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Predicate Testing

- Introduction
- Basic Concepts
- Predicate Coverage
- Program-Based Predicate Testing
- Summary

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Motivation

- Predicates are expressions that can be evaluated to a boolean value, i.e., true or false.
- Many decision points can be encoded as a predicate, i.e., which action should be taken under what condition?
- Predicate-based testing is about ensuring those predicates are implemented correctly.

Applications

- Program-based: Predicates can be identified from the branching points of the source code
  - e.g.: if ((a > b) || c) { … } else { … }
- Specification-based: Predicates can be identified from both formal and informal requirements as well as behavioral models such as FSM
  - "if the printer is ON and has paper then send the document for printing"
- Predicate testing is required by US FAA for safety critical avionics software in commercial aircraft

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Predicate

- A predicate is an expression that evaluates to a Boolean value
- Predicates may contain:
  - Boolean variables
  - Non-boolean variables that are compared with the relational operators {>, <, =, ≥, ≤, ≠}
  - Boolean function calls
- The internal structure is created by logical operators:
  - ¬, ∧, ∨, →, ⊕, ↔

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Clause

- A clause is a predicate that does not contain any of the logical operators
- Example: (a = b) ∨ C ∧ p(x) has three clauses: a relational expression (a = b), a boolean variable C, and a boolean function call p(x)

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Predicate Faults

- An incorrect boolean operator is used
- An incorrect boolean variable is used
- Missing or extra boolean variables
- An incorrect relational operator is used
- Parentheses are used incorrectly

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Example

- Assume that $(a < b) \vee (c > d) \wedge e$ is a correct boolean expression:
  - $(a < b) \wedge (c > d) \wedge e$
  - $(a < b) \vee (c > d) \wedge f$
  - $(a < b) \vee (c > d)$
  - $(a = b) \vee (c > d) \wedge e$
  - $(a = b) \vee (c \leq d) \wedge e$
  - $(a < b \vee c > d) \wedge e$

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Predicate Coverage

- For each predicate p, TR contains two requirements: p evaluates to true, and p evaluates to false.
- Example: $((a > b) \vee C) \wedge p(x))$

	a	b	C	p(x)
1	5	4	true	true
2	5	6	false	false

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Clause Coverage

- For each clause c, TR contains two requirements: c evaluates to true, and c evaluates to false.
- Example: ((a > b) ∨ C) ∧ p(x))

	a	b	C	p(x)
1	5	4	true	true
2	5	6	false	false

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Predicate vs Clause Coverage

- Does predicate coverage subsume clause coverage? Does clause coverage subsume predicate coverage?
- Example: p = a ∨ b

	a	b	a ∨ b
1	T	T	T
2	T	F	T
3	F	T	T
4	F	F	F

Combinatorial Coverage

- For each predicate p, TR has test requirements for the clauses in p to evaluate to each possible combination of truth values
- Example: (a ∨ b) ∧ c

	a	b	c	(a ∨ b) ∧ c
1	T	T	T	T
2	T	T	F	F
3	T	F	T	T
4	T	F	F	F
5	F	T	T	T
6	F	T	F	F
7	F	F	T	F
8	F	F	F	F

Active Clause

- The major clause is the clause on which we are focusing; all of the other clauses are minor clauses.
  - Typically each clause is treated in turn as a major clause
- Determination: Given a major clause c in predicate p, c determines p if the minor clauses have values so that changing the truth value of c changes the truth value of p.
  - Note that c and p do not have to have the same value.
- Example: p = a ∨ b

Active Clause Coverage (ACC)

- For each predicate p and each major clause c of p, choose minor clauses so that c determines p. TR has two requirements for each c: c evaluates to true and c evaluates to false.
- Example: p = a v b

	a	b
c = a	T	f
	F	f
c = b	f	T
	f	F

General Active Clause Coverage (GACC)

- The same as ACC, and it does not require the minor clauses have the same values when the major clause evaluates to true and false.
- Does GACC subsume predicate coverage?

Correlated Active Clause Coverage (CACC)

- The same as ACC, but it requires the entire predicate to be true for one value of the major clause and false for the other.
- Example: a ↔ b

CACC (2)

- Example: a ∧ (b ∨ c)

	a	b	c	a ∧ (b ∨ c)
1	T	T	T	T
2	T	T	F	T
3	T	F	T	T
5	F	T	T	F
6	F	T	F	F
7	F	F	T	F

Restricted Active Clause Coverage (RACC)

- The same as ACC, but it requires the minor clauses have the same values when the major clause evaluates to true and false.
- Example: a ∧ (b ∨ c)

	a	b	c	a ∧ (b ∨ c)
1	T	T	T	T
5	F	T	T	F
2	T	T	F	T
6	F	T	F	F
3	T	F	T	T
7	F	F	T	F

CACC vs RACC (1)

- Consider a system with a valve that might be either open or closed, and several modes, two of which are "operational" and "standby".
- Assume the following two constraints: (1) The valve must be open in "operational" and closed in all other modes; (2) The mode cannot be both "operational" and "standby" at the same time.
- Let a = "The valve is closed", b = "The system status is operational", and c = "The system status is standby". Then, the two constraints can be formalized as (1) ¬ a ↔ b; (2) ¬ (b ∧ c)

CACC vs RACC (2)

- Suppose that a certain action can be taken only if the valve is closed and the system status is in Operational or Standby, i.e., a ∧ (b ∨ c)

	a	b	c	(a ∧ b) ∨ c	Constraints violated
1	T	T	T	T	1 & 2
2	T	T	F	T	1
3	T	F	T	T	
4	T	F	F	F	
5	F	T	T	F	2
6	F	T	F	F	
7	F	F	T	F	1
8	F	F	F	F	1

Inactive Clause Coverage (ICC)

- A complementary criterion to ACC that ensures that the major clause that should NOT affect the predicate does NOT, in fact, affect the predicate.
- For each predicate p and each major clause c of p, choose minor clauses so that c does not determine p. TR has four requirements for each clause c: (1) c evaluates to true with p = true; (2) c evaluates to false with p = true; (3) c evaluates to true with p = false; and (4) c evaluates to false with p = true.

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GICC & RICC

- GICC does not require the values of the minor clauses to be the same when the major clause evaluates to true and false.
- RICC requires the values the minor clauses to be the same when the major clause evaluates to true and false.

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Making Active Clauses

- Let p be a predicate and c a clause. Let $p_{c=true}$ (or $p_{c=false}$) be the predicate obtained by replacing every occurrence of c with true (or false)
- The following expression describes the exact conditions under which the value of c determines the value of p:

$$p_c = p_{c=true} \oplus p_{c=false}$$

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Example (1)

- Consider $p = a \vee b$ and $p = a \wedge b$.

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Example (2)

- Consider $p = a \wedge b \vee a \wedge \neg b$.

Example (3)

- Consider p = a ∧ (b ∨ c).

Finding Satisfying Values

- How to choose values that satisfy a given coverage goal?

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Example (1)

- Consider p = (a ∨ b) ∧ c:

a	x < y
b	done
c	List.contains(str)

How to choose values to satisfy predicate coverage?

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Example (2)

	a	b	c	p
1	t	t	t	t
2	t	t	f	f
3	t	f	t	t
4	t	f	f	f
5	f	t	t	t
6	f	t	f	f
7	f	f	t	f
8	f	f	f	f

{1, 3, 5} × {2, 4, 6, 7, 8}

Example (3)

- Suppose we choose {1, 2}.

a	b	c
x = 3 y = 5	done = true	List = ["Rat", "cat", "dog"] str = "cat"
x = 0, y = 7	done = true	List = ["Red", "White"] str = "Blue"

Example (4)

- What about clause coverage?

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Example (5)

- What about *GACC*, *CACC*, and *RACC*?

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Reachability & Controllability

- Reachability: A test must be able to reach the predicate being tested.
- Controllability: Internal variables must be rewritten in terms of external input variables
- In general, finding values to satisfy reachability and controllability is undecidable.

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TriType

```
1 // Jeff Offut - Java version Feb 2003
2 // The old standby: classify triangles
3  import java.io.*;
4
5  class trityp
6  {
7     private static String[] triTypes = { "",    // Ignore 0.
8              "scalene", "isosceles", "equilateral", "not a valid
                    triangle");
9     private static String instructions = "This is the ancient
      TriTyp program.\nEnter three integers that represent the lengths
       of the sides of a triangle.\nThe triangle will be categorized as
       either scalene, isosceles, equilateral\nor invalid.\n";
10
11  public static void main (String[] argv)
12  {  // Driver program for trityp
13     int A, B, C;
14     int T;
16     System.out.println (instructions);
17     System.out.println ("Enter side 1: ");
18     A = getN();
19     System.out.println ("Enter side 2: ");
20     B = getN();
21     System.out.println ("Enter side 3: ");
22     C = getN();
23     T = Triang (A, B, C);
24
25     System.out.println ("Result is: " + triTypes [T]);
26  }
27
28  // ====================================

29  // The main triangle classification method
30  private static int Triang (int Side1, int Side2, int Side3)
31  {
32     int tri_out;
33
34     // tri_out is output from the routine:
35     //    Triang = 1 if triangle is scalene
36     //    Triang = 2 if triangle is isosceles
37     //    Triang = 3 if triangle is equilateral
38     //    Triang = 4 if not a triangle
```

```
39
40     // After a quick confirmation that it's a legal
41     // triangle, detect any sides of equal length
42     if (Side1 <= 0 || Side2 <= 0 || Side3 <= 0)
43     {
44        tri_out = 4;
45        return (tri_out);
46     }
48     tri_out = 0;
49     if (Side1 == Side2)
50        tri_out = tri_out + 1;
51     if (Side1 == Side3)
52        tri_out = tri_out + 2;
53     if (Side2 == Side3)
54        tri_out = tri_out + 3;
55     if (tri_out == 0)
56     {  // Confirm it's a legal triangle before declaring
57        // it to be scalene
58
59        if (Side1+Side2 <= Side3 || Side2+Side3 <= Side1 ||
60            Side1+Side3 <= Side2)
61           tri_out = 4;
62        else
63           tri_out = 1;
64        return (tri_out);
65     }
67     /* Confirm it's a legal triangle before declaring  */
68     /* it to be isosceles or equilateral  */
69
70     if (tri_out > 3)
71        tri_out = 3;
72     else if (tri_out == 1 && Side1+Side2 > Side3)
73        tri_out = 2;
74     else if (tri_out == 2 && Side1+Side3 > Side2)
75        tri_out = 2;
76     else if (tri_out == 3 && Side2+Side3 > Side1)
77        tri_out = 2;
78     else
79        tri_out = 4;
80     return (tri_out);
81  } // end Triang
```

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Predicates

```
42: (Side1 <= 0 || Side2 <= 0 || Side3 <= 0)
49: (Side1 == Side2)
51: (Side1 == Side3)
53: (Side2 == Side3)
55: (triOut == 0)
59: (Side1+Side2 <= Side3 || Side2+Side3 <= Side1 ||
       Side1+Side3 <= Side2)
70: (triOut > 3)
72: (triOut == 1 && Side1+Side2 > Side3)
74: (triOut == 2 && Side1+Side3 > Side2)
76: (triOut == 3 && Side2+Side3 > Side1)
```


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Reachability

```
42: True
49: P1 = s1>0 && s2>0 && s3>0
51: P1
53: P1
55: P1
59: P1 && triOut = 0
62: P1 && triOut = 0
      && (s1+s2 > s3) && (s2+s3 > s1) && (s1+s3 > s2)
70: P1 && triOut != 0
72: P1 && triOut != 0 && triOut <= 3
74: P1 && triOut != 0 && triOut <= 3 && (triOut !=1 || s1+s2<=s3)
76: P1 && triOut != 0 && triOut <= 3 && (triOut !=1 || s1+s2<=s3)
     && (triOut !=2 || s1+s3<=s2)
78: P1 && triOut != 0 && triOut <= 3 && (triOut !=1 || s1+s2<=s3)
     && (triOut !=2 || s1+s3 <= s2) && (triOut !=3 || s2+s3 <= s1)
```

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Solving Internal Vars

At line 55, triOut has a value in the range (0 .. 6)

```
triOut = 0   s1!=s2   &&   s1!=s3   &&   s2!=s3
         1   s1=s2    &&   s1!=s3   &&   s2!=s3
         2   s1!=s2   &&   s1=s3    &&   s2!=s3
         3   s1!=s2   &&   s1!=s3   &&   s2=s3
         4   s1=s2    &&   s1!=s3   &&   s2=s3
         5   s1!=s2   &&   s1=s3    &&   s2=s3
         6   s1=s2    &&   s1=s3    &&   s2=s3
```


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Reduced Reachability

```
42: True
49: P1 = s1>0 && s2>0 && s3>0
51: P1
53: P1
55: P1
59: P1 && s1 != s2 && s2 != s3 && s2 != s3                    (triOut = 0)
62: P1 && s1 != s2 && s2 != s3 && s2 != s3                    (triOut = 0)
        && (s1+s2 > s3) && (s2+s3 > s1) && (s1+s3 > s2)
70: P1 && P2 = (s1=s2 || s1=s3 || s2=s3)                        (triOut != 0)
72: P1 && P2 && P3 = (s1!=s2 || s1!=s3 || s2!=s3)             (triOut <= 3)
74: P1 && P2 && P3 && (s1 != s2 || s1+s2<=s3)
76: P1 && P2 && P3 && (s1 != s2 || s1+s2<=s3)
    && (s1 != s3 || s1+s3<=s2)
78: P1 && P2 && P3 && (s1 != s2 || s1+s2<=s3)
    && (s1 != s3 || s1+s3<=s2) && (s2 != s3 || s2+s3<=s1)
```

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Predicate Coverage

		True				False			
	Predicate	A	B	C	EO	A	B	C	EO
P42:	(Side1 <= 0 || Side2 <= 0 || Side3 <= 0)	0	0	0	4	1	1	1	3
P49:	(Side1 == Side2)	1	1	1	3	1	2	2	3
P51:	(Side1 == Side3)	1	1	1	3	1	2	2	2
P53:	(Side2 == Side3)	1	1	1	3	2	1	2	2
P55:	(triOut == 0)	1	2	3	4	1	1	1	3
P59:	(Side1+Side2 <= Side3 || Side2+Side3 <= Side1 || Side1+Side3 <= Side2)	1	2	3	4	2	3	4	1
P70:	(triOut > 3)	1	1	1	3	2	2	3	2
P72:	(triOut == 1 && Side1+Side2 > Side3)	2	2	3	2	2	2	4	4
P74:	(triOut == 2 && Side1+Side3 > Side2)	2	3	2	2	2	4	2	4
P76:	(triOut == 3 && Side2+Side3 > Side1)	3	2	2	2	4	2	2	4

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Clause Coverage

		True				False			
	Predicate	A	B	C	EO	A	B	C	EO
P42:	(Side1 <= 0)	0	1	1	4	1	1	1	3
	(Side2 <= 0)	1	0	1	4	1	1	1	3
	(Side3 <= 0)	1	1	0	4	1	1	1	3
P59:	(Side1+Side2 <= Side3)	2	3	6	4	2	3	4	1
	(Side2+Side3 <= Side1)	6	2	3	4	2	3	4	1
	(Side1+Side3 <= Side2)	2	6	3	4	2	3	4	1
P72:	(triOut == 1)	2	2	3	2	2	3	2	2
	(Side1+Side2 > Side3)	2	2	3	2	2	2	5	4
P74:	(triOut == 2)	2	3	2	2	2	4	2	4
	(Side1+Side3 > Side2)	2	3	2	2	2	5	2	4
P76:	(triOut == 3)	3	2	2	2	1	2	1	4
	(Side2+Side3 > Side1)	3	2	2	2	5	2	2	4

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CACC Coverage

	Predicate	Clauses			A	B	C	EO
P42:	(Side1 <= 0)	T	f	f	0	1	1	4
	(Side2 <= 0)	F	f	f	1	1	1	3
	(Side3 <= 0)	f	T	f	1	0	1	4
		f	f	T	1	1	0	4
P59:	(Side1+Side2 <= Side3)	T	f	f	2	3	6	4
	(Side2+Side3 <= Side1)	F	f	f	2	3	4	1
	(Side1+Side3 <= Side2)	f	T	f	6	2	3	4
		f	f	T	2	6	3	4
P72:	(triOut == 1)	T	t	-	2	2	3	2
	(Side1+Side2 > Side3)	F	t	-	2	3	3	2
		t	F	-	2	2	5	4
P74:	(triOut == 2)	T	t	-	2	3	2	2
	(Side1+Side3 > Side2)	F	t	-	2	3	3	2
		t	F	-	2	5	2	4
P76:	(triOut == 3)	T	t	-	3	2	2	2
	(Side2+Side3 > Side1)	F	t	-	3	6	3	4
		t	F	-	5	2	2	4

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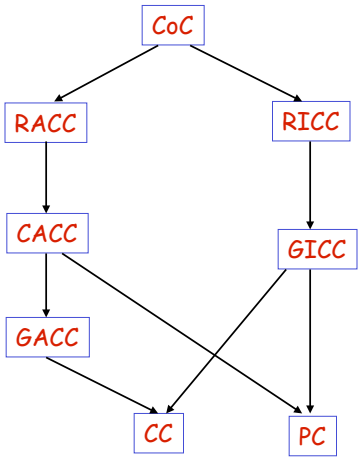
Subsumption



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Recap

- Predicate testing is about ensuring that each decision point is implemented correctly.
- If we flip the value of an active clause, we will change the value of the entire predicate.
- Different active clause criteria are defined to clarify the requirements on the values of the minor clauses.
- Reachability and controllability are two practical challenges that have to be met when we apply predicate testing to programs.