Intro to Software Testing

chapter 8.1

Semantic Logic Coverage

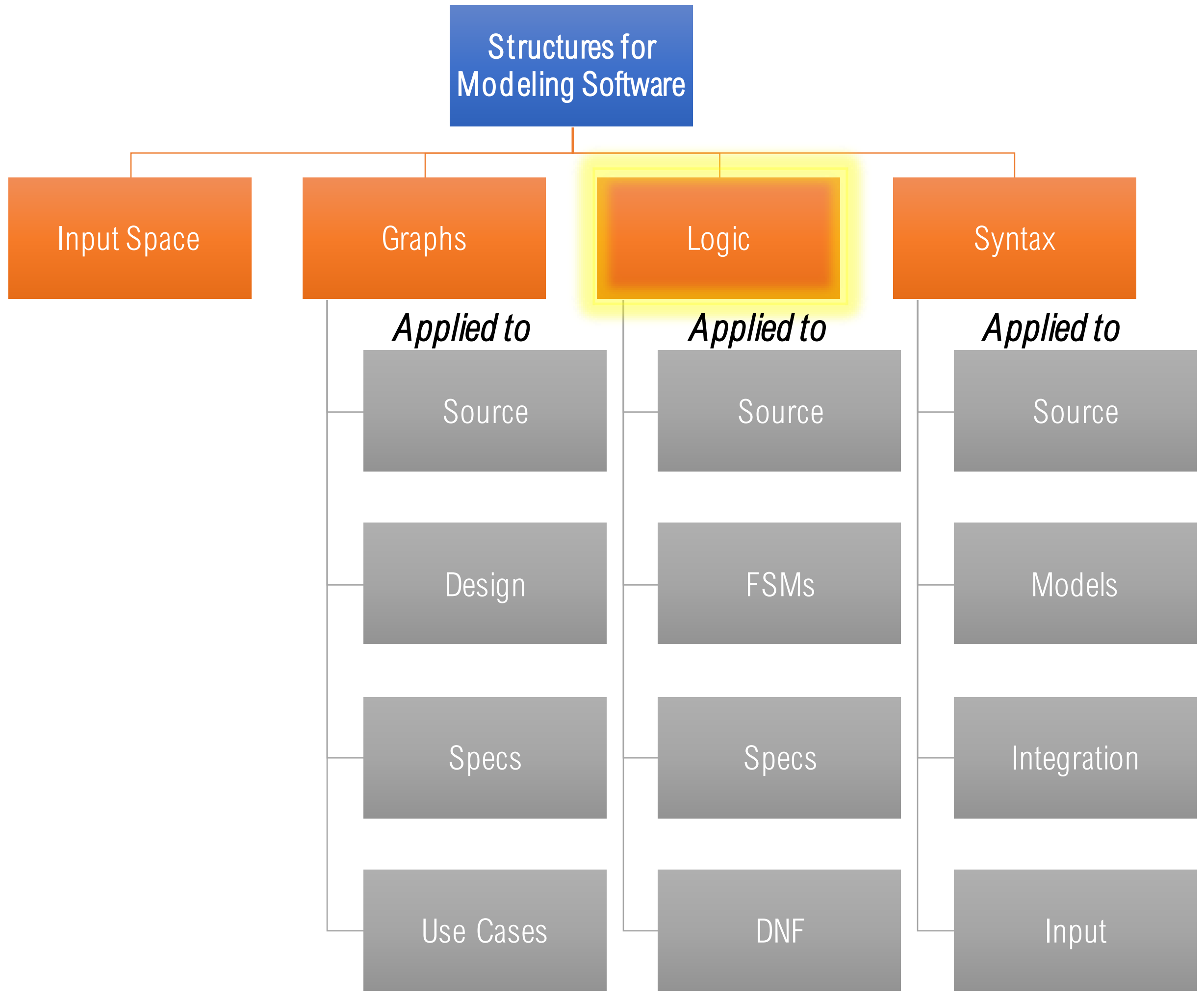
Dr. Brittany Johnson-Matthews

(Dr. B for short)

https://go.gmu.edu/SWE637

Adapted from slides by Jeff Offutt and Bob Kurtz

Logic Coverage



Semantic Logic Criteria

Logic expressions show up in many situations

Logic expressions can come from many sources

- Decisions in programs
- FSMs and state charts
- Requirements

Covering logic expressions is *required* by the US Federal Aviation Administration (FAA) for safety-critical software (regulation DO-178B/C)

- MCDC – Modified Condition/Decision Coverage

Tests are intended to choose some subset of the total number of *truth assignments* (e.g. true/false) to the expressions

Logic predicates and Clauses

Predicate: an expression that evaluates to a boolean value

Predicates can contain

- Boolean variables or function calls
- Non-Boolean variables that contain relational operators (<, >, ==, <=, >=, !=)
- Logical operators
  - $\neg$ *negation* operator (Java: !)
  - $\wedge$ *and* operator (Java: &&)
  - $\vee$ *or* operator (Java: ||)
  - $\oplus$ *exclusive or* operator (Java: ^)
  - $\rightarrow$ *implication* operator
  - $\leftrightarrow$ *equivalence* operator

Clause: a predicate without logical operators

Semantic Logic Criteria

$$(a < b) \vee f(z) \wedge d \vee (m >= n*o)$$

This predicate has four clauses:

- $(a < b)$: a relational expression
- $f(z)$: a boolean function
- d : a boolean variable
- $(m >= n*o)$: a relational expression

Predicate and Clause statistics

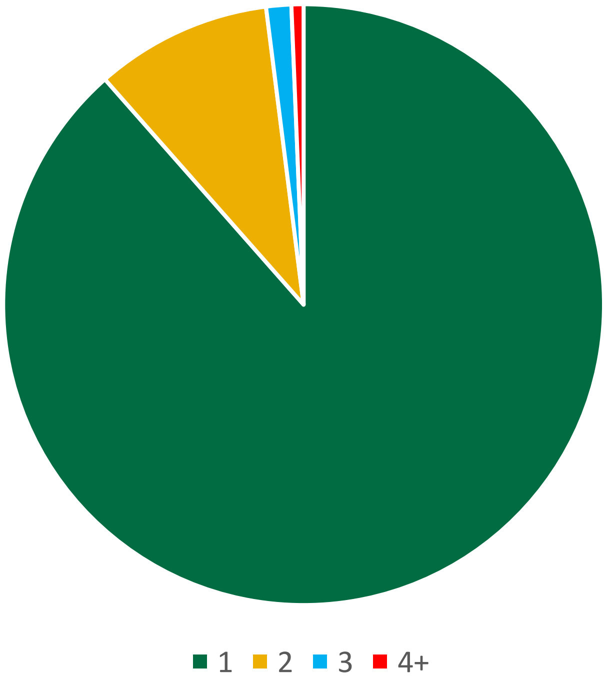
From a study of 63 open-source programs which contained > 400,000 predicates:

88.5% had only 1 clause

9.5% had 2 clauses

1.35% had 3 clauses

Only **0.65%** had 4 or more clauses



Predicate and Clause statistics

Predicates can be derived from:

- Decisions in program source code
- Guards on finite state machine transitions
- Decisions in UML activity graphs
- Requirements, both formal and informal
- SQL queries
- …and more

Logic Coverage Criteria

We use predicates in testing to:

- Develop a model of the software as one or more predicates
- Require tests to satisfy some combination of clauses

Abbreviations:

- ***P*** is a set of predicates
- ***p*** is a predicate in ***P***
- ***C*** is the set of clauses in ***P***
- ***Cp*** is the set of clauses in predicate ***p***
- ***c*** is a clause in ***C***

Predicate Coverage

The first (and simplest) criterion requires that each predicate be evaluated to both true and false

DEFINITION

Predicate Coverage (PC) – For each p in P, TR contains two requirements: p evaluates to true, and p evaluates to false

When predicates come from conditions on graph edges, this is equivalent to *edge coverage*

Predicate Coverage Example

$$(a < b) \vee d \wedge (m >= n*o)$$

Predicate must evaluate to true

Predicate must evaluate to false

Predicate Coverage Example

$$(a < b) \vee d \wedge (m >= n*o)$$

Predicate must evaluate to true

Example test case:

a=5, *b*=10, *d*=true, *m*=1, *n*=1, *o*=1

$= ((5 < 10) \vee \text{true}) \wedge (1 >= 1*1)$

$= (\text{true} \vee \text{true}) \wedge (\text{true})$

= true

Predicate Coverage Example

$$(a < b) \lor d \land (m >= n*o)$$

Predicate must evaluate to true

Example test case:
a=5, *b*=10, *d*=true, *m*=1, *n*=1, *o*=1
= ((5 < 10) ∨ true) ∧ (1 >= 1*1)
= (true ∨ true) ∧ (true)
= true

Predicate must evaluate to false

Example test case:
a=10, *b*=5, *d*=false, *m*=1, *n*=1, *o*=1
= ((10 < 5) ∨ false) ∧ (1 >= 1*1)
= (false ∨ false) ∧ (true)
= false

Clause Coverage

Predicate coverage does not require evaluation of all clauses, so a more complete criterion is clause coverage

DEFINITION

Clause Coverage (CC) – For each ***c*** in ***C***, ***TR*** contains two requirements: ***c*** evaluates to true, and ***c*** evaluates to false

Does clause coverage subsume predicate coverage?

Clause Coverage

Predicate coverage does not require evaluation of all clauses, so a more complete criterion is clause coverage

DEFINITION

Clause Coverage (CC) – For each c in C, TR contains two requirements: c evaluates to true, and c evaluates to false

Does clause coverage subsume predicate coverage?

No! Consider $a \vee b$, the clauses can be satisfied with (a=true, b=false) and (a=false, b=true) but the predicate is always true

Clause Coverage Example

$(a < b) \vee d \wedge (m >= n*o)$

Clauses must evaluate to true

In this case we arbitrarily choose to set all clauses to true at the same time, but that is not required

Clause Coverage Example

$$(a < b) \vee d \wedge (m >= n*o)$$

Clauses must evaluate to true

In this case we arbitrarily choose to set all clauses to true at the same time, but that is not required

$(a<b)$: a=5, b=10

d : true

$(m >= n*o)$: m=1, n=1, o=1

Clause Coverage Example

$(a < b) \vee d \wedge (m >= n*o)$

Clauses must evaluate to true

In this case we arbitrarily choose to set all clauses to true at the same time, but that is not required

$(a<b)$: a=5, b=10

d : true

$(m >= n*o)$: m=1, n=1, o=1

Clauses must evaluate to false

$(a<b)$: a=10, b=5

d : false

$(m >= n*o)$: m=1, n=2, o=2

Limitations of PC and CC

PC does not fully exercise all the clauses, especially with short-circuit evaluation

- $(a < b) \vee (c < d)$: if $(a<b)$ is true, then $(c<d)$ is not evaluated

CC does not always ensure PC (and so CC *does not subsume* PC)

- We can satisfy CC without causing the entire predicate to be both true and false
- That doesn't seem like something we want to do…

The simplest solution is to just test *all combinations*

Combinatorial Coverage

DEFINITION

Combinatorial Coverage (CoC) – For each ***p*** in ***P***, ***TR*** contains a test requirement for the clauses in C_p to evaluate to each possible combination of truth values

Combinatorial coverage is conceptually simple and complete, but very expensive

Results in *2^N tests*, where N is the number of clauses

Combinatorial Coverage Example

	a<b	d	m>=n*o	$((a < b) \vee d) \wedge (m >= n*o)$
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

Is there a better way?

Testing literature has lots of suggestions, some of them confusing or conflicting

The general idea is simple: *test each clause independently from the other clauses*

  But what does “independently” mean?

Active Clauses

Clause coverage has a weakness: the values don't always make a difference

- Consider the first test case for clause coverage where each clause was true
  $((5 < 10) \lor \textbf{true}) \land \mathbf{(1 >= 1*1)}$
- If we change *only one clause*, then only changing the last clause can change the evaluation of the predicate!
  - *Given these values*, the third clause *determines* the predicate

Active Clauses

To really test the results of a clause, the clause should be the determining factor to the value of the predicate

Determination: a selected clause $\boldsymbol{c_i}$ in predicate $\boldsymbol{p}$, called the *major clause*, determines $\boldsymbol{p}$ if and only if the values of the remaining *minor clauses* $\boldsymbol{c_j}$ are such that changing the value of $\boldsymbol{c_i}$ changes the value of $\boldsymbol{p}$

Such a condition makes clause $\boldsymbol{c_i}$ *active*

Active Clauses

Consider $p = a \vee b$	Consider $p = a \wedge b$
If a=false, then b determines p	If a=true, then b determines p
If b=false, then a determines p	If b=true, then a determines p

The goal is to find test cases for each selected major clause when the clause determines the value of the predicate

This is formalized in a *family of criteria* that have subtle but important differences

Active Clause Coverage Example

$$p = a \lor b$$

	a	b	$a \lor b$
1	T	T	T
2	T	F	T
3	F	T	T
4	F	F	F

Active Clause Coverage Example

$$p = a \vee b$$

	a	b	$a \vee b$
1	T	T	T
2	T	F	T
3	F	T	T
4	F	F	F

Select ***a*** as the major clause, then choose values for minor clause ***b*** such that changing ***a*** changes ***p***, so ***a*** determines ***p*** and ***a*** is the *active clause*

Active Clause Coverage Example

$$p = a \vee b$$

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

Select ***a*** as the major clause, then choose values for minor clause ***b*** such that changing ***a*** changes ***p***, so ***a*** determines ***p*** and ***a*** is the *active clause*

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

Select ***b*** as the major clause, then choose values for minor clause ***a*** such that changing ***b*** changes ***p***, so ***b*** determines ***p*** and ***b*** is the *active clause*

Calculating Determination

Finding values for minor clauses is easy for simple predicates, but hard for complex ones

Definitional approach:

- $p_{c=true}$ is predicate p with every occurrence of clause c replaced by **true**
- $p_{c=false}$ is predicate p with every occurrence of clause c replaced by false

To find values for minor clauses, *exclusive or* $p_{c=true}$ and $p_{c=false}$

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

- After solving, p_c describes exactly the values needed for c to determine p

Determination example

Consider $p = a \vee b$

Determination example

Consider $p = a \vee b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

Determination example

Consider $p = a \vee b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \vee b) \oplus (\text{false} \vee b)$

Determination example

Consider $p = a \vee b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \vee b) \oplus (\text{false} \vee b)$

$p_a = \text{true} \oplus b$

Determination example

Consider $p = a \vee b$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \vee b) \oplus (\text{false} \vee b)$$

$$p_a = \text{true} \oplus b$$

$$p_a = \neg b$$

Determination example

Consider $p = a \vee b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \vee b) \oplus (\text{false} \vee b)$

$p_a = \text{true} \oplus b$

$p_a = \neg b$

Thus a determines p when b=false

Determination example

Consider $p = a \wedge b$

Determination example

Consider $p = a \wedge b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

Determination example

Consider $p = a \wedge b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \wedge b) \oplus (\text{false} \wedge b)$

Determination example

Consider $p = a \wedge b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \wedge b) \oplus (\text{false} \wedge b)$

$p_a = b \oplus \text{false}$

Determination example

Consider $p = a \wedge b$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \wedge b) \oplus (\text{false} \wedge b)$$

$$p_a = b \oplus \text{false}$$

$$p_a = b$$

Determination example

Consider $p = a \wedge b$

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$p_a = (\text{true} \wedge b) \oplus (\text{false} \wedge b)$

$p_a = b \oplus \text{false}$

$p_a = b$

Thus a determines p when b = true

Determination example

Consider $p = a \vee (b \wedge c)$

Determination example

Consider $p = a \vee (b \wedge c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

Determination example

Consider $p = a \vee (b \wedge c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \vee (b \wedge c)) \oplus (\text{false} \vee (b \wedge c))$$

Determination example

Consider $p = a \vee (b \wedge c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \vee (b \wedge c)) \oplus (\text{false} \vee (b \wedge c))$$

$$p_a = \text{true} \oplus b \wedge c$$

Determination example

Consider $p = a \vee (b \wedge c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \vee (b \wedge c)) \oplus (\text{false} \vee (b \wedge c))$$

$$p_a = \text{true} \oplus b \wedge c$$

$$p_a = \neg(b \wedge c)$$

Determination example

Consider $p = a \vee (b \wedge c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \vee (b \wedge c)) \oplus (\text{false} \vee (b \wedge c))$$

$$p_a = \text{true} \oplus b \wedge c$$

$$p_a = \neg(b \wedge c)$$

$$p_a = \neg b \vee \neg c$$

Determination example

Consider $p = a \lor (b \land c)$

$$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$$

$$p_a = (\text{true} \lor (b \land c)) \oplus (\text{false} \lor (b \land c))$$

$$p_a = \text{true} \oplus b \land c$$

$$p_a = \lnot(b \land c)$$

$$p_a = \lnot b \lor \lnot c$$

Thus a determines p when b=false or c=false

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	$a \vee (b \wedge c)$	p_a	p_b	p_c
1	T	T	T	T			
2	T	T	F	T			
3	T	F	T	T			
4	T	F	F	T			
5	F	T	T	T			
6	F	T	F	F			
7	F	F	T	F			
8	F	F	F	F			

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	$a \vee (b \wedge c)$	p_a	p_b	
1	T	T	T	T			
2	T	T	F	T	✓		
3	T	F	T	T			
4	T	F	F	T			
5	F	T	T	T			
6	F	T	F	F	✓		
7	F	F	T	F			
8	F	F	F	F			

Select ***a*** as the major clause, then choose values for minor clauses ***b*** and ***c*** such that changing only ***a*** changes ***p***, thus ***a*** determines ***p***

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	$a \vee (b \wedge c)$	p_a	p_b	
1	T	T	T	T			
2	T	T	F	T	✓		
3	T	F	T	T	✓		
4	T	F	F	T			
5	F	T	T	T			
6	F	T	F	F	✓		
7	F	F	T	F	✓		
8	F	F	F	F			

Select ***a*** as the major clause, then choose values for minor clauses ***b*** and ***c*** such that changing only ***a*** changes ***p***, thus ***a*** determines ***p***

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

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

Select ***a*** as the major clause, then choose values for minor clauses ***b*** and ***c*** such that changing only ***a*** changes ***p***, thus ***a*** determines ***p***

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

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

Select ***b*** as the major clause, then choose values for minor clauses ***a*** and ***c*** such that changing only ***b*** changes ***p***, thus ***b*** determines ***p***

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	$a \lor (b \land c)$	p_a	p_b	p_c
1	T	T	T	T			
2	T	T	F	T	✓		
3	T	F	T	T	✓		
4	T	F	F	T	✓		
5	F	T	T	T		✓	
6	F	T	F	F	✓		
7	F	F	T	F	✓	✓	
8	F	F	F	F	✓		

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	$a \lor (b \land c)$	p_a		
1	T	T	T	T			
2	T	T	F	T	✓		
3	T	F	T	T	✓		
4	T	F	F	T	✓		
5	F	T	T	T		✓	✓
6	F	T	F	F	✓		✓
7	F	F	T	F	✓	✓	
8	F	F	F	F	✓		

Select ***c*** as the major clause, then choose values for minor clauses ***a*** and ***b*** such that changing only ***c*** changes ***p***, thus ***c*** determines ***p***

Tabular method for Determination

A truth table can sometimes be easier than logic evaluation

Row	a	b	c	a □ (b □ c)	p_a	p_b	
1	T	T	T	T			
2	T	T	F	T	✓(1)		
3	T	F	T	T	✓(2)		
4	T	F	F	T	✓(3)		
5	F	T	T	T		✓(4)	✓(5)
6	F	T	F	F	✓(1)		✓(5)
7	F	F	T	F	✓(2)	✓(4)	
8	F	F	F	F	✓(3)		

Instead of color-coding, we can tag the matching pairs with ID numbers

Active Clause Coverage

DEFINITION

Active Clause Coverage (ACC) – For each p in P and each major clause c_i in C_p, choose minor clauses c_j (j!=i) such that c_i determines p. TR has two requirements for c_i: c_i evaluates to true and c_i evaluates to false

MCDC Ambiguity

Do the minor clauses have to *retain the same values* while the major clause changes between true and false?

Example: given $p = a \vee (b \wedge c)$, if a is the major clause then when we vary the major clause:

a=true, *b*=false, *c*=true

a=false, *b*=false, *c*=false

Vary the major clause

Is this allowed, or not?

This question has caused confusion among safety-critical testers for years

Resolving the Ambiguity

Three possible answers (which leads to three different coverage criteria)

- Minor clauses *do not* need to be the same
- Minor clauses can *force the predicate* to become both true and false
- Minor clauses *do* need to be the same

General Active Clause Coverage

Minor clauses *do not* need to be the same

DEFINITION

General Active Clause Coverage (GACC) – For each p in P and each major clause c_i in C_p, choose minor clauses c_j (j!=i) such that c_i determines p. TR has two requirements for c_i: c_i evaluates to true and c_i evaluates to false. The values chosen for minor clauses c_j do not need to be the same when c_i is true as when c_i is false, and the value of p does not need to change.

It is possible to satisfy GACC without satisfying predicate coverage

Correlated Active Clause Coverage

Minor clauses can *force the predicate*

DEFINITION

Correlated Active Clause Coverage (CACC) – For each p in P and each major clause c_i in C_p, choose minor clauses c_j (j!=i) such that c_i determines p. TR has two requirements for c_i: c_i evaluates to true and c_i evaluates to false. The values chosen for minor clauses c_j must cause p to be true for one value of major clause c_i and false for the other value of c_i.

Subsumes predicate coverage

This is "masking MCDC"*

* DOT/FAA/AR-01/18 "An Investigation of Three Forms of the Modified Condition Decision Coverage (MCDC) Criterion", April 2001

Restrictive Active Clause Coverage

Minor clauses *do* need to be the same

DEFINITION

Restricted Active Clause Coverage (RACC) – For each p in P and each major clause c_i in C_p, choose minor clauses c_j (j!=i) such that c_i determines p. TR has two requirements for c_i: c_i evaluates to true and c_i evaluates to false. The values chosen for minor clauses c_j must must be the same when c_i is true as when c_i is false.

This is "unique-cause MCDC", the common interpretation of MCDC*

Often leads to *infeasible test requirements*

* DOT/FAA/AR-01/18 "An Investigation of Three Forms of the Modified Condition Decision Coverage (MCDC) Criterion", April 2001

Active Clause Comparison

To satisfy an active clause coverage criterion, pick a pair of tests where…

Criterion	Major clause determines p	Major clause changes value	Changing major clause changes p	Minor clauses are held the same
GACC	✓	✓		
CACC	✓	✓	✓	
RACC	✓	✓	✓	✓

GACC vs. CACC vs. RACC Example

Evaluation process

1. Select a major clause
2. Determine the conditions for the minor clauses where the major clause determines the predicate
3. For GACC, select a pair of conditions where the value of the major clause changes (the value of the minor clauses and *p* may or may not change)
4. For CACC, select a pair of conditions where the value of the major clause changes and the value of *p* changes (the minor clauses may or may not change)
5. For RACC, select a pair of conditions where the value of the major clause changes, the values of the minor clauses are held constant, and the value of p changes

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

1. Select a major clause -- *a*

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

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the XOR approach:

$p_a = p_{a=\text{true}} \oplus p_{a=\text{false}}$

$\text{p}_a = (\text{T} \wedge b) \vee (\neg \text{T} \wedge \neg b \wedge c) \oplus (\text{F} \wedge b) \vee (\neg \text{F} \wedge \neg b \wedge c)$

$\text{p}_a = b \vee (\text{F} \wedge \neg b \wedge c) \oplus \text{F} \vee (\text{T} \wedge \neg b \wedge c)$

$\text{p}_a = b \oplus \neg b \wedge c$

$p_a = b \vee c$

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the truth table approach:

	a	b	c	p=(a∧b)∨(¬a∧¬b∧c)	p_a
1	T	T	T	T	√1
2	T	T	F	T	
3	T	F	T	F	
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	
7	F	F	T	T	
8	F	F	F	F	

Select inputs such that ***a*** changes, ***b*** and ***c*** do not change, and ***p*** changes… thus ***a*** determines ***p*** when ***b*** ∧ ***c***

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the truth table approach:

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	✓1
2	T	T	F	T	✓2
3	T	F	T	F	
4	T	F	F	F	
5	F	T	T	F	✓1
6	F	T	F	F	✓2
7	F	F	T	T	
8	F	F	F	F	

Select inputs such that ***a*** changes, ***b*** and ***c*** do not change, and ***p*** changes… thus ***a*** determines ***p*** wh en ***b*** $\wedge \neg$***c***

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the truth table approach:

	a	b	c	p=(a∧b)∨(¬a∧¬b∧c)	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

Select inputs such that ***a*** changes, ***b*** and ***c*** do not change, and ***p*** changes… thus ***a*** determines ***p*** when ¬***b*** ∧ ***c***

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the truth table approach:

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

Select inputs such that ***a*** changes, ***b*** and ***c*** do not change… but ***p*** DOES NOT change, thus ***a*** DOES NOT determines ***p*** when $\neg b \wedge \neg c$

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

2. Determine the conditions for the minor clauses where the major clause determines the predicate

Using the truth table approach:

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	✓1
2	T	T	F	T	✓2
3	T	F	T	F	✓3
4	T	F	F	F	
5	F	T	T	F	✓1
6	F	T	F	F	✓2
7	F	F	T	T	✓3
8	F	F	F	F	

$p_a = b \vee c$

GACC vs. CACC vs. RACC Example

To satisfy an active clause coverage criterion, pick a pair of tests where…

Criterion	Major clause determines p	Major clause changes value	Changing major clause changes p	Minor clauses are held the same
GACC	✓	✓		
CACC	✓	✓	✓	
RACC	✓	✓	✓	✓

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

3. For GACC, select a pair of conditions where the value of the major clause changes (the value of the minor clauses and *p* may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

GACC Pairs:
(1,5)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

3. For GACC, select a pair of conditions where the value of the major clause changes (the value of the minor clauses and *p* may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

GACC Pairs:
(1,5) or (1,6)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

3. For GACC, select a pair of conditions where the value of the major clause changes (the value of the minor clauses and *p* may or may not change)

	a	b	c	p=(a∧b)∨(¬a∧¬b∧c)	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

GACC Pairs: (1,5) or (1,6) or (1,7) okay because p does not need to change

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

3. For GACC, select a pair of conditions where the value of the major clause changes (the value of the minor clauses and *p* may or may not change)

	a	b	c	$p=(a\wedge b)\vee(\neg a\wedge\neg b\wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

GACC Pairs: any one of (1,5), (1,6), (1,7), (2,5), (2,6), (2,7), (3,5), (3,6), (3,7)

GACC vs. CACC vs. RACC Example

To satisfy an active clause coverage criterion, pick a pair of tests where…

Criterion	Major clause determines p	Major clause changes value	Changing major clause changes p	Minor clauses are held the same
GACC	✓	✓		
CACC	✓	✓	✓	
RACC	✓	✓	✓	✓

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

4. For CACC, select a pair of conditions where the value of the major clause changes and the value of *p* changes (the minor clauses may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

CACC Pairs:
(1,5)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

4. For CACC, select a pair of conditions where the value of the major clause changes and the value of p changes (the minor clauses may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

CACC Pairs:
(1,5) or (1,6)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

4. For CACC, select a pair of conditions where the value of the major clause changes and the value of *p* changes (the minor clauses may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

CACC Pairs:
(1,5) or (1,6)
but not (1,7) because p doesn't change!

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

4. For CACC, select a pair of conditions where the value of the major clause changes and the value of *p* changes (the minor clauses may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

CACC Pairs: any one of (1,5), (1,6), (2,5), (2,6) *but not (2,7)*

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

4. For CACC, select a pair of conditions where the value of the major clause changes and the value of *p* changes (the minor clauses may or may not change)

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

CACC Pairs: any one of (1,5), (1,6), (2,5), (2,6), (3,7) ***but not (3,5) or (3,6)***

GACC vs. CACC vs. RACC Example

To satisfy an active clause coverage criterion, pick a pair of tests where…

Criterion	Major clause determines p	Major clause changes value	Changing major clause changes p	Minor clauses are held the same
GACC	✓	✓		
CACC	✓	✓	✓	
RACC	✓	✓	✓	✓

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

5. For RACC, select a pair of conditions where the value of the major clause changes, the values of the minor clauses are held constant, and the value of p changes

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	✓1
2	T	T	F	T	✓2
3	T	F	T	F	✓3
4	T	F	F	F	
5	F	T	T	F	✓1
6	F	T	F	F	✓2
7	F	F	T	T	✓3
8	F	F	F	F	

RACC Pairs:
(1,5)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

5. For RACC, select a pair of conditions where the value of the major clause changes, the values of the minor clauses are held constant, and the value of p changes

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	✓1
2	T	T	F	T	✓2
3	T	F	T	F	✓3
4	T	F	F	F	
5	F	T	T	F	✓1
6	F	T	F	F	✓2
7	F	F	T	T	✓3
8	F	F	F	F	

RACC Pairs:
(1,5) or (2,6)

GACC vs. CACC vs. RACC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

5. For RACC, select a pair of conditions where the value of the major clause changes, the values of the minor clauses are held constant, and the value of p changes

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_a
1	T	T	T	T	√1
2	T	T	F	T	√2
3	T	F	T	F	√3
4	T	F	F	F	
5	F	T	T	F	√1
6	F	T	F	F	√2
7	F	F	T	T	√3
8	F	F	F	F	

RACC Pairs:
(1,5) or
(2,6) or
(3,7)

Inactive Clause Coverage

Taking the opposite approach – major clauses *do not affect* the predicates

DEFINITION

Inactive Clause Coverage (ICC) – For each p in P and each major clause c_i in C_p, choose minor clauses c_j (j!=i) such that c_i *does not* determine p. ***TR*** has four requirements for c_i: (1) c_i evaluates to true with p true, (2) c_i evaluates to false with p true, (3) c_i evaluates to true with p false, and (4) c_i evaluates to false with p false.

Why bother? It's useful for testing safety interlock systems to ensure that during certain circumstances a control variable does not have any effect on operation

General Inactive Clause Coverage

DEFINITION

General Inactive Clause Coverage (GICC) – For each $\boldsymbol{p}$ in $\boldsymbol{P}$ and each major clause $\boldsymbol{c}_i$ in $\boldsymbol{C}_p$, choose minor clauses $\boldsymbol{c}_j$ (j!=i) such that $\boldsymbol{c}_i$ *does not* determine $\boldsymbol{p}$. The values chosen for minor clauses $\boldsymbol{c}_j$ *do not* need to be the same when $\boldsymbol{c}_i$ is true as when $\boldsymbol{c}_i$ is false.

DEFINITION

Restricted Inactive Clause Coverage (RICC) – For each $\boldsymbol{p}$ in $\boldsymbol{P}$ and each major clause $\boldsymbol{c}_i$ in $\boldsymbol{C}_p$, choose minor clauses $\boldsymbol{c}_j$ (j!=i) such that $\boldsymbol{c}_i$ *does not* determine $\boldsymbol{p}$. The values chosen for minor clauses $\boldsymbol{c}_j$ *must be* the same when $\boldsymbol{c}_i$ is true as when $\boldsymbol{c}_i$ is false.

Inactive Clause Comparison

To satisfy an inactive clause coverage criterion, pick a pair of tests where…

Criterion	Major clause determines p	Major clause changes	Changing major clause changes p	Minor clauses are held the same
GICC	⌋	⎫	⌋	
RICC	⌋	⎫	⌋	⎫

By definition, if the major clause does not determine *p*, then changing the major clause will not change *p*

GICC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

Selecting clause c as the major clause

For GICC, select a pair of conditions where the major clause does not determine *p*, the value of the major clause changes, and the value of p does not change

	a	b	c	p=(a∧b)∨(¬a∧¬b∧c)	p_c
1	T	T	T	T	
2	T	T	F	T	
3	T	F	T	F	
4	T	F	F	F	
5	F	T	T	F	
6	F	T	F	F	
7	F	F	T	T	✓1
8	F	F	F	F	✓1

GICC Pairs:
(1,2)

c determines *p* for rows 7 and 8

GICC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

For GICC, select a pair of conditions where the major clause does not determine *p*, the value of the major clause changes, and the value of p does not change

	a	b	c	$p=(a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$	p_c
1	T	T	T	T	
2	T	T	F	T	
3	T	F	T	F	
4	T	F	F	F	
5	F	T	T	F	
6	F	T	F	F	
7	F	F	T	T	✓1
8	F	F	F	F	✓1

GICC Pairs:
one of
(1,2), (3,4),
(3,6), (5,4),
(5,6)

RICC Example

Consider $p = (a \wedge b) \vee (\neg a \wedge \neg b \wedge c)$

For RICC, select a pair of conditions where the major clause does not determine *p*, the value of the major clause changes, and the value of p does not change, and the minor clauses are the same

	a	b	c	p=(a∧b)∨(¬a∧¬b∧c)	p_c
1	T	T	T	T	
2	T	T	F	T	
3	T	F	T	F	
4	T	F	F	F	
5	F	T	T	F	
6	F	T	F	F	
7	F	F	T	T	✓1
8	F	F	F	F	✓1

RICC Pairs:
(1,2) or (3,4) or (5,6)

Infeasibility

Infeasible test requirements are common

Given $p = (a > b \wedge b > c) \vee (c > a)$

If $(a > b)$=**true** and $(b > c)$=**true**, then $(c > a)$=**true** is infeasible

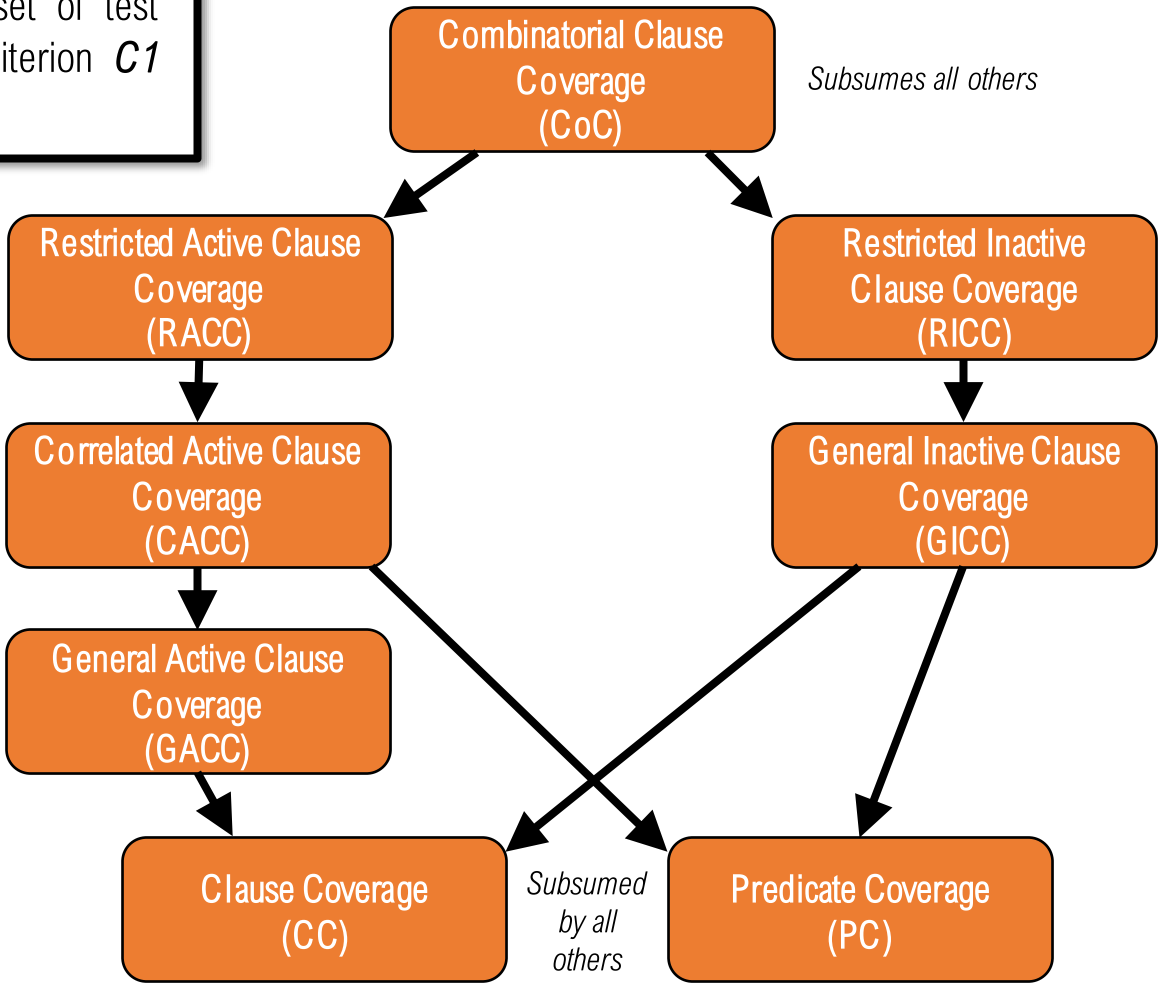
As with ISP and graph criteria, infeasible test requirements must be *recognized and ignored*

Recognizing infeasible test requirements is difficult, and in general *undecidable*

Logic Criteria Subsumption

DEFINITION

A test criterion *C1* **subsumes** *C2* if and only if every set of test cases that satisfies criterion *C1* also satisfies *C2*



Logic Coverage Summary

Predicates are often very simple – in practice, most have fewer than 3 clauses

- That's good news, because fewer clauses *significantly* simplifies testing
- With only one clause, predicate coverage is sufficient
- With 2 or 3 clauses, combinatorial coverage may be practical
- With more complex clauses, ACC and ICC criteria are practical

Testing safety-critical software often requires MCDC (or RACC or CACC)