Introduction to Dynamic Analysis

Reference material

- **Introduction to dynamic analysis**
  - Zhu, Hong, Patrick A. V. Hall, and John H. R. May, "Software Unit Test Coverage and Adequacy," ACM Computing Surveys, vol. 29, no.4, pp. 366-427, December, 1997

Common Definitions

- Failure-- result that deviates from the expected or specified intent
- Fault/defect-- a flaw that could cause a failure
- Error -- erroneous belief that might have led to a flaw that could result in a failure
- Static Analysis -- the static examination of a product or a representation of the product for the purpose of inferring properties or characteristics
- Dynamic Analysis -- the execution of a product or representation of a product for the purpose of inferring properties or characteristics
- Testing -- the (systematic) selection and subsequent "execution" of sample inputs from a product's input space in order to infer information about the product's behavior.
  - usually trying to uncover failures
  - the most common form of dynamic analysis
- Debugging -- the search for the cause of a failure and subsequent repair

Validation and Verification: V&V

- Validation -- techniques for assessing the quality of a software product
- Verification -- the use of analytic inference to (formally) prove that a product is consistent with a specification of its intent
  - the specification could be a selected property of interest or it could be a specification of all expected behaviors and qualities

    e.g., all deposit transactions for an individual will be completed before any withdrawal transaction will be initiated

  - a form of validation
  - usually achieved via some form of static analysis

Correctness

- a product is correct if it satisfies all the requirement specifications
  - correctness is a mathematical property
  - requires a specification of intent
  - specifications are rarely complete
  - difficult to prove poorly-quantified qualities such as user-friendly
- a product is behaviorally or functionally correct if it satisfies all the specified behavioral requirements

Reliability

- measures the dependability of a product
  - the probability that a product will perform as expected
  - sometimes stated as a property of time e.g., mean time to failure
- Reliability vs. Correctness
  - reliability is relative, while correctness is absolute

  (but only wrt a specification)
  - given a "correct" specification, a correct product is reliable, but not necessarily vice versa

Robustness

- behaves "reasonably" even in circumstances that were not expected
    - making a system robust more than doubles development costs
    - a system that is correct may not be robust, and vice versa

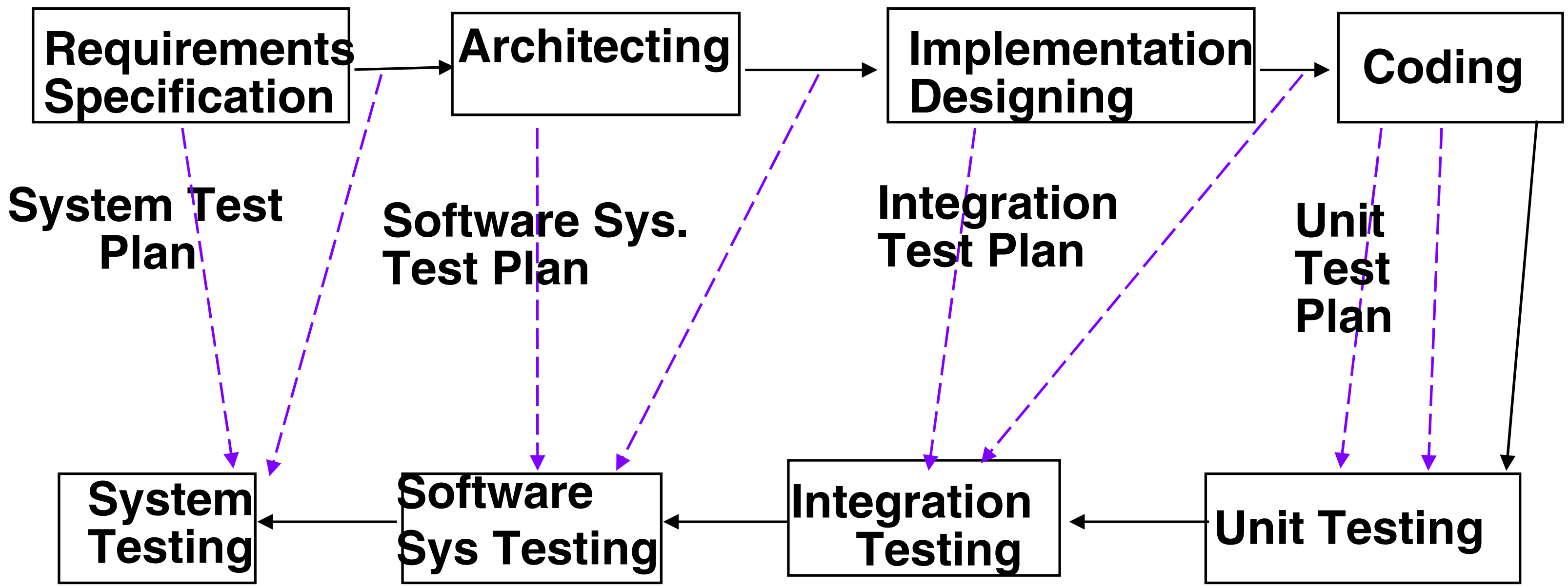
Approaches

- Dynamic Analysis
  - Assertions
  - Error seeding, mutation testing
  - Coverage criteria
  - Fault-based testing
  - Specification-based testing
  - Object oriented testing
  - Regression testing
- Static Analysis
  - Inspections
  - Software metrics
  - Symbolic execution
  - Dependence Analysis
  - Data flow analysis
  - Software Verification

Types of Testing--what is tested

- Unit testing-exercise a single simple component
  - Procedure
  - Class
- Integration testing-exercise a collection of inter-dependent components
  - Focus on interfaces between components
- System testing-exercise a complete, stand-alone system
- Acceptance testing-customer's evaluation of a system
  - Usually a form of system testing
- Regression testing-exercise a changed system
  - Focus on modifications or their impact

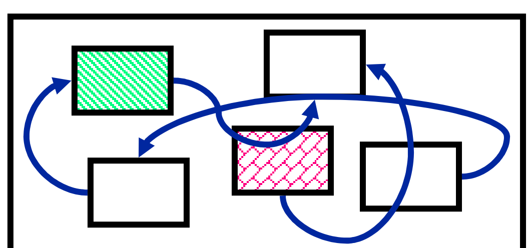
Test planning



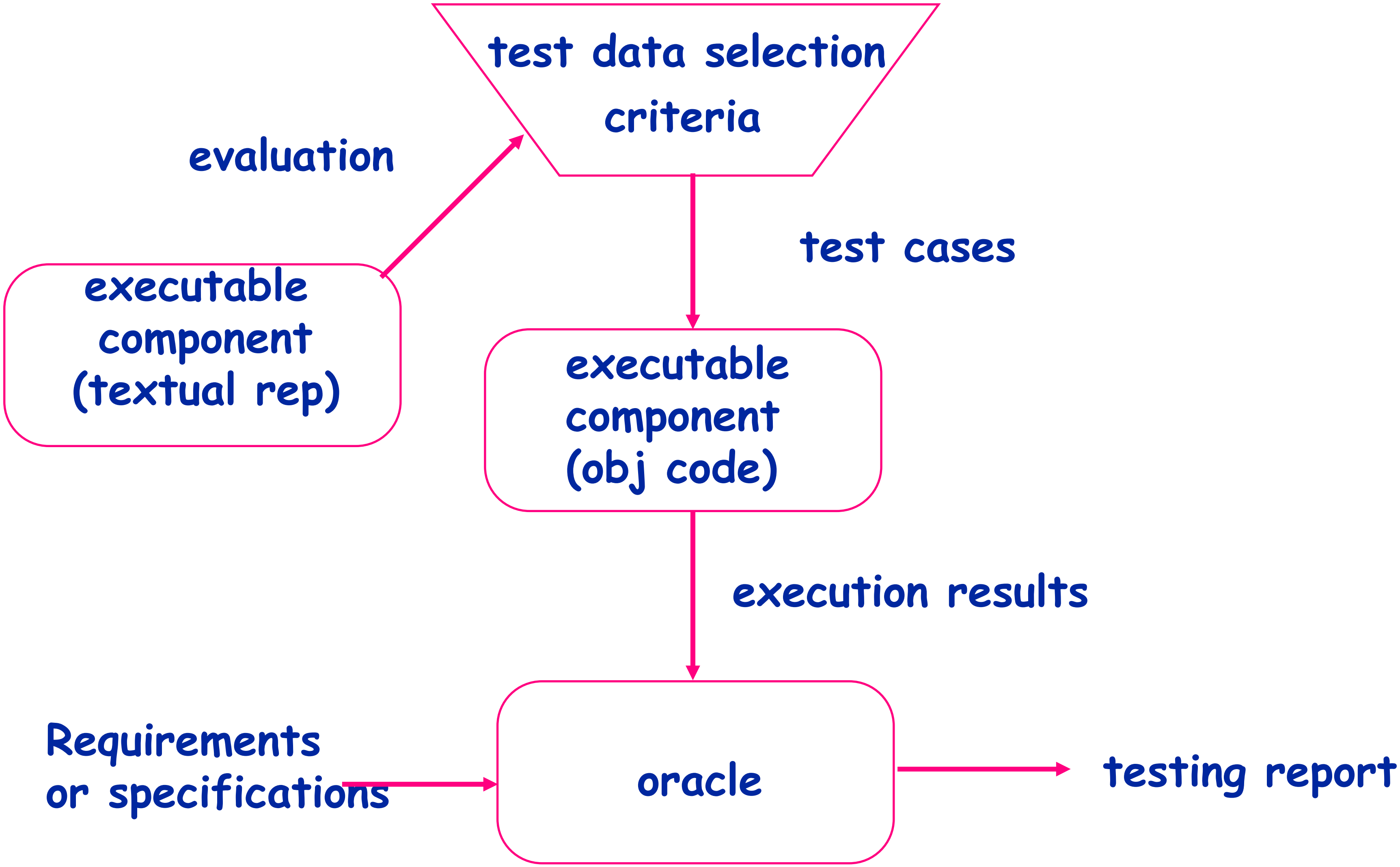
Approaches to testing

- Black Box/Functional/Requirements based

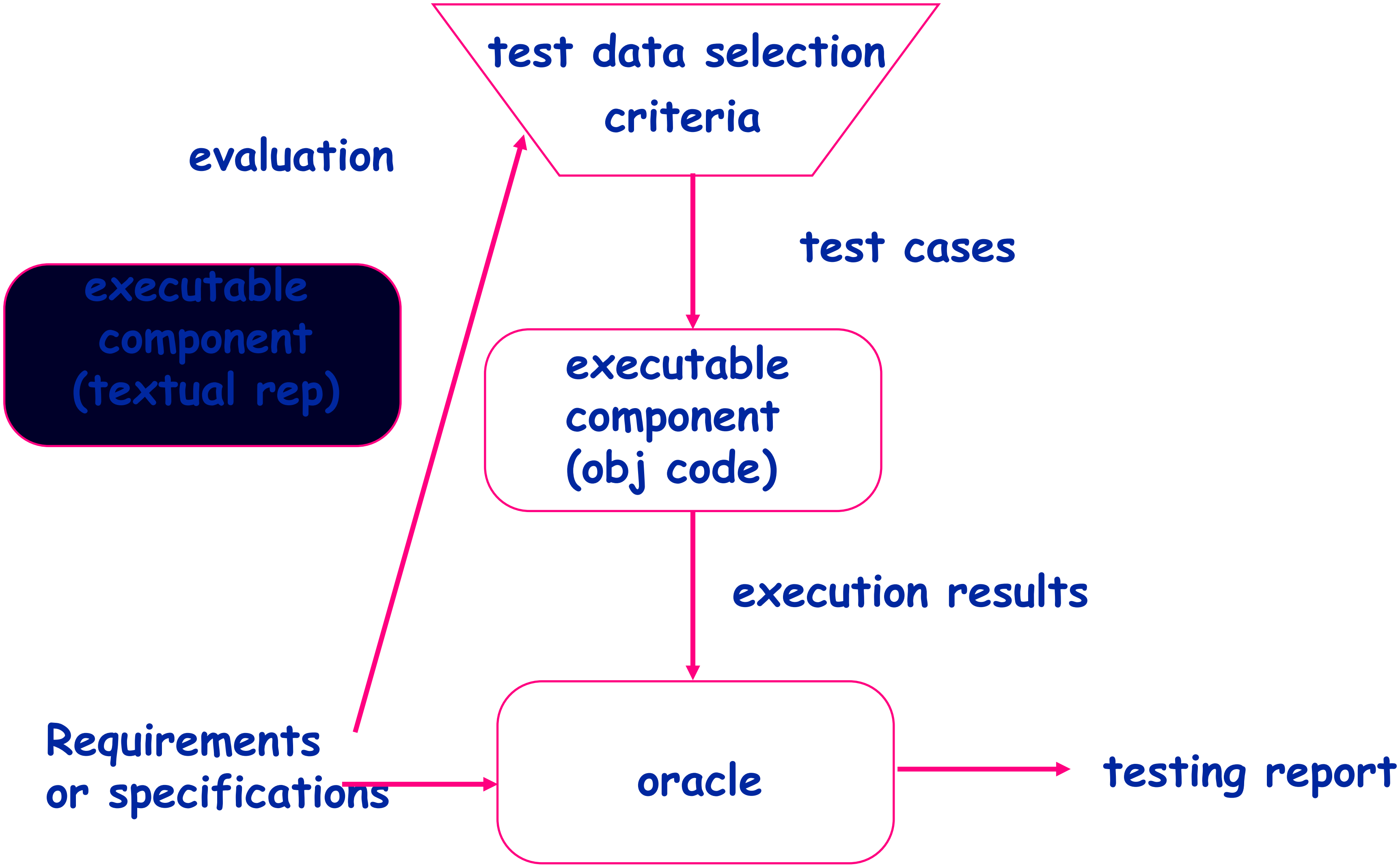
- White Box/Structural/Implementation based



White box testing process



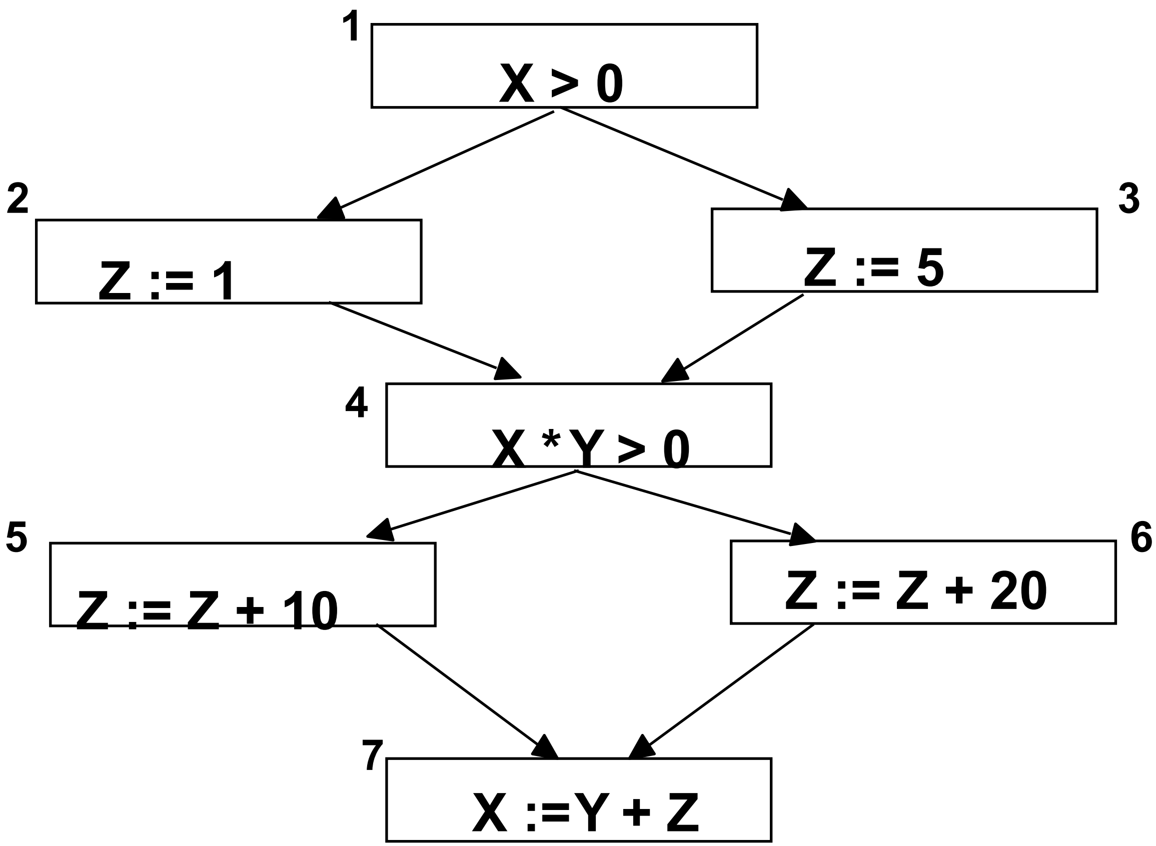
Black box testing process



Why black AND white box?

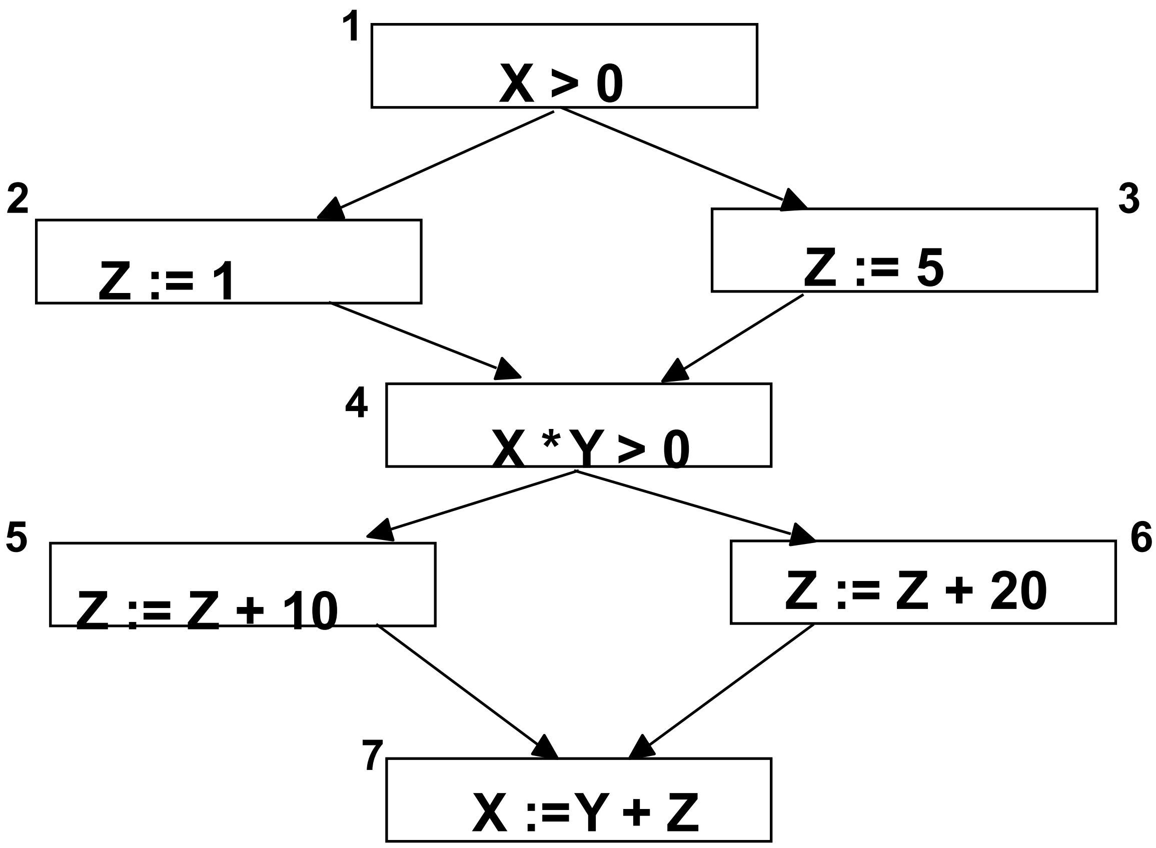
- Black box
  - May not have access to the source code
  - Often do not care how s/w is implemented, only how it performs
- White box
  - Want to take advantage of all the information
  - Looking inside indicates structure=> helps determine weaknesses

Paths



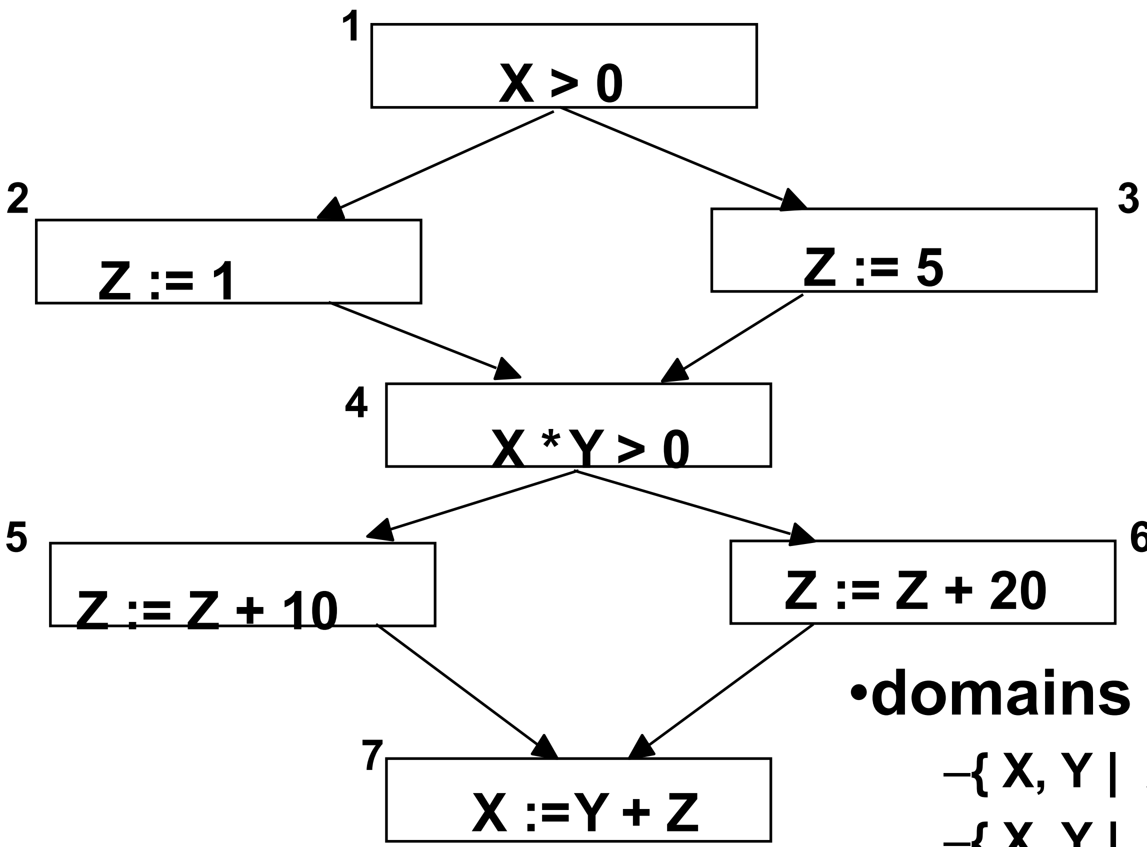
- Paths:
  - 1, 2, 4, 5, 7
  - 1, 2, 4, 6, 7
  - 1, 3, 4, 5, 7
  - 1, 3, 4, 6, 7

Paths can be identified by predicate outcomes



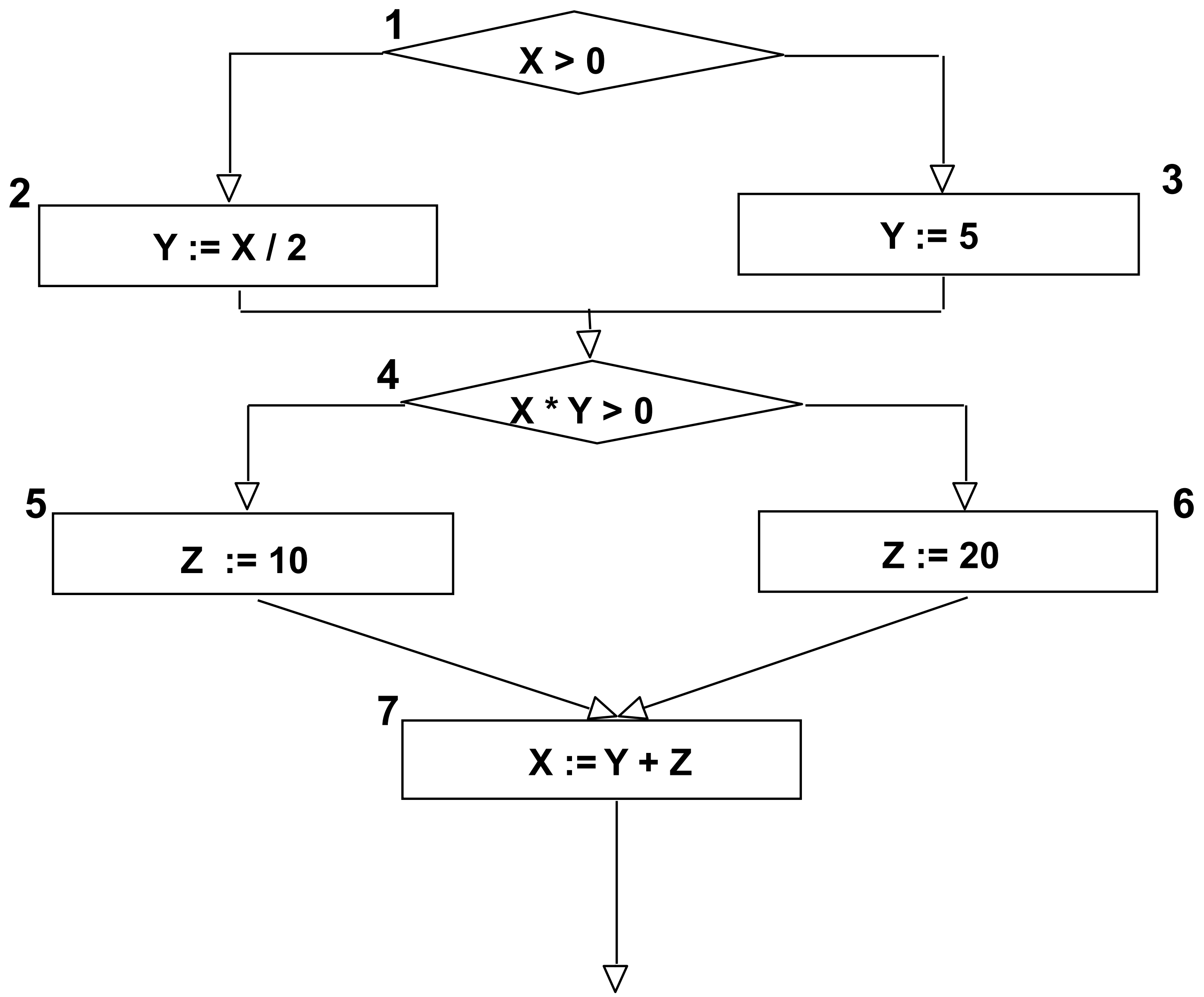
- outcomes
  - t, t
  - t, f
  - f, t
  - f, f

Paths can be identified by domains

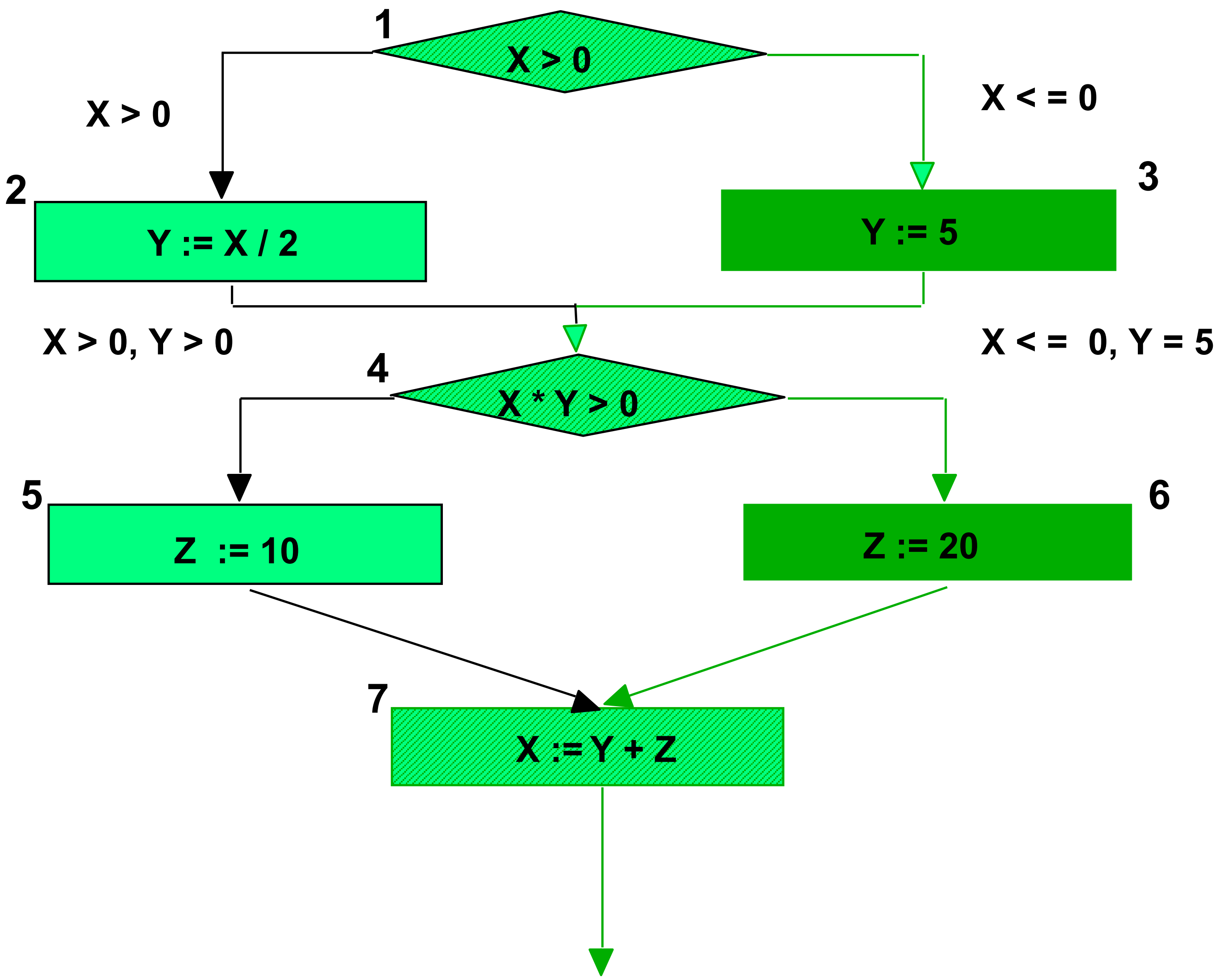


- domains
  - { X, Y | X > 0 and X * Y > 0}
  - { X, Y | X > 0 and X * Y < = 0 }
  - { X, Y | X < = 0 and X * Y > 0}
  - { X, Y | X < = 0 and X * Y < = 0}

Example with an infeasible path



Example with an infeasible path

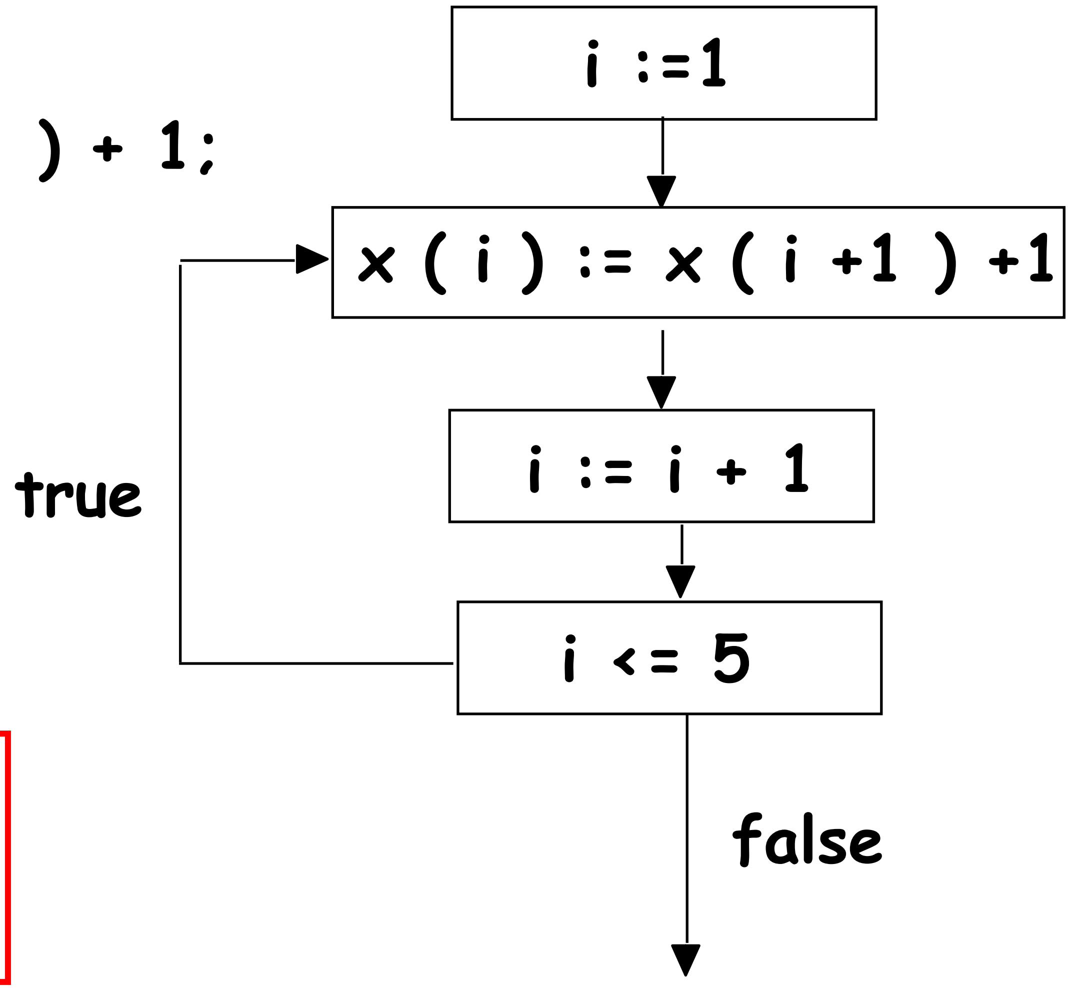


Example Paths

- Feasible path: 1, 2, 4, 5, 7
- Infeasible path: 1, 3, 4, 5,7
- Determining if a path is feasible or not requires additional semantic information
  - In general, unsolveable
  - In practice, intractable

Another example of an infeasible path

For i :=1 to 5 do
x (i) := x (i +1) + 1;
end for:



Note, implicit instructions are explicitly represented

Infeasible paths vs. unreachable code and dead code

unreachable code

```
X := X + 1;
Goto loop;
Y := Y + 5;
```

Never executed

dead code

```
X := X + 1;
X := 7;
X := X + Y;
```

'Executed', but irrelevant

Test Selection Criteria

- How do we determine what are good test cases?
- How do we know when to stop testing?

Test Adequacy

Test Selection Criteria

- A test set T is a finite set of inputs (test cases) to an executable component
- Let D(S) be the domain of execution for program/component/system S
- Let S(T) be the results of executing S on T
- A test selection criterion C(T,S) is a predicate that specifies whether a test set T satisfies some selection criterion for an executable component S.
- Thus, the test set T that satisfies the Criterion C is defined as:

$$\{ t \epsilon T \mid T \subseteq D(S) \text{ and } C(T, S) \}$$

Ideal Test Criterion

- A test criterion is ideal if for any executable system S and every $T \subseteq D(S)$ such that $C(T, S)$, if S (T) is correct, then S is correct
  - of course we want $T \ll D(S)$
  - In general, $T = D(S)$ is the only test criterion that satisfies ideal

In general, there is no ideal test criterion

"Testing shows the presence, not the absence of bugs"
E. Dijkstra

- Dijkstra was arguing that verification was better than testing
- But verification has similar problems
  - can't prove an arbitrary program is correct
    - can't solve the halting problem
  - can't determine if the specification is complete
- Need to use dynamic and static techniques that compliment each other

Effectiveness a more reasonable goal

- A test criterion *C* is ***effective*** if for any executable system S and every T $\subseteq$ D (S) such that C(T, S),

  $\Rightarrow$if S (T) is correct, then S is highly reliable

  OR

  $\Rightarrow$ if S (T) is correct, then S is guaranteed (or is highly likely) not to contain any faults of a particular type

- Currently can not do either of these very well
  - Some techniques (static and dynamic) can provide some guarantees

Two Uses for Testing Criteria

- Stopping rule--when has a system been tested enough
- Test data evaluation rule--evaluates the quality of the selected test data
  - May use more than one criterion
  - May use different criteria for different types of testing
    - regression testing versus acceptance testing

Black Box/Functional Test Data Selection

- Typical cases
- Boundary conditions/values
- Exceptional conditions
- Illegal conditions (if robust)
- Fault-revealing cases
  - based on intuition about what is likely to break the system
- Other special cases

Functional Test Data Selection

- Stress testing
  - large amounts of data
  - worse case operating conditions
- Performance testing
- Combinations of events
  - select those cases that appear to be more error-prone
  - Select 1 way, 2 way, … n way combinations

Sequences of events

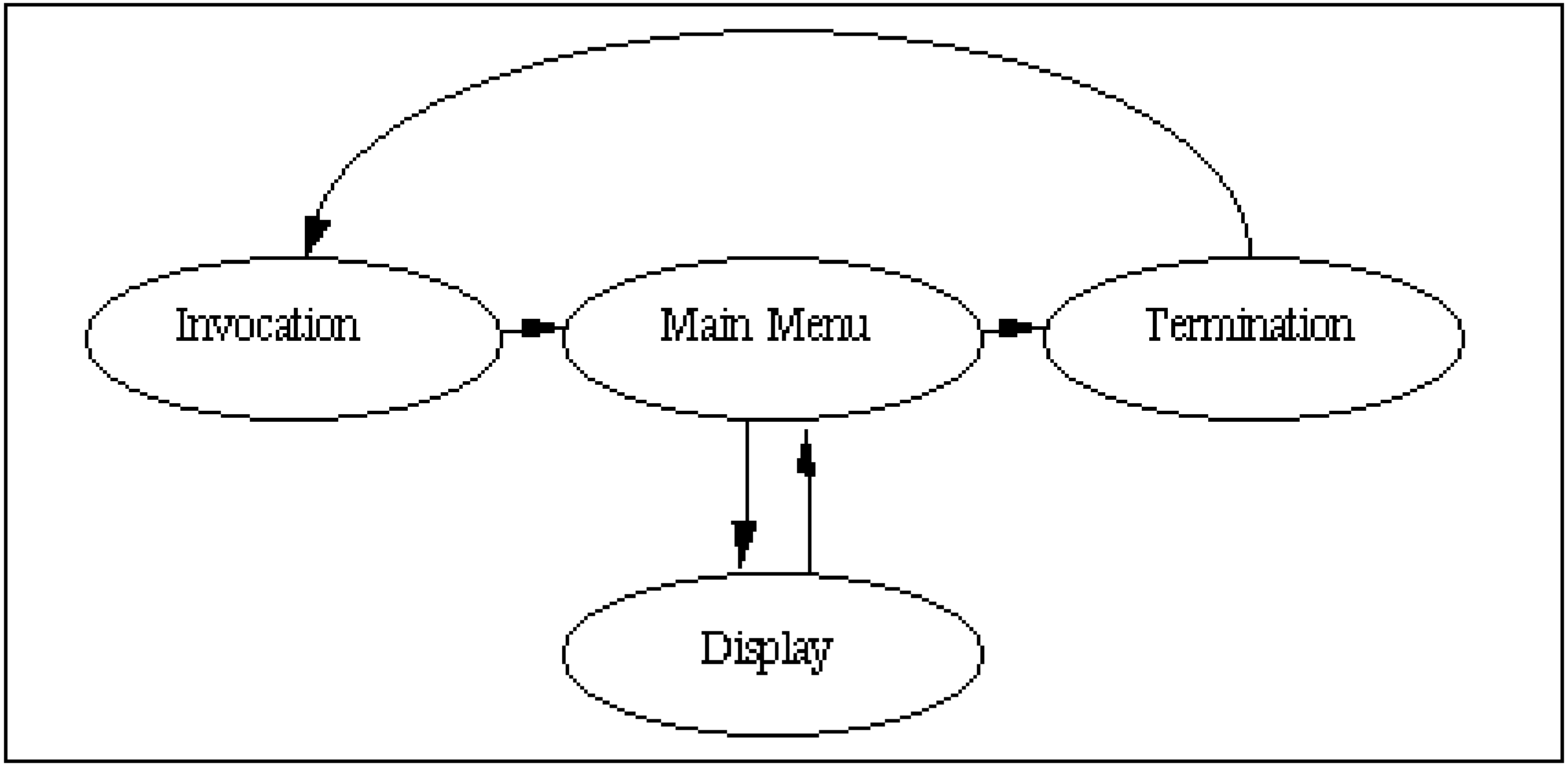
- Common representations for selecting sequences of events
  - Decision tables
  - Usage scenarios

Decision Table

events	t1	t2	t3	t5	t6	t7	...
e1	x	x	x		-		
e2		x	x	x	x		x
e3	x			x		x	
e4	-		x		x		x
...		x			x	x	-

Usage Scenarios

Graphical Usage Model of a Simple System



Overview of Dynamic Analysis Techniques

- Testing Processes
  - Unit, Integration, System, Acceptance, Regression, Stress
- Testing Approaches
  - Black Box versus White Box
- Black Box Strategies
  - Test case selection criteria
  - Representations for considering combinations of events/states

White Box/Structural Test Data Selection

- Coverage based
- Fault-based
  - e.g., mutation testing, RELAY
- Failure-based
  - domain and computation based
  - use representations created by symbolic execution

Coverage Criteria

- control-flow adequacy criteria
- G = (N, E, s, f) where
  - the nodes N represent executable instructions (statement or statement fragment)
  - the edges E represent the potential transfer of control
  - s ϵ N is a designated start node
  - f ϵ N is a designated final node
  - E = { (n_i, n_j) | syntactically, the execution of n_j follows the execution of n_i}

Control-Flow-Graph-Based Coverage Criteria

- Statement Coverage
- Branch Coverage
- Path Coverage
- Hidden Paths
- Loop Guidelines
  - General
  - Boundary - Interior

Statement Coverage

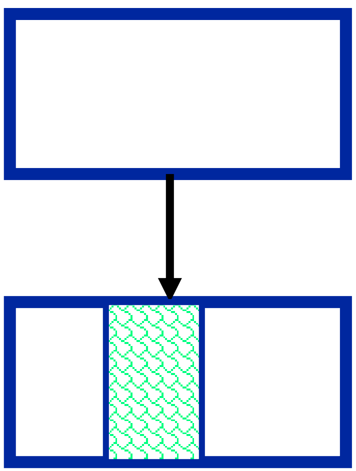
- requires that each statement in a program be executed at least once
- formally:
  - a set P of paths in the CFG satisfies the statement coverage criterion iff for each $n_i \in N$, $\exists\ p \in P$ such that n_i is on path p
    - defined in terms of paths

Statement Coverage

- only about 1/3 of NASA statements were executed before software was released (Stucki 1973)
- usually can achieve 85% coverage easily, but why not 100%?
    - unreachable code
    - complex sequence (should be tested!)
- Microsoft reports 80-90% code coverage

How does OO affect coverage?

- Often only parts of a reused component are actually executed by a system
  - Would expect good coverage for unit testing
  - More restricted coverage for integration testing



Coincidental Correctness

- Executing a statement does not guarantee that a fault on that path will be revealed

- Example:

  y := x * 2

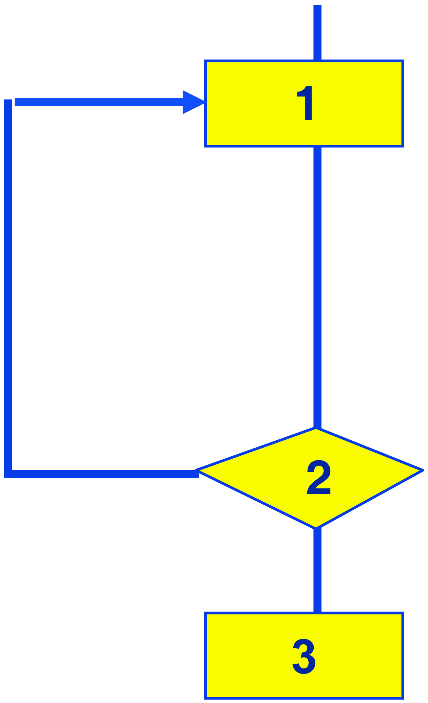
  y := x ** 2

  If x = 2 then the fault is not exposed

Branch Coverage

- Requires that each branch in a program (each edge in a control flow graph) be executed at least once
  - e.g., Each predicate must evaluate to each of its possible outcomes
- Branch coverage is stronger than statement coverage

Branch Coverage



STATEMENT COVERAGE: PATH 1, 2, 3

BRANCH COVERAGE: PATH 1, 2, 1, 2, 3

Hidden Path (branch) Coverage

- **Requires that each condition in a compound predicate be tested**

  Example:

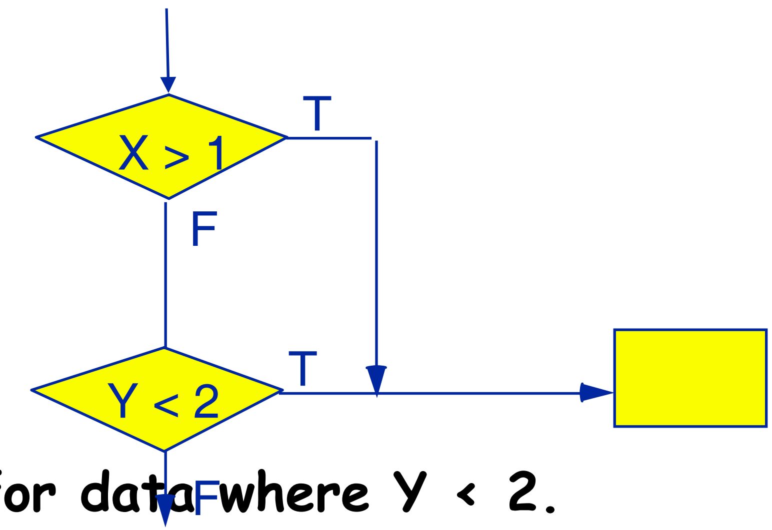
  $(X > 1) \vee (Y < 2)$

  Test Data:

  X = 2, Y = 5 ->T

  X = 1, Y = 5 ->F

  but, true branch is never tested for data where Y < 2.



(X > 1)	(Y < 2)
T	F
F	T
T	T
F	F

Path Coverage

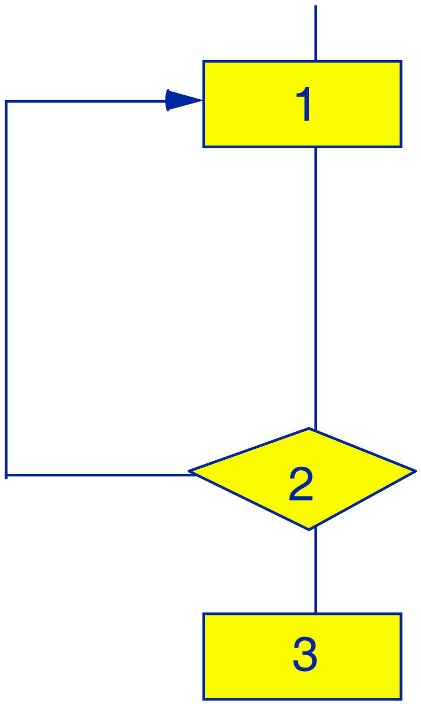
- Requires that every executable path in the program be executed at least once
- In most programs, path coverage is impossible
  - Example:

```
read N;
SUM :=  0;
for I = 1 to N do
    read X;
    SUM := SUM + X;
endfor
```

- How do we choose a set of paths?

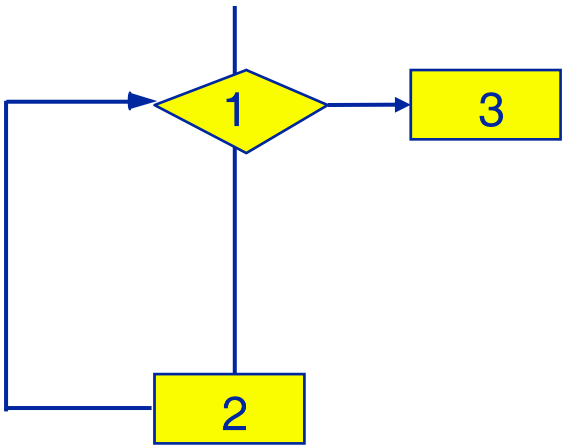
Loop Coverage

- Path 1, 2, 1, 2, 3 executes all branches (and all statements) but does not execute the loop well.



Typical Guidelines for loop coverage

- fall through case
- minimum number of iterations
- minimum +1 number of iterations
- maximum number of iterations

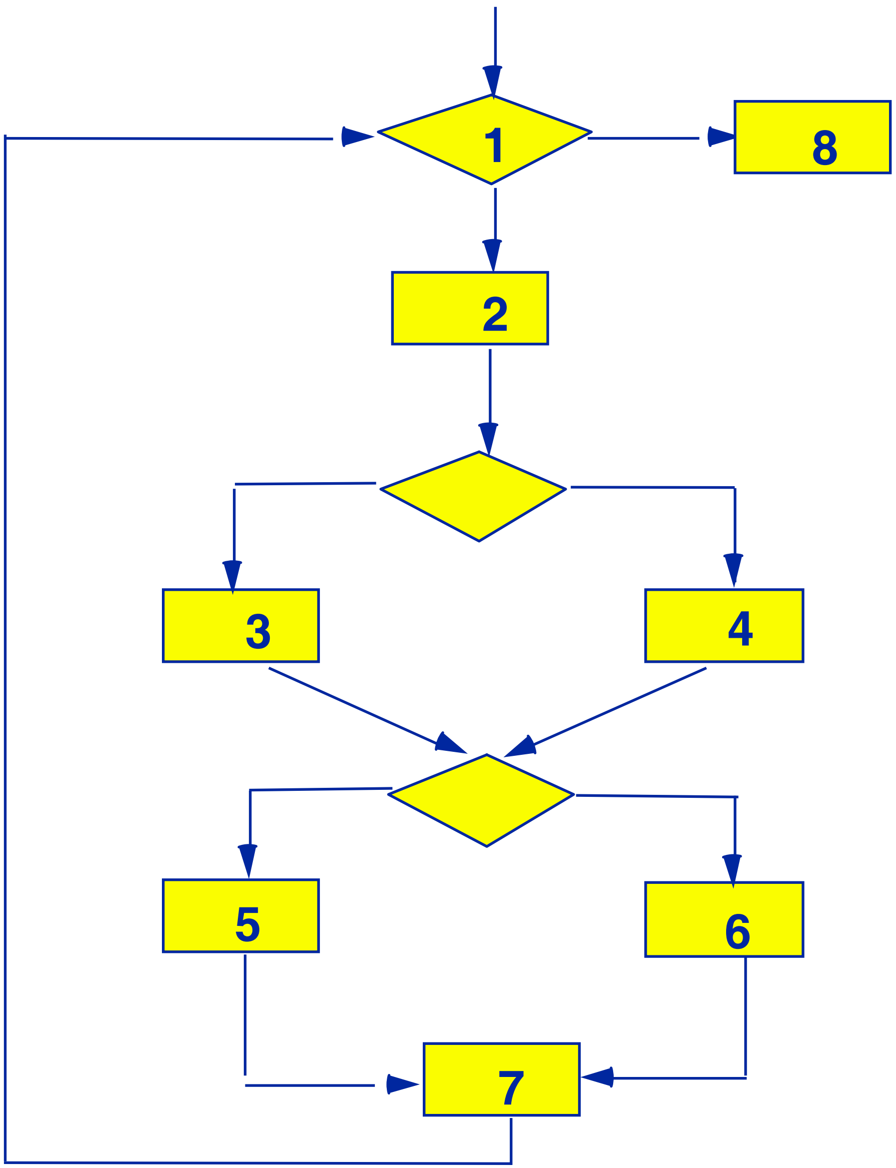


1, 3
1,2,3
1,2,1,2,3
$(1, 2,)^n$ 3

Boundary - Interior Criteria

- boundary test of a loop causes the loop to be entered but not iterated
- interior test of a loop causes a loop to be entered and then iterated at least once
- both boundary and interior tests are to be selected for each unique path through the the loop

Example



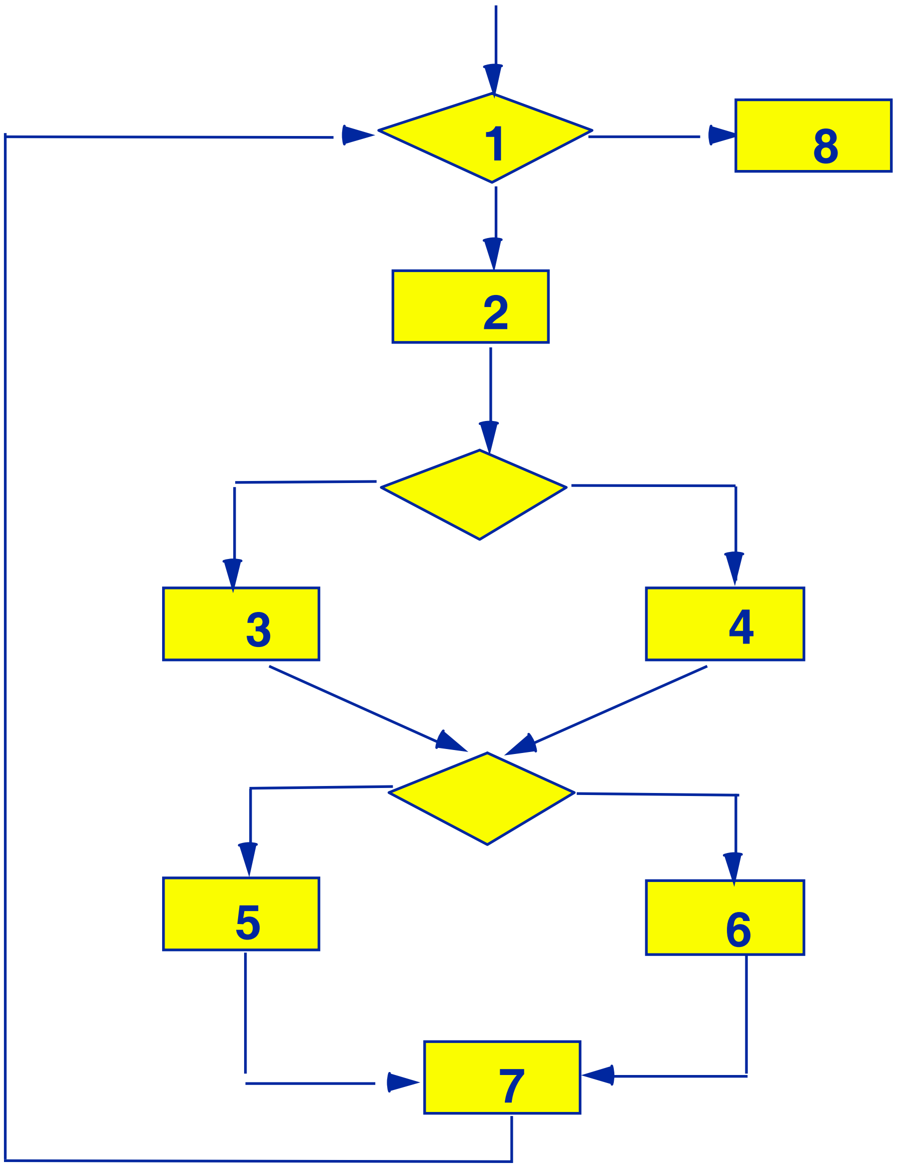
Paths for Example

Boundary paths

1,2,3,5,7	a
1,2,3,6,7	b
1,2,4,5,7	c
1,2,4,6,7	d

Interior paths
(for 2 executions of the loop)

a,a
a,b
a,c
a,d
b,a
b,b
...
x,y for x,y = a, b, c, d



Selecting paths that satisfy these criteria

- static selection
  - some of the associated paths may be infeasible
- dynamic selection
  - monitors coverage and displays areas that have not been satisfactorily covered

Problem with coverage criteria:

- Fault detection may depend upon
  - Specific combinations of statements, not just coverage of those statements
  - Astutely selected test data that reveals the fault, not just test data that executes the statement/branch/path
- Will look at semantically richer models
- First look at some axioms about testing criteria

Example program (symbolic evaluation)

```
 procedure Contrived is
 X, Y, Z : integer;
1   read X, Y;
2   if X ≥ 3 then
3        Z := X+Y;
    else
4        Z := 0;
    endif;
5   if Y > 0 then
6        Y := Y + 5;
    endif;
7   if X - Y < 0 then
8        write Z;
 else
9        write Y;
 endif;
 end Contrived;
```

Stmt	PV	PC
1	$X \leftarrow x$ $Y \leftarrow y$	true
2,3	$Z \leftarrow x+y$	$true \wedge x \geq 3 = x \geq 3$
5,6	$Y \leftarrow y+5$	$x \geq 3 \wedge y > 0$
7,9		$x \geq 3 \wedge y > 0 \wedge x-(y+5) \geq 0$ $= x \geq 3 \wedge y > 0 \wedge (x-y) \geq 5$

Presenting the results

```
   procedure Contrived is
   X, Y, Z  : integer;
1          read X, Y;
2          if X ≥ 3 then
3       Z := X+Y;
           else
4       Z := 0;
           endif;
5          if Y > 0 then
6       Y := Y + 5;
           endif;
7          if X - Y < 0 then
8       write Z;
   else
9       write Y;
   endif
   end Contrived
```

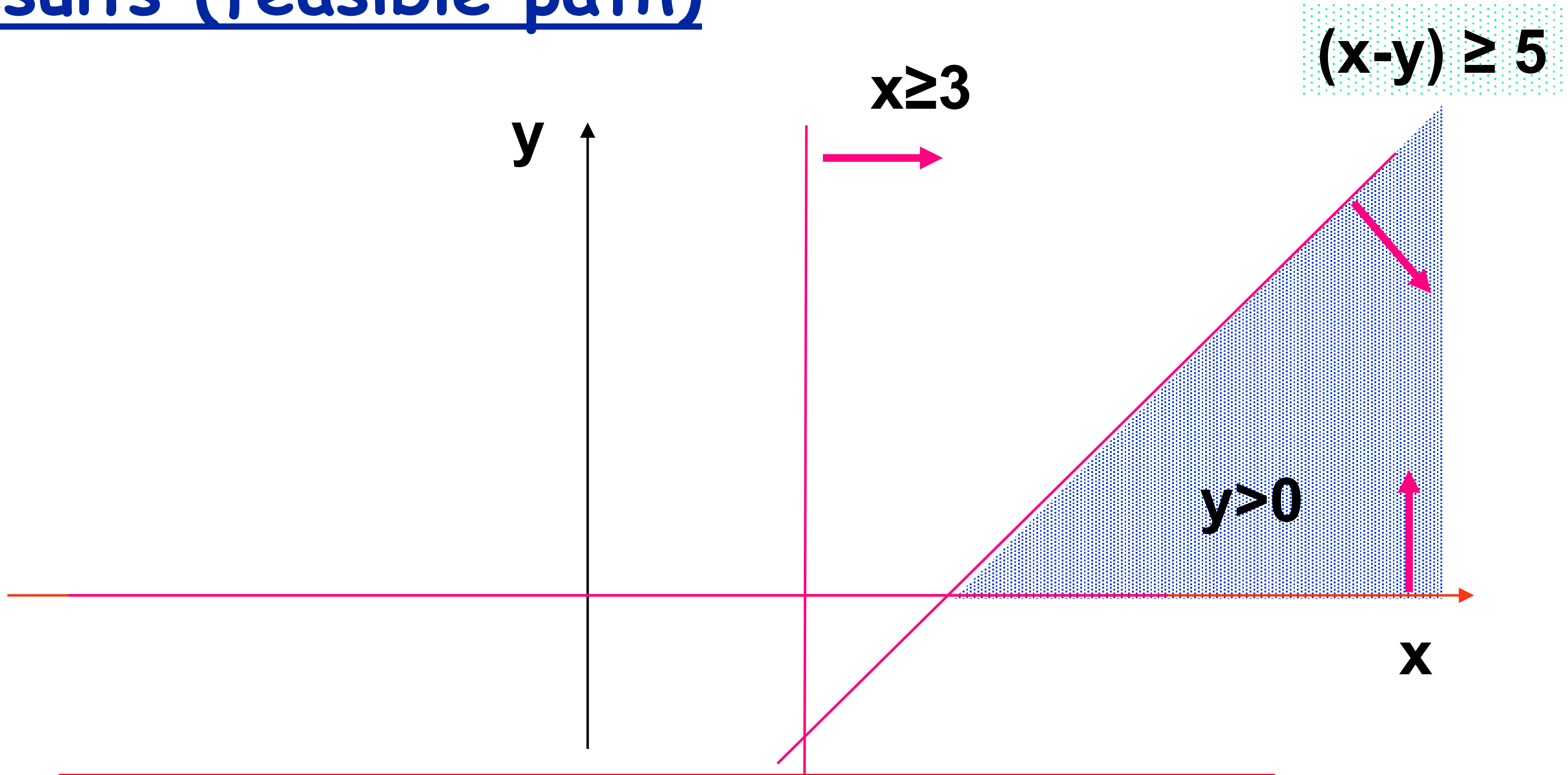
Statements	PV	PC
1	$X \leftarrow x$ $Y \leftarrow y$	true
2,3	$Z \leftarrow x+y$	$true \wedge x \geq 3 = x \geq 3$
5,6	$Y \leftarrow y+5$	$x \geq 3 \wedge y > 0$
7,9		$x \geq 3 \wedge y > 0 \wedge x-(y+5) \geq 0 =$ $x \geq 3 \wedge y > 0 \wedge (x-y) \geq 5$

P = 1, 2, 3, 5, 6, 7, 9

$D[P] = \{ (x,y) \mid x \geq 3 \wedge y > 0 \wedge x-y \geq 5 \}$

$C[P] = PV.Y = y + 5$

Results (feasible path)



P = 1, 2, 3, 5, 6, 7, 9

D[P] = { (x,y)|x≥3∧y>0∧x-y≥5}

C[P] = PV.Y = y +5

Evaluating another path

```
  procedure Contrived is
  X, Y, Z : integer;
1   read X, Y;
2   if X ≥ 3 then
3       Z := X+Y;
    else
4       Z := 0;
    endif;
5   if Y > 0 then
6       Y := Y + 5;
    endif;
7   if X - Y < 0 then
8       write Z;
  else
9       write Y;
  endif;
  end Contrived;
```

Stmts	PV	PC
1	$X \leftarrow x$ $Y \leftarrow y$	true
2,3	$Z \leftarrow x+y$	$true \wedge x \geq 3 = x \geq 3$
5,7		$x \geq 3 \wedge y \leq 0$
7,8		$x \geq 3 \wedge y \leq 0 \wedge x-y < 0$

```
        procedure EXAMPLE is
        X, Y, Z  : integer;
1               read X, Y;
2               if X ≥ 3 then
3            Z := X+Y;
                else
4            Z := 0;
                endif;
5               if Y > 0 then
6            Y := Y + 5;
                endif;
7               if X - Y < 0 then
8            write Z;
        else
9            write Y;
        endif
        end EXAMPLE
```

Stmts	PV	PC
1	$X \leftarrow x$ $Y \leftarrow y$	true
2,3	$Z \leftarrow x+y$	$true \wedge x \geq 3 = x \geq 3$
5,7		$x \geq 3 \wedge y \leq 0$
7,8		$x \geq 3 \wedge y \leq 0 \wedge x-y < 0$

P = 1, 2, 3, 5, 7, 8

$D[P] = \{ (x,y) \mid x \geq 3 \wedge y \leq 0 \wedge x-y<0 \}$

infeasible path!

Results (infeasible path)