<Condition> prefix ) is
  values              := solve( prefix );
  if solution is available then
    path              := executeConcrete( values );
    pathCondition     := executeSymbolic( path );
    extension         := pathCondition[ |prefix| … ];
    foreach non-empty prefix p of extension do
      if p = p’ ○ [ brn(c) ] for some p’,c then
        explore( prefix ○ p’ ○ [ brn(¬c) ] );
      end
    end
  end
end
```

Obtain concrete values for prefix

Obtain path condition without the given prefix

For each additional branching condition, explore negation

Testing starts with a call explore([ ])

Example: Roots

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) throw new DivisionByZeroException( );
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) throw new DivisionByZeroException( );
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) throw new DivisionByZeroException( );
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

Example: Step 1

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) abort;
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) abort;
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) abort;
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

- Start by calling explore([ ])
- Solving path condition for [ ] yields arbitrary values, e.g., A=1, B=2, C=3
- Test passes and yields path condition (Q ≡ B×B – 4×A×C) [$\neg$(Q>0 $\wedge$ A≠0), $\neg$(Q=0)]
- Recurs on [$\neg$(Q>0 $\wedge$ A≠0), Q=0] and [Q>0 $\wedge$ A≠0]

We omit the brn since there are no assumptions in this example

Example: Step 2

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) abort;
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) abort;
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) abort;
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

- Solving $\neg(Q>0 \land A\neq0) \land Q=0$ yields e.g. A=0, B=0, C=0
- Test fails and yields path condition $[\neg(Q>0 \land A\neq0), Q=0, A=0]$
- Recurs on $[\neg(Q>0 \land A\neq0), Q=0, A\neq0]$

Example: Step 3

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) abort;
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) abort;
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) abort;
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

- Solving $\neg(Q>0 \wedge A\neq0) \wedge Q=0 \wedge A\neq0$ yields e.g. A=1, B=0, C=0
- Test passes and yields path condition $[\ \neg(Q>0 \wedge A\neq0), Q=0, A\neq0\ ]$
- No further recursion because path condition is identical to prefix

Example: Step 4

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) abort;
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) abort;
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) abort;
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

- Solving
  $Q>0 \wedge A \neq 0$
  yields e.g. A=-1, B=3, C=-1
- Test passes and yields path condition
  $[\ (Q>0 \wedge A \neq 0),\ A \neq 0,\ A \neq 0\ ]$
- Recurs on
  $[\ (Q>0 \wedge A \neq 0),\ A=0\ ]$ and
  $[\ (Q>0 \wedge A \neq 0),\ A \neq 0,\ A=0\ ]$

Example: Step 5

```
void roots( int a, int b, int c ) {
  int q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    int r = Math.sqrt( q );
    if( a == 0 ) abort;
    x1 = (-b + r) / (2 * a);
    if( a == 0 ) abort;
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    if( a == 0 ) abort;
    x1 = -b / (2 * a);
  } else { numRoots = 0; }
}
```

- Solving
  $(Q>0 \wedge A \neq 0) \wedge A=0$
  yields no result
- The path is infeasible, that is, this division by zero cannot occur
- Analogous for the condition
  $(Q>0 \wedge A \neq 0) \wedge A \neq 0 \wedge A=0$

GCD Example: Step 1

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- Start by calling explore([ ])
- Solving path condition for [ ] yields arbitrary values, e.g., A=0, B=0
- Test passes and yields path condition [asm(0<=A), asm(0<=B), brn(A=0)]
- Recurs on [asm(0<=A), asm(0<=B), brn(A≠0)]

GCD Example: Step 2

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- Solving
  $0 <= A \wedge 0 <= B \wedge A \neq 0$
  yields e.g. A=1, B=0
- Test passes and yields path condition
  [asm(0<=A), asm(0<=B), brn($\neg$A=0), brn($\neg$B≠0)]
- Recurs on
  [asm(0<=A), asm(0<=B), brn($\neg$A=0), brn(B≠0)]

GCD Example: Step 3

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- Solving
  $0<=A \wedge 0<=B \wedge A\neq 0 \wedge B\neq 0$
  yields e.g. A=1, B=1
- Test passes and yields path condition
  [asm(0<=A), asm(0<=B), brn(¬A=0), brn(B≠0), brn(¬A>B), brn(¬B–A≠0)]
- Recurs on
  […, brn(¬A>B), brn(B–A≠0)]
  and […, brn(A>B)]

GCD Example: Step 4

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- Solving
  $0<=A \land 0<=B \land A\neq 0 \land B\neq 0 \land \neg A>B \land B–A\neq 0$
  yields e.g. A=1, B=2
- Test passes and yields path condition
  [asm(0<=A), asm(0<=B), brn(¬A=0), brn(B≠0), brn(¬A>B), brn(B–A≠0), brn(¬A>B–A), brn(¬B–A–A≠0)]
- Recurs on […, brn(B–A–A≠0)]

GCD Example: Step 5

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- Solving
  $0<=A \wedge 0<=B \wedge A\neq 0 \wedge B\neq 0 \wedge \neg A>B \wedge B-A\neq 0 \wedge \neg A>B-A \wedge B-A-A\neq 0$
  yields e.g. A=1, B=3
- Test passes and yields path condition
  […, brn($\neg$(B–A–A–A≠0))]
- **Every additional recursion tests one more loop iteration**

GCD Example: Observations

```
int gcd( int a, int b ) {
  assume 0 <= a;
  assume 0 <= b;
  if( a == 0 )
    return b;
  while( b != 0 ) {
    if( a > b )
      a = a – b;
    else
      b = b – a;
  }
  return a;
}
```

- The simplified concolic testing procedure **might not terminate**
  - Not surprising; for loops, we generally cannot statically enumerate all paths
- Some branches might not be covered because the algorithm gets stuck exploring a loop before exploring the branch

Improved Procedure: Termination

```
procedure explore( Seq<Condition> prefix ) is
  values            := solve( prefix );
  if solution is available then
    path            := executeConcrete( values );
    pathCondition   := executeSymbolic( path );
    extension       := pathCondition[ |prefix| … ];
    foreach non-empty prefix p of extension do
      if p = p’ ○ [ brn(c) ] for some p’,c then
        explore( prefix ○ p’ ○ [ brn(¬c) ] );
      end
    end
  end
end
```

Bound number of loop iterations or use a time-out

Method Calls in Path Conditions

- Results of method calls may be used as conditions

```
Seq prefix( Seq s, int n ) {
  if ( s.length( ) < n )  return s;
  else                    …
}
```

- For simple methods, interprocedural symbolic execution may produce an expression for the result
  - For example, getters
- For non-trivial methods, the result **cannot be summarized automatically**
  - For example, iteration would typically require quantified expressions

Calls in Path Conditions: Encoding

- Idea: Replace expressions that cannot be encoded as constraints by their concrete values
  - Adapt definition of procedure executeSymbolic

```
Seq prefix( Seq s, int n ) {
  if ( s.length( ) < n )  return s;
  else                    …
}
```

Solver could choose for instance S=[e], N=1

- Execute, e.g., with S=[ ], N=0
- The observed path condition is ¬(S.length( ) < N)
- In the encoding, replace call by concrete result to obtain [brn(¬0<N)]
- Recurs on [brn(0<N)]

Calls in Path Conditions: Encoding (cont'd)

- Using a concrete method result makes sense only as long as the method arguments remain the same
  - Fix method arguments by adding assumptions

```
Seq prefix( Seq s, int n ) {
  if ( s.length( ) < n )  return s;
  else                    …
}
```

- Execute, e.g., with S=[ ], N=0
- The observed path condition is ¬(S.length( ) < N)
- Encode path condition as [asm(S=[ ]), brn(¬0<N)]
- Recurs on [asm(S=[ ]), brn(0<N)]

Solver could choose for instance S=[ ], N=1

Method Calls in Path Conditions (cont'd)

- Replacing calls by concrete values may lead to constraints on other inputs that can be solved

```
Seq prefix( Seq s, int n ) {
  if ( s.length( ) < n )  return s;
  else                    …
}
```

Path condition:
[asm(S=[ ]), brn(0<N)]

- However, when method results are constrained by values other than symbolic values, the resulting constraints do not provide useful conditions

```
void sort( Seq s ) {
  if ( s.length( ) == 0 )      return;
  else                         …
}
```

Path condition:
[asm(S=[ ]), brn(0=0)]

```
void copy( Seq from, Seq to ) {
  if ( from.length( ) != to.length( ) ) throw …;
  else …
}
```

Path condition:
[asm(F=[ ]), asm(T=[ ]), brn(0≠0)]

Reminder: Limitations: Constraint Solving

```
void roots( double a, double b, double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    double r = Math.sqrt( q );
    x1 = (-b + r) / (2 * a);
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    x1 = -b / (2 * a);
  } else {
    numRoots = 0;
  }
}
```

- Nonlinear constraint $b^2 - 4ac > 0 \wedge a \neq 0$ over reals is difficult to solve
- Without a solution, no test data will be provided
  - Neither for the other branches

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Improved Procedure: Simplifying Constraints

```
procedure explore( Seq<Condition> prefix ) is
  values             := solve( prefix );
  if solution is available then
    path             := executeConcrete( values );
    pathCondition    := executeSymbolic( path );
    extension        := pathCondition[ |prefix| … ];
    foreach non-empty prefix p of extension do
      if p = p’ ○ [ brn(c) ] for some p’,c then
        explore( prefix ○ p’ ○ [ brn(¬c) ] );
      end
    end
  end
end
```

When solver returns “unknown”, simplify constraint by replacing symbolic variable by a concrete value and retry solving

Example: Step 1

```
void roots( double a,
            double b,
            double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    // ignore
  } else if( q == 0 ) {
    // ignore
  } else {
    // ignore
  }
}
```

- Solving path condition for [ ] yields arbitrary values, e.g., A=1, B=2, C=3
- Test yields path condition ($Q \equiv B \times B - 4 \times A \times C$) [brn($\neg$($Q>0 \wedge A \neq 0$)), brn($\neg Q=0$)]
- Recurs on [brn($\neg(Q>0 \wedge A \neq 0)$), brn($Q=0$)] and [brn($Q>0 \wedge A \neq 0$)]

Example: Step 2

```
void roots(   double a,
              double b,
              double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    // ignore
  } else if( q == 0 ) {
    // ignore
  } else {
    // ignore
  }
}
```

- Solving $\neg(Q>0 \wedge A\neq0) \wedge Q=0$ yields, e.g., A=0, B=0, C=0
- Test yields path condition [brn($\neg(Q>0 \wedge A\neq0)$), brn(Q=0)]

Example: Step 3

```
void roots( double a,
            double b,
            double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    // ignore
  } else if( q == 0 ) {
    // ignore
  } else {
    // ignore
  }
}
```

- Solving $Q>0 \wedge A\neq 0$ (for reals) yields unknown
- Replace one variable with a concrete value from the parent run via an assumption
  [ass(A=1), brn($Q>0 \wedge A\neq 0$)]
- Now solver yields e.g.
  A=1, B=0, C= –1/4

Simplifying Constraints with Concrete Values

- Replacing a variable with a concrete value
  - Might **reduce the complexity** (e.g., replacing A in A×B>0 goes from non-linear to linear arithmetic)
  - **Reduces the size** (number of free variables)
- Strategy does not necessarily succeed
  - New constraint might be unsatisfiable (e.g., A=0 on previous slide)
  - Solver might still yield “unknown”
- Use heuristics to identify set of variables to be replaced

Summary

- Automatic test case generation reduces the test effort tremendously
  - Achieve very high code coverage
  - Find test data
  - Actively search bugs
- Large effort remains
  - Writing oracles and assertions
  - Writing preconditions as assumptions
  - Writing factories to create test data (objects)
- Very active research area