Logic Coverage

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Covering Logic Expressions

- 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 tr uth assignments to the expressions

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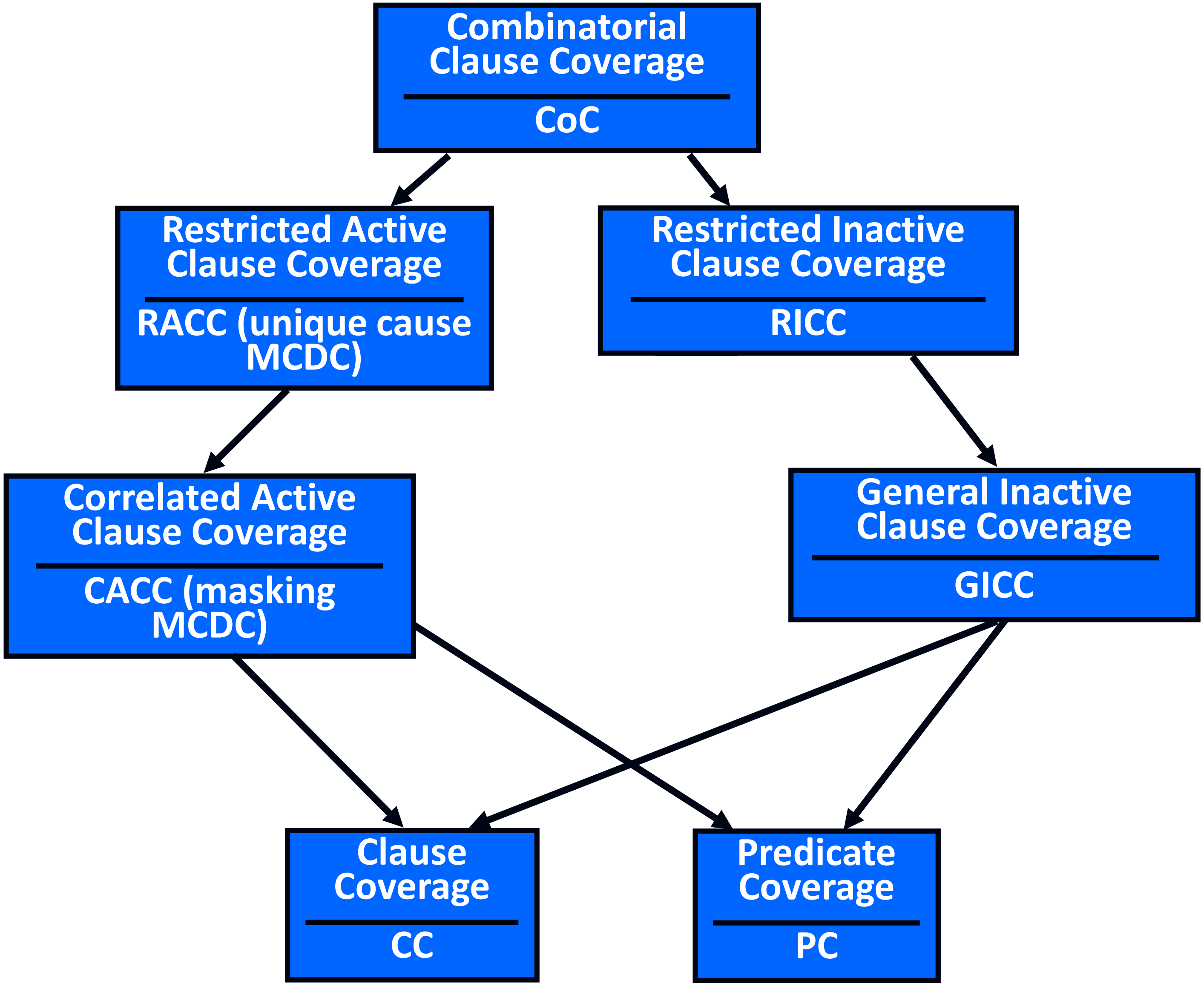
Logic Coverage Criteria Subsumption



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 >, <, ==, >=, <=, !=
  - 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

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Examples

- $(a < b) \vee f(z) \wedge D \wedge (m >= n*o)$
- Four clauses:
  - $(a < b)$ – relational expression
  - $f(z)$ – boolean-valued function
  - D – boolean variable
  - $(m >= n*o)$ – relational expression
- Most predicates have few clauses
- Sources of predicates
  - Decisions in programs
  - Guards in finite state machines
  - Decisions in UML activity graphs
  - Requirements, both formal and informal
  - SQL queries

Testing and Covering Predicates

- 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

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Predicate and Clause Coverage

- The first (and simplest) two criteria require that each predicate and each clause 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.

a.k.a. "decision coverage" in literature

- 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.

a.k.a. "condition coverage" in literature

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Predicate Coverage Example

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

predicate coverage

Predicate = true

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

= (5 < 10) ∨ true ∧ (1 >= 1*1)

= true ∨ true ∧ TRUE

= true

Predicate = false

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

= (10 < 5) ∨ false ∧ (1 >= 1*1)

= false ∨ false ∧ TRUE

= false

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Clause Coverage Example

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

Clause coverage

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

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

D = true
D = true

D = false
D = false

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

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

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
    - Ex. $x > 3 \rightarrow x > 1$
      - Two test cases { x=4, x=0} satisfy CC but not PC
- Condition/decision coverage is a hybrid metric composed by CC union PC

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 C_p to evaluate to each possible combination of truth values.

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

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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

- Clause coverage has a weakness
  - The values do not always make a difference to a whole predicate
- To really test the results of a clause, the clause should be the determining factor in the value of the predicate

Determination :

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 c_i active**

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Determining Predicates

$P = A \vee B$	$P = A \wedge B$
if *B = true*, *p* is always true.	if *B = false*, *p* is always false.
so if *B = false*, *A* determines *p*.	so if *B = true*, *A* determines *p*.
if *A = false*, *B* determines *p*.	if *A = true*, *B* determines *p*.

- Goal : Find tests for each clause when the clause determines the v alue of the predicate
- This is formalized in several criteria that have subtle, but very imp ortant, differences

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Active Clause Coverage

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, 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.

$p = a \vee b$

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 required by the Federal Avionics Administration (FAA) for safety critical software
- Ambiguity : Do the minor clauses have to have the same values when the major clause is true and false?

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Resolving the Ambiguity

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

Major clause : a

a = true, b = false, c = true

a = false, b = false, c = fal…

c = false

Is this allowed ?

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

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 c_j <u>must be the same</u> 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 of MCDC by aviation developers
  - Often called "unique-cause MCDC"
- RACC often leads to <u>infeasible</u> test requirements

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Correlated Active Clause Coverage

Correlated Active Clause Coverage (CACC) : For each p in P and each major clause ci 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 $p(c_i = true)$!= $p(c_i = false)$.

- A more recent interpretation
  - Also known as "Masking MCDC"
- 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
5	F	T	T	F
6	F	T	F	F
7	F	F	T	F

major clause

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
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

major clause

RACC can only be satisfied by one of the three pairs above

Inactive Clause Coverage

- 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, $j \neq i$, 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.

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General and Restricted ICC

- Unlike ACC, the notion of correlation is not relevant
  - c_i 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, $j \mathrel{!}= i$, 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, $j \mathrel{!}= i$, so that c_i does not determine *p*. The values chosen for the minor clauses c_j 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.

Modified condition/decision coverage (MCDC)

- Standard requirement for safety critical systems such as avioni cs and automotive (e.g., DO 178B/C, ISO26262)
- Modified condition/decision coverage (MCDC) requires
  - Satisfying CC and DC, and
  - every condition in a decision should be shown to **<u>independently</u>** affect that decision's outcome
- Example: C = A || B
  - Which test cases are necessary to satisfy
    - Condition coverage
    - Decision coverage
    - Condition/decision coverage
    - MCDC coverage

	A	B	C
TC1	T	T	T
TC2	T	F	T
TC3	F	T	T
TC4	F	F	F

Minimum Testing to Achieve MCDC [Chilenski and Miller'94]

- For C = A && B,
  - All conditions (i.e., A and B) should be true so that decision (i.e., C) becomes true
    - 1 test case required
  - Each and every input should be exclusively false so that decision becomes false.
    - 2 (or n for n-ary and) test cases required

	A	B	C
TC1	T	T	T
TC2	T	F	F
TC3	F	T	F
TC4	F	F	F

- For C= A || B
  - All conditions (i.e., A and B) should be false so that decision (i.e., C) becomes false
    - 1 test case required
  - Each and every input should be exclusively true so that decision becomes true.
    - 2 (or n for n-ary or) test cases required

	A	B	C
TC1	T	T	T
TC2	T	F	T
TC3	F	T	T
TC4	F	F	F

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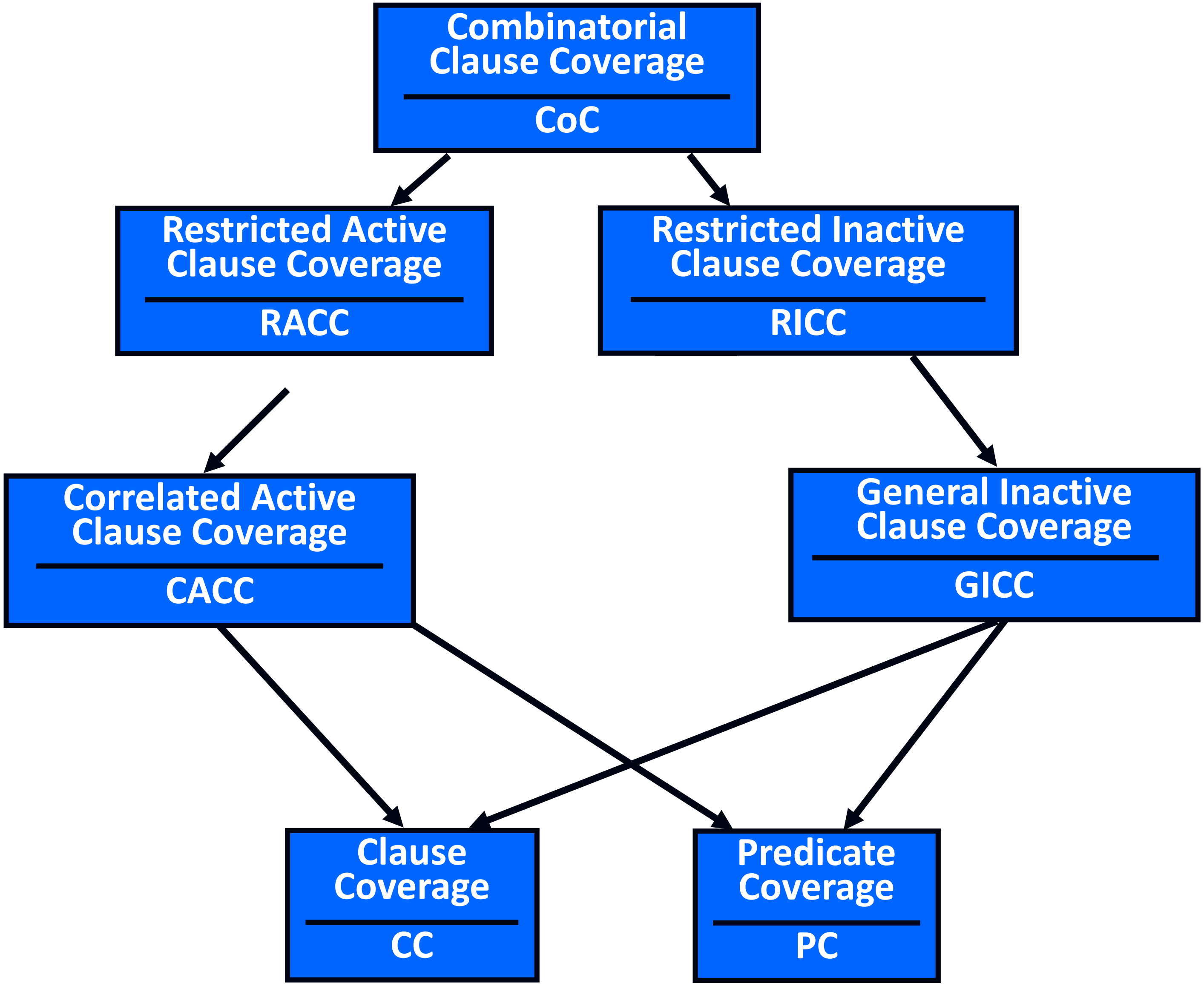

Making Clauses Determine a Predicate

- 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 deter mine p
- Note that we have to calculate $\neg p_c \wedge$ p=true and/or $\neg p_c \wedge$ p=false to get values for minor clauses for Inactive Coverage Criteria

Examples

$p = a \vee b$

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

$= (true \vee b)$ XOR $(false \vee b)$

$=$ true XOR b

$= \neg b$

$p = a \wedge b$

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

$= (true \wedge b) \oplus (false \wedge b)$

$= b \oplus false$

$= b$

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

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

$= (true \vee (b \wedge c)) \oplus (false \vee (b \wedge c))$

$= true \oplus (b \wedge c)$

$= \neg (b \wedge c)$

$= \neg b \vee \neg c$

- "*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

A More Subtle Example

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

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

$= ((true \wedge b) \vee (true \wedge \neg b)) \oplus ((false \wedge b) \vee (false \wedge \neg b))$

$= (b \vee \neg b) \oplus false$

$= true \oplus false$

$= true$

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

$p_b = p_{b=true} \oplus p_{b=false}$

$= ((a \wedge true) \vee (a \wedge \neg true)) \oplus ((a \wedge false) \vee (a \wedge \neg false))$

$= (a \vee false) \oplus (false \vee a)$

$= a \oplus a$

$= false$

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

Infeasible Test Requirements

- Consider the predicate:

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

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

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

- Recognizing infeasible test requirements is hard, and in general, undecidable

Example

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

	a	b	c	p	p_a	p_b	p_c
1	T	T	T	T	T	F	T
2	T	T	F	F	F	T	T
3	T	F	T	T	T	F	F
4	T	F	F	T	T	T	F
5	F	T	T	F	T	F	F
6	F	T	F	F	F	F	F
7	F	F	T	F	T	F	F
8	F	F	F	F	T	F	F

- Conditions under which each of the clauses determines p
  - p_a: $(\neg b \vee c)$
  - p_b: $a \wedge \neg c$
  - p_c: $a \wedge b$

- All pairs of rows satisfying CACC
  - a: {1,3,4} x {5,7,8}, b: {(2,4)}, c:{(1,2)}
- All pairs of rows satisfying RACC
  - a: {(1,5),(3,7),(4,8)}
  - Same as CACC pairs for b, c
- GICC
  - a: {(2,6)} for p=F, no feasible pair for p=T
  - b: {5,6}x{7,8} for p=F, {(1,3) for p=T
  - c: {5,7}x{6,8} for p=F, {(3,4)} for p=T
- RICC
  - a: same as GICC
  - b: {(5,7),(6,8)} for p=F, {(1,3)} for p=T
  - c: {(5,6),(7,8)} for p=F, {(3,4)} for p=T

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 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?