Introduction to Software Testing
Chapter 8.1
Logic Coverage

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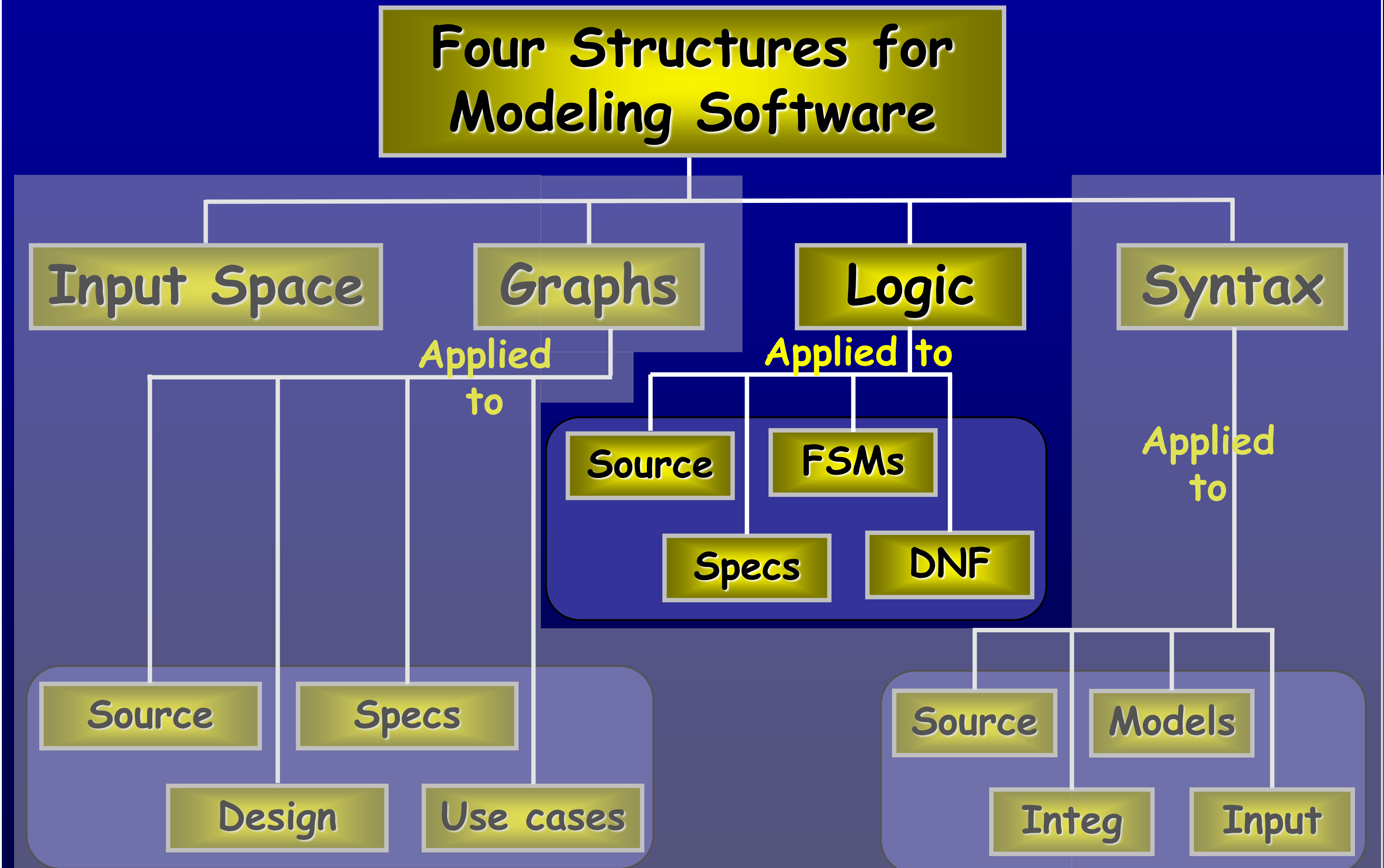
Ch. 8 : Logic Coverage



Semantic Logic Criteria (8.1)

- Logic expressions show up in many situations
- **Covering logic expressions** is required by the US Federal Aviation Administration for safety critical software
- Logical expressions can come from many sources
  - Decisions in programs
  - FSMs and statecharts
  - Requirements
- Tests are intended to choose some subset of the total number of truth assignments to the expressions

Logic Predicates and Clauses

- A *predicate* is an expression that evaluates to a boolean value
- Predicates can contain
  - boolean variables
  - non-boolean variables that contain >, <, ==, >=, <=, != (relational expression)
  - boolean function calls
- Internal structure is created by logical operators
  - $\neg$ – the *negation* operator
  - $\wedge$ – the *and* operator
  - $\vee$ – the *or* operator
  - $\rightarrow$ – the *implication* operator
  - $\oplus$ – the *exclusive or* operator
  - $\leftrightarrow$ – the *equivalence* operator
- A *clause* is a predicate with no logical operators

Example and Facts

- $(a < b) \vee f(z) \wedge D \wedge (m >= n*o)$ has four clauses:
  - $(a < b)$ – relational expression
  - $f(z)$ – boolean-valued function
  - D – boolean variable
  - $(m >= n*o)$ – relational expression
- Most predicates have few clauses
  - 88.5% have 1 clauses
  - 9.5% have 2 clauses
  - 1.35% have 3 clauses
  - Only .65% have 4 or more !

from a study of 63 open source programs, >400,000 predicates

- Sources of predicates
  - Decisions in programs
  - Guards in finite state machines
  - Decisions in UML activity graphs
  - Requirements, both formal and informal
  - SQL queries

Translating from English

- "I am interested in SWE 637 and CS 652"
- *course = swe637 OR course = cs652*

Humans have trouble translating from English to Logic

- "If you leave before 6:30 AM, take Braddock to 495, if you leave after 7:00 AM, take Prosperity to 50, then 50 to 495"
- $(time < 6{:}30 \rightarrow path = Braddock) \wedge (time > 7{:}00 \rightarrow path = Prosperity)$

- Hmm … this is incomplete !
- $(time < 6{:}30 \rightarrow path = Braddock) \wedge (time >= 6{:}30 \rightarrow path = Prosperity)$

Logic Coverage Criteria (8.1.1)

- We use predicates in testing as follows :
  - Developing a model of the software as one or more predicates
  - Requiring tests to satisfy some combination of clauses

- Abbreviations:
  - *P* is the set of predicates
  - *p* is a single predicate in *P*
  - *C* is the set of clauses in *P*
  - C_p is the set of clauses in predicate *p*
  - *c* is a single clause in *C*

Predicate and Clause Coverage

- The first (and simplest) two criteria require that each predicate (*decision*) and each clause (*condition*) be evaluated to both true and false

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 edges*, this is equivalent to edge coverage
- **PC does not evaluate all the clauses**, so …

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

Predicate Coverage Example

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

predicate coverage

Predicate = true

a = 5, b = 10, D = true, m = 1, n = 1, o = 1

$= (5 < 10) \lor true \land (1 >= 1*1)$

$= true \lor true \land TRUE$

= true

Predicate = false

a = 10, b = 5, D = false, m = 1, n = 1, o = 1

$= (10 < 5) \lor false \land (1 >= 1*1)$

$= false \lor false \land TRUE$

= false

Clause Coverage Example

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

Clause coverage

(a < b) = true	(a < b) = false	D = true	D = false
a = 5, b = 10	a = 10, b = 5	D = true	D = false

m >= n*o = true	m >= n*o = false
m = 1, n = 1, o = 1	m = 1, n = 2, o = 2

true cases

false cases

Two tests

1) a = 5, b = 10, D = true, m = 1, n = 1, o = 1

2) a = 10, b = 5, D = false, m = 1, n = 2, o = 2

Problems with PC and CC

- PC does not fully exercise all the clauses, especially in the presence of short circuit evaluation
- CC does not always ensure PC
  - That is, we can satisfy CC without causing the predicate to be both true and false
  - This is definitely not what we want !
- The simplest solution is to test all combinations …

Combinatorial Coverage

- CoC requires every possible combination
- Sometimes called Multiple Condition Coverage

Combinatorial Coverage (CoC) : For each p in P, TR has test requirements for the clauses in Cp to evaluate to each possible combination of truth values.

	a < b	D	m >= n*o	((a < b) ∨ D) ∧ (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

Combinatorial Coverage

- This is simple, neat, clean, and comprehensive …
- But quite expensive!
- 2^N tests, where N is the number of clauses
  - Impractical for predicates with more than 3 or 4 clauses
- The literature has lots of suggestions – some confusing
- The general idea is simple:

Test each clause independently from the other clauses

- Getting the details right is hard
- What exactly does "independently" mean ?
- The book presents this idea as "*making clauses active*" …

Active Clauses (8.1.2)

- Clause coverage has a weakness : The values do not always make a difference (in terms of true or false for the predicate)
- Consider the <u>first test</u> for clause coverage, which caused each clause to be true:
  - $((\underline{5 < 10}) \vee true) \wedge (1 >= 1*1)$
- Only the first clause *counts* ! (actually the first clause **doesn't** affect the predicate value)
- To really test the results of a clause, the clause should be the determining factor in <u>the value of the predicate</u>

Determination **:**

You flip the clause, and the predicate changes value

A clause c_i in predicate *p*, called the *major clause*, *determines* *p* if and only if the values of the remaining *minor clauses* c_j are such that changing c_i changes the value of *p*

- This is considered to *make the clause <u>active</u>*

Determining Predicates

$P = A \vee B$

if B = *true*, p is always true.

so if B = *false*, A determines p.

if A = *false*, B determines p.

$P = A \wedge B$

if B = *false*, p is always false.

so if B = *true*, A determines p.

if A = *true*, B determines p.

- Goal : Find tests for each clause when the clause determines the value of the predicate
- This is formalized in a family of criteria that have subtle, but very important, differences

Active Clause Coverage

<u>Active Clause Coverage (ACC)</u> : For each *p* in *P* and each major clause c_i in *Cp*, choose minor clauses c_j, *j != i*, so that c_i determines *p*. TR has two requirements for each c_i : c_i evaluates to true and c_i evaluates to false.

<u>p = a ∨ b</u>

1) a = true, b = false
2) a = false, b = false
3) a = false, b = true
4) ~~a = false, b = false~~

a is major clause

b is major clause

Duplicate

- This is a form of MCDC, which is <u>required by the FAA</u> for safety critical software
- Ambiguity : Do the minor clauses have to have the same values <u>when</u> the major clause is <u>true</u> and <u>false</u>?

Resolving the Ambiguity

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

Major clause : a

a = true, b = false, c = true

a = false, b = false, c = false

Is this allowed ?

- This question caused confusion among testers for years
- Considering this carefully leads to three separate criteria :
  - Minor clauses do not need to be the same (GACC)
  - Minor clauses do need to be the same (RACC)
  - Minor clauses force the predicate to become both true and false (CACC)

General Active Clause Coverage

General Active Clause Coverage (GACC) : For each p in P and each major clause c_i in Cp, choose minor clauses c_j, j != i, so that ci determines p. TR has two requirements for each ci : c_i evaluates to true and c_i evaluates to false. The values chosen for the minor clauses c_j do not need to be the same when c_i is true as when c_i is false, that is, $c_j(c_i = true) = c_j(c_i = false)$ for all c_j OR $c_j(c_i = true) \mathrel{!=} c_j(c_i = false)$ for all c_j.

- This is complicated !
- It is possible to satisfy GACC without satisfying predicate coverage
- We really want to cause predicates to be both true and false !

Restricted Active Clause Coverage

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

- This has been a common interpretation by aviation developers
- RACC often leads to infeasible test requirements
- There is no logical reason for such a restriction

Correlated Active Clause Coverage

Correlated Active Clause Coverage (CACC) : For each p in P and each major clause c_i in Cp, choose minor clauses c_j, j != i, so that c_i determines p. TR has two requirements for each c_i : c_i evaluates to true and c_i evaluates to false. The values chosen for the minor clauses c_j must cause p to be true for one value of the major clause c_i and false for the other, that is, it is required that $p(c_i = true) \mathrel{!=} p(c_i = false)$.

- A more recent interpretation
- Implicitly allows minor clauses to have different values
- Explicitly satisfies (subsumes) predicate coverage

CACC and RACC

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

major clause

P_a : b=true or c = true

CACC can be satisfied by choosing any of rows 1, 2, 3 AND any of rows 5, 6, 7 – a total of nine pairs

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

RACC can only be satisfied by row pairs (1, 5), (2, 6), or (3, 7)

Only three pairs

CACC and RACC

- Some logical expressions can be completely satisfied under CACC, but have infeasible test requirements under RACC
  - If dependency relationships exist among the clauses, i.e., some combinations of values for the clauses are prohibited

- 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.

- This leads to the following clause definitions:
  - a = *"The valve is closed"*
  - b = *"The system status is Operational"*
  - c = *"The system status is Standby"*

CACC and RACC

- Suppose that a certain action can be taken only if the valve is closed and the system status is either in *Operational or Standby*. *That is,*

  p = valve is closed AND (system status is Operational OR system status is Standby)

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

- The constraints above can be formalized as

  1. $\neg a \leftrightarrow b$
  2. $\neg(b \wedge c)$

RACC is infeasible for *a in this predicate*

Constraint 1 rules out the rows where *a and b have the same values, that is, rows 1, 2, 7, and 8.*

Constraint 2 rules out the rows where *b and c are both true, that is,* rows 1 and 5.

	a	b	c	$a \wedge (b \vee c)$	
~~1~~	~~T~~	~~T~~	~~T~~	~~T~~	violates constraints 1 & 2
~~2~~	~~T~~	~~T~~	~~F~~	~~T~~	violates constraint 1
3	T	F	T	T	
4	T	F	F	F	
~~5~~	~~F~~	~~T~~	~~T~~	~~F~~	violates constraint 2
6	F	T	F	F	
~~7~~	~~F~~	~~F~~	~~T~~	~~F~~	violates constraint 1
~~8~~	~~F~~	~~F~~	~~F~~	~~F~~	violates constraint 1

Inactive Clause Coverage (8.1.3)

- The active clause coverage criteria ensure that "major" clauses do affect the predicates
- Inactive clause coverage takes the opposite approach – major clauses do not affect the predicates

Inactive Clause Coverage (ICC) : For each p in P and each major clause c_i in Cp, choose minor clauses c_j, j != i, so that c_i does not determine p. TR has four requirements for each 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.

General and Restricted ICC

- Unlike ACC, the notion of correlation is not relevant
  - ci does not determine p, so cannot correlate with p
- Predicate coverage is always guaranteed

General Inactive Clause Coverage (GICC) : For each p in P and each major clause c_i in Cp, choose minor clauses c_j, j != i, so that c_i does not determine p. The values chosen for the minor clauses c_j do not need to be the same when c_i is true as when c_i is false, that is, $c_j(c_i = true) = c_j(c_i = false)$ for all c_j OR $c_j(c_i = true) \mathrel{!=} c_j(c_i = false)$ for all c_j.

Restricted Inactive Clause Coverage (RICC) : For each p in P and each major clause c_i in Cp, choose minor clauses c_j, j != i, so that c_i does not determine p. The values chosen for the minor clauses cj must be the same when c_i is true as when c_i is false, that is, it is required that $c_j(c_i = true) = c_j(c_i = false)$ for all c_j.

Infeasibility & Subsumption (8.1.4)

- Consider the predicate:

$$(a > b \wedge b > c) \vee c > a$$

- $(a > b) = true$, $(b > c) = true$, $(c > a) = true$ is <u>infeasible</u>

- As with graph-based criteria, <u>infeasible test requirements</u> have to be recognized and ignored

- Recognizing <u>infeasible test requirements</u> is hard, and in general, undecidable

- Software testing is <u>inexact</u> – <u>engineering</u>, <u>not science</u>

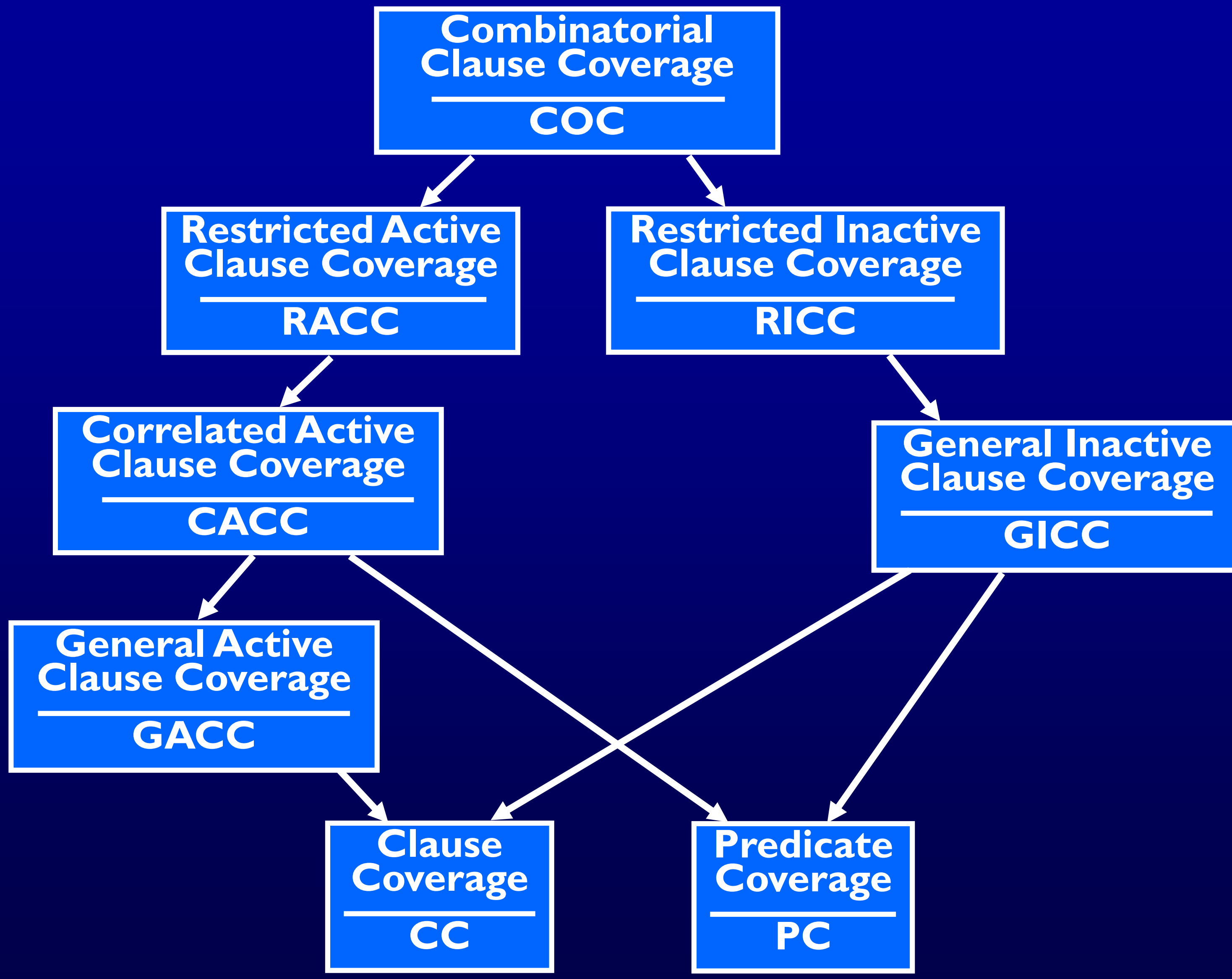
Infeasibility and Subsumption

- Infeasibility is often a problem because clauses are sometimes related to one another
- Consider

  while (i < n && a[i] != 0) {*do something to a[i]*}

  // to avoid evaluating a[i] if i is out of range
- *Clearly, it is not going to be possible to develop a test case where i < n is false and a[i] != 0 is true*
- In principle, the issue of infeasibility for clause and predicate criteria is no different from that for graph criteria
  - In both cases, the solution is to satisfy test requirements that are feasible, and then decide how to treat infeasible test requirements
  - The simplest solution is to simply ignore infeasible requirements, which usually does not affect the quality of the tests
  - However, a better solution for some infeasible test requirements is to consider the counterparts of the requirements in a subsumed coverage criterion (similar to that of best-effort touring in Chapter 2)

Logic Criteria Subsumption



Making Clauses Determine a Predicate

(8.1.5)

- Finding values for minor clauses c_j is easy for simple predicates
- But how to find values for more complicated predicates ?
- Definitional approach:
  - $p_{c=true}$ is predicate p with every occurrence of c replaced by *true*
  - $p_{c=false}$ is predicate p with every occurrence of c replaced by *false*
- To find values for the minor clauses, connect $p_{c=true}$ and $p_{c=false}$ with exclusive *OR*

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

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

Examples

$p = a \vee b$

$$
\begin{aligned}
P_a &= P_{a=true} \oplus P_{a=false} \\
&= (true \vee b) \text{ XOR } (false \vee b) \\
&= true \text{ XOR } b \\
&= \neg b
\end{aligned}
$$

$p = a \wedge b$

$$
\begin{aligned}
P_a &= P_{a=true} \oplus P_{a=false} \\
&= (true \wedge b) \oplus (false \wedge b) \\
&= b \oplus false \\
&= b
\end{aligned}
$$

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

$$
\begin{aligned}
P_a &= P_{a=true} \oplus P_{a=false} \\
&= (true \vee (b \wedge c)) \oplus (false \vee (b \wedge c)) \\
&= true \oplus (b \wedge c) \\
&= \neg (b \wedge c) \\
&= \neg b \vee \neg c
\end{aligned}
$$

- **"*NOT b* $\vee$ *NOT c*" means either *b* or *c* can be false**
- **RACC requires the same choice for both values of *a*, CACC does not**

Repeated Variables

- The definitions in this chapter yield the same tests no matter how the predicate is expressed

- $(a \vee b) \wedge (c \vee b) == (a \wedge c) \vee b$

How do you know they are equivalent?

- $(a \wedge b) \vee (b \wedge c) \vee (a \wedge c)$
  – Only has 8 possible tests, not 64

Why? How do you know two a's, b's, and c's are equivalent to one a, b, and c?

- Use the simplest form of the predicate, and ignore contradictory truth table assignments

A More Subtle Example

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

$$\begin{aligned} p_a &= p_{a=true} \oplus p_{a=false} \\ &= ((true \wedge b) \vee (true \wedge \neg b)) \oplus ((false \wedge b) \vee (false \wedge \neg b)) \\ &= (b \vee \neg b) \oplus false \\ &= true \oplus false \\ &= true \end{aligned}$$

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

$$\begin{aligned} p_b &= p_{b=true} \oplus p_{b=false} \\ &= ((a \wedge true) \vee (a \wedge \neg true)) \oplus ((a \wedge false) \vee (a \wedge \neg false)) \\ &= (a \vee false) \oplus (false \vee a) \\ &= a \oplus a \\ &= false \end{aligned}$$

- ***a*** **always determines the value of this predicate**
- ***b*** **never determines the value – *b* is irrelevant ! (b is redundant)**

Subtle Examples

$p = a \leftrightarrow b$

$$p_a = p_{a=true} \oplus p_{a=false}$$
$$= (true \leftrightarrow b) \oplus (false \leftrightarrow b)$$
$$= b \oplus \neg b$$
$$= true$$

$p = a \wedge b \vee a \wedge \neg b$

$$p_b = p_{b=true} \oplus p_{b=false}$$
$$= (a \wedge true \vee a \wedge \neg true) \oplus (a \wedge false \vee a \wedge \neg false)$$
$$= (a \vee false) \oplus (false \vee a) = a \oplus a$$
$$= false$$

- "p_a is true" indicates that, for any value of b, a determines the value of p *without regard to the value for b*
- This means that for a predicate p where the p_c is the constant true, the ICC criteria are infeasible with respect to c
- Inactive clause coverage is likely to result in infeasible test requirements when applied to expressions that use equivalence or exclusive-or operators
- If a predicate p contains a clause c such that p_c evaluates to the constant false, the ACC criteria are infeasible with respect to the same choice. (i.e., the clause c is redundant which is a signal of something wrong with the predicate!)

Tabular Method for Determination

- The math sometimes gets complicated
- A truth table can sometimes be simpler
- Example

b & diffe to d

A ar va

Fi als of

For and valu

Likewise, for clause *c*, only one pair, TFT and TFF, cause *c* to determine the value of *p*

	a	b	c	$a \wedge (b \vee c)$	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	F		*	*
5	F	T	T	F	*		
6	F	T	F	F	*		
7	F	F	T	F	*		
8	F	F	F	F			

In sum, <u>three</u> separate pairs of rows can cause *a* to determine the value of *p*, and only <u>one</u> pair each for *b* and *c*

Logic Coverage Summary

- Predicates are often very simple—in practice, most have less than 3 clauses
  - In fact, most predicates only have one clause !
  - With only 1 clause, PC is enough
  - With 2 or 3 clauses, CoC is practical
  - Advantages of ACC and ICC criteria significant for large predicates
    - CoC is impractical for predicates with many clauses
- Control software often has many complicated predicates, with lots of clauses
- Question … why don't complexity metrics count the number of clauses in predicates?