Introduction to Software Testing
Chapter 3.1, 3.2
Logic Coverage

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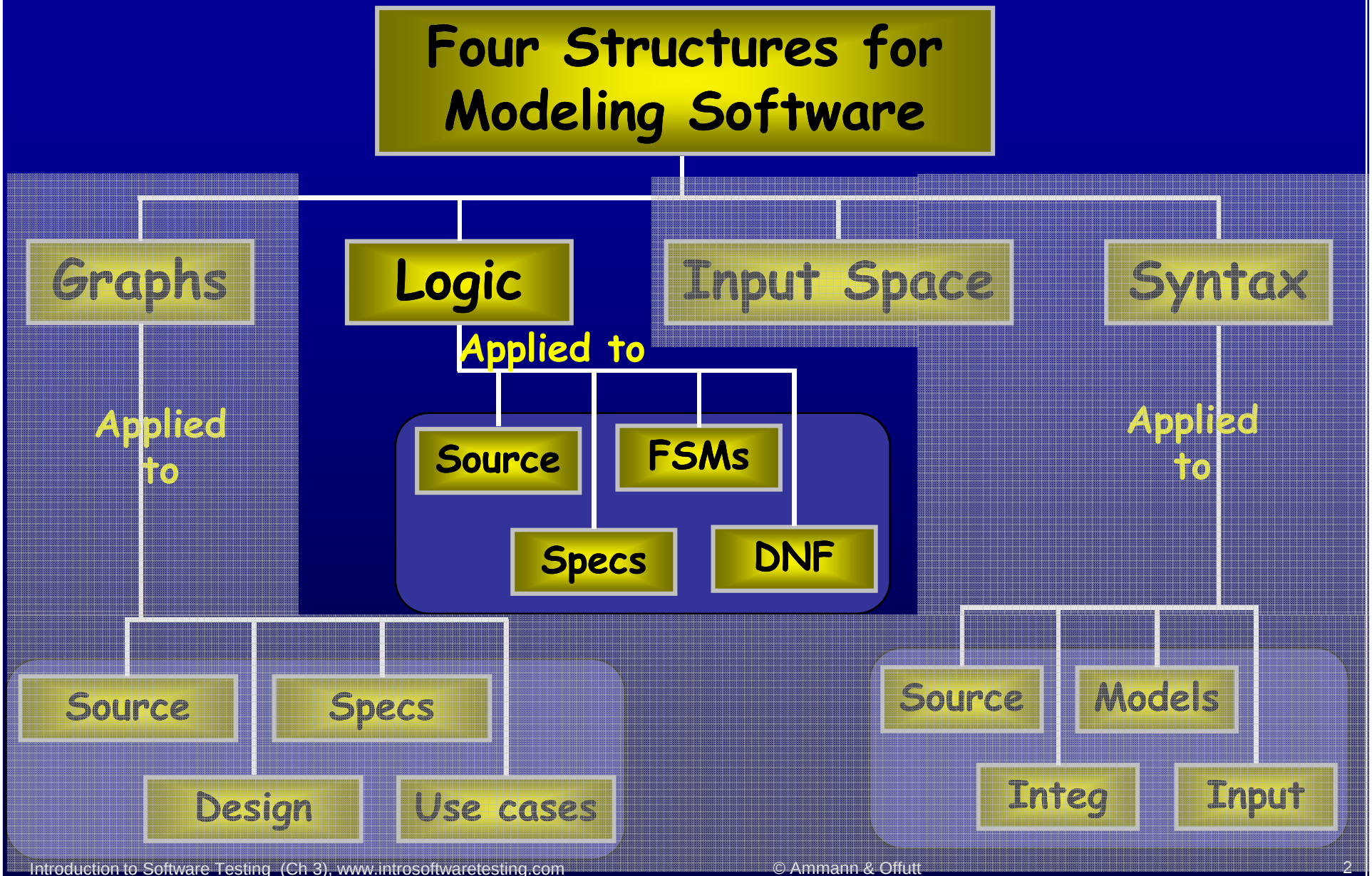
Ch. 3 : Logic Coverage



Covering Logic Expressions (3.1)

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

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
  - It would be nice to quantify that claim!
- 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"**
- $time < 6{:}30 \rightarrow path = Braddock \vee time > 7{:}00 \rightarrow path = Prosperity$
- **Hmm … this is incomplete !**
- $time < 6{:}30 \rightarrow path = Braddock \vee time >= 6{:}30 \rightarrow path = Prosperity$

Testing and Covering Predicates (3.2)

- **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 and each clause be evaluated to both true and false**

<u>Predicate Coverage (PC)</u> : 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 …**

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

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

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

$= \text{true} \vee \text{true} \wedge \text{TRUE}$

= true

Predicate = false

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

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

$= \text{false} \vee \text{false} \wedge \text{TRUE}$

= false

Clause Coverage Example

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

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

false cases

true 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 <u>not</u> 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

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

<u>Determination</u> : **A clause C_i in predicate *p*, called the <u>major clause</u>, <u>determines</u> *p* if and only if the values of the remaining <u>minor clauses</u> C_j are such that changing C_i changes the value of *p***

- **This is considered to *make the clause active***

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 several criteria that have subtle, but very important, differences**

Active Clause Coverage

Active Clause Coverage (ACC) : For each *p* in *P* and each major clause *ci* in *Cp*, choose minor clauses *cj*, *j* != *i*, so that *ci* determines *p*. TR has two requirements for each *ci* : *ci* evaluates to true and *ci* 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 FAA for safety critical software
- Ambiguity : Do the minor clauses have to have the same values when the major clause is true and false?

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
  - Minor clauses do need to be the same
  - Minor clauses force the predicate to become both true and false

General Active Clause Coverage

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

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

Restricted Active Clause Coverage

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

- **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

<u>Correlated Active Clause Coverage (CACC)</u> : For each *p* in *P* and each major clause *ci* in *Cp*, choose minor clauses *cj*, *j* != *i*, so that *ci* determines *p*. TR has two requirements for each *ci*: *ci* evaluates to true and *ci* evaluates to false. The values chosen for the minor clauses *cj* must <u>cause *p* to be</u> true for one value of the major clause *ci* and false for the other, that is, it is required that *p(ci = true) != p(ci = 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
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 <u>do affect</u> the predicates**
- **Inactive clause coverage takes the opposite approach – major clauses <u>do not affect</u> the predicates**

<u>Inactive Clause Coverage (ICC)</u> : For each *p* in *P* and each major clause *ci* in *Cp*, choose minor clauses *cj*, *j* != *i*, so that *ci* <u>does not</u> determine *p*. TR has <u>four</u> requirements for each *ci*: (1) *ci* evaluates to true with *p* true, (2) *ci* evaluates to false with *p* true, (3) *ci* evaluates to true with *p* false, and (4) *ci* evaluates to false with *p* false.

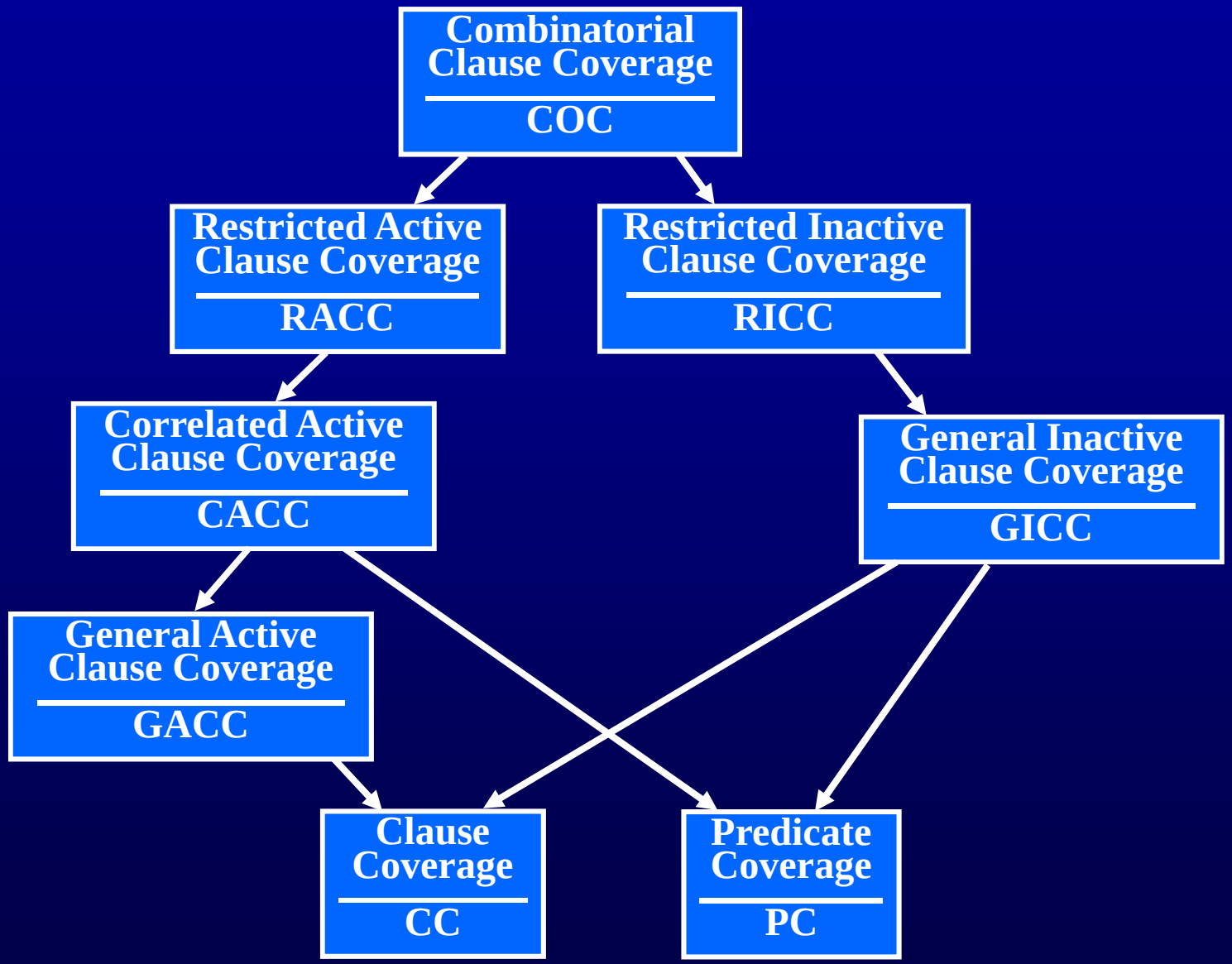
General and Restricted ICC

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

<u>General Inactive Clause Coverage (GICC)</u> : For each *p* in *P* and each major clause *ci* in *Cp*, choose minor clauses *cj*, *j != i*, so that *ci* <u>does not</u> determine *p*. The values chosen for the minor clauses *cj* <u>do not</u> need to be the same when *ci* is true as when *ci* is false, that is, *cj(ci = true) = cj(ci = false)* for all *cj* OR *cj(ci = true) != cj(ci = false)* for all *cj*.

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

Logic Coverage Criteria Subsumption



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:
  - *pc=true* is predicate *p* with every occurrence of *c* replaced by *true*
  - *pc=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

$p = a \vee b$

$p_a = p_{a=true} \oplus p_{a=false}$
$= (true \vee b)$ **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

Repeated Variables

- **The definitions in this chapter yield the same tests no matter how the predicate is expressed**
- **$(a \vee b) \wedge (c \vee b) == (a \wedge c) \vee b$**
- **$(a \wedge b) \vee (b \wedge c) \vee (a \wedge c)$**
  - **Only has 8 possible tests, not 64**
- **Use the simplest form of the predicate, and ignore contradictory truth table assignments**

A More Subtle Example

$$\underline{p = (a \wedge b) \vee (a \wedge \neg b)}$$

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

$$\underline{p = (a \wedge b) \vee (a \wedge \neg b)}$$

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

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

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**

- **Software testing is inexact – engineering, not science**

Logic Coverage Summary

- **Predicates are often very simple**
  - **PC may be enough**
  - **COC is practical**
- **Control software often has many complicated predicates, with lots of clauses**
- **Question … why don't complexity metrics count the number of clauses in predicates?**