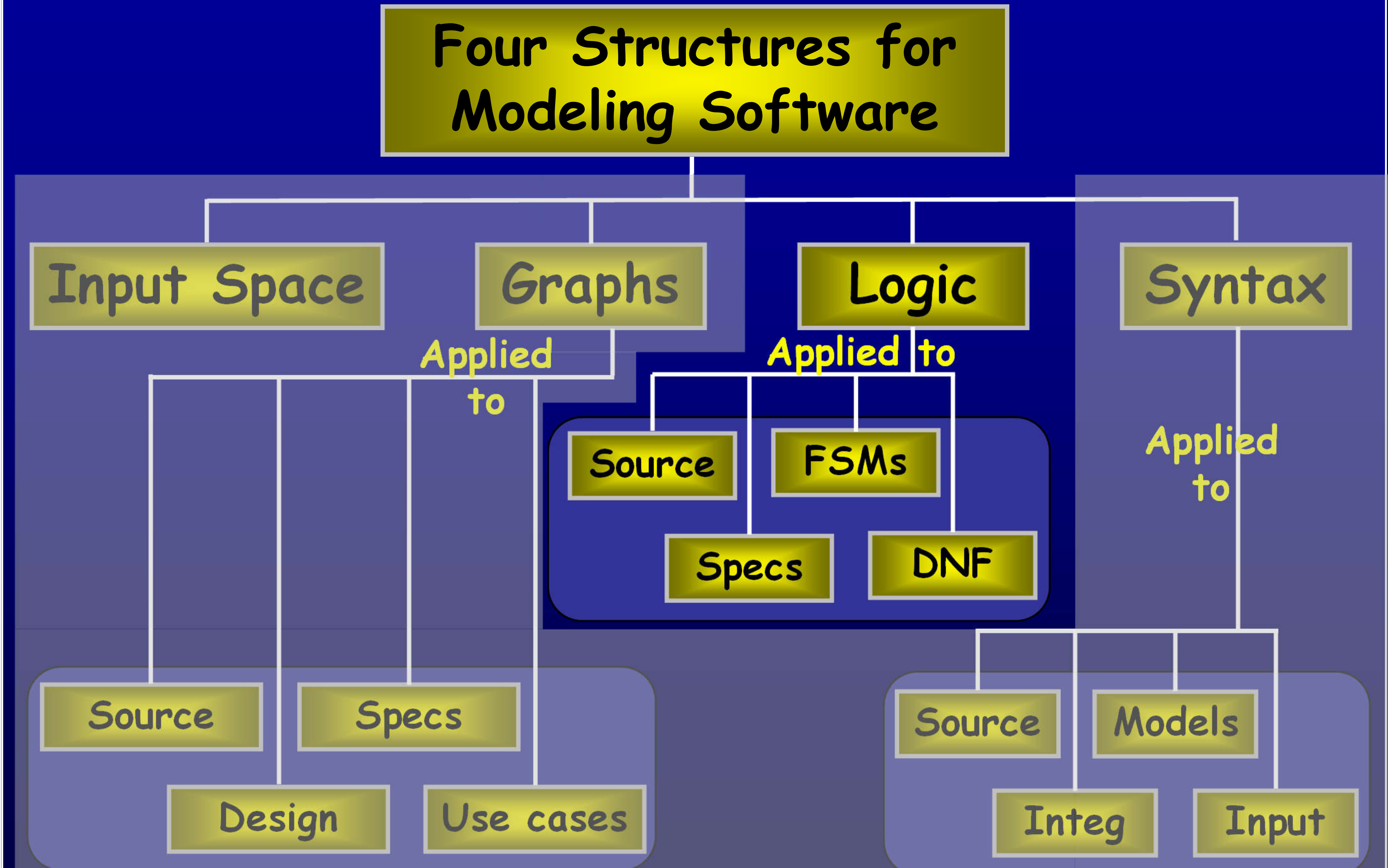
CS 5154

Logic Coverage

Owolabi Legunsen

The following are modified versions of the publicly-available slides for Chapter 8 in the Ammann and Offutt Book, "Introduction to Software Testing"
(http://www.cs.gmu.edu/~offutt/softwaretest)

Logic Coverage



Semantic Logic Criteria

- 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

- *Predicate* : an expression that evaluates to a boolean value
- Predicates can contain
  - boolean variables
  - non-boolean variables that are related by >, <, ==, >=, <=, !=
  - function calls that return booleans
- 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

- $(a < b) \lor f(z) \land D \land (m >= n*o)$ 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 clause
  - 9.5% have 2 clauses
  - 1.35% have 3 clauses
  - Only 0.65% have 4 or more !

from a study of non-FAA, 63 open-source programs with >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 CS 5154 and CS 5150"
- *course == cs5154 OR course == cs5150*

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

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

- Abbreviations that we will use in later slides:
  - *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 evaluate 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.

- If predicates are conditions on edges, PC 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

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

predicate coverage

Predicate = true

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

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

= $true \vee true \wedge TRUE$

= true

Predicate = false

a = 5, b = 10, D = true, m = 0, n = 1, o = 1

= $(5 < 10) \vee true \wedge (0 >= 1*1)$

= $true \vee true \wedge FALSE$

= 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
  - Example: $a \vee b$
  - 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 C_p 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

- CoC 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
- Consider the first test for clause coverage, which caused each clause to be true:
  - $((5 < 10) \vee true) \wedge (1 >= 1*1)$
  - Only the last clause *counts* !
- 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 active*

Determining Predicates

$P = A \lor B$	$P = A \land B$
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 value of the predicate
- This goal is formalized in a family of criteria that have subtle, but very important, differences

Active Clause Coverage

Active Clause Coverage (ACC) : 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.

$p = a \vee b$

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

a is major clause (rows 1 and 2)

b is major clause (rows 3 and 4)

Duplicate (row 4)

- 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 when it is 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 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 <u>not</u> 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 $c_j(c_i = true) != c_j(c_i = false)$ for all c_j.

- This is complicated !
- We can satisfy GACC without satisfying predicate coverage
- We 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 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.

- This was 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 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 <u>cause p to be</u> true for one value of the major clause c_i and false for the other, that is, it is required that $p(c_i = true) \neq p(c_i = false)$.

- 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

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 != 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
  - 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 != 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 $c_j(c_i = true)$!= $c_j(c_i = false)$ 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.

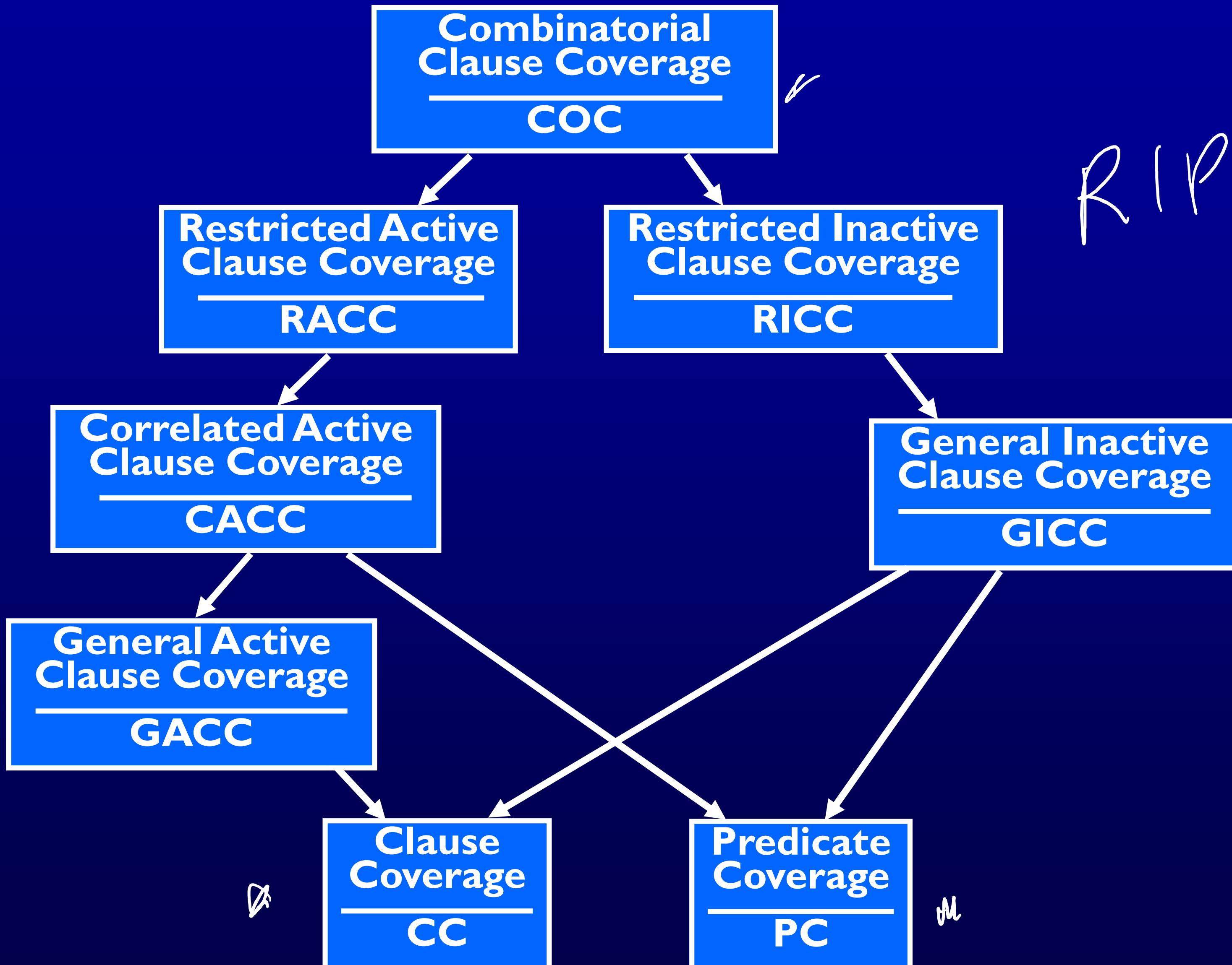
Infeasibility & Subsumption

- 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

Logic Criteria Subsumption



RIPR

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 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**

XOR Identity Rules

Exclusive-OR (*xor*, $\oplus$) means both cannot be true

That is, A *xor* B means

"*A or B is true, but not both*"

$$p = A \oplus A \wedge b$$
$$= A \wedge \neg b$$

$$p = A \oplus A \vee b$$
$$= \neg A \wedge b$$

with fewer symbols …

p = A xor (A and b)
= A and !b

p = A xor (A or b)
= !A and b

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 !**

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, three separate pairs of rows can cause *a* to determine the value of *p*, and only one 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 one clause, PC is enough
  - With 2 or 3 clauses, CoC is practical
  - Advantages of ACC & 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

Next

- Applying Logic Coverage to source code
- Group assignments, start working on your projects
- Reminder: HW2 is due on Monday 3/29 at 9:30am EST