Software Verification and Validation

White-box testing. Test coverage

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White-box Testing

Tests are generated based on *internal structure* of code
Other (better) names: glass box, clear box, open box

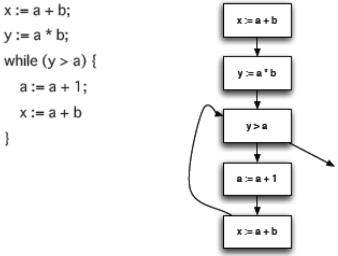
Another classification:
behavioral testing (black-box) / *structural* (white-box)

Comparison:
– black-box: at any level / white-box: mostly module/unit testing
– white-box: code change ⇒ tests change
– white-box: easier detection of *coding errors*,
but cannot detect *omission errors* (in code or spec)

Program structure: Terminology

Control flow graph (CFG)
graph representation of program
and implicitly its execution paths

nodes = instructions
edges (labeled w. conditions):
  sequencing between instructions



Usually, straight-line code is grouped together ⇒

basic block =
  a sequence of statements with just one entry and one exit point
  (no jumps into middle of code, or from code outside)

Image: `https://vinaytech.wordpress.com/2008/10/04/abstract-syntax-tree/`

Code coverage

= a criterion to measure if a set of tests is *adequate*

What good are such criteria ? For questions as:

What program properties should we examine ?

What test data do we select for such properties ?

What *quantitative* objectives do we set for testing ?

Did we test enough ?

Burnstein, Practical Software Testing

The impossible ideal: test all program executions

⇒ i.e., *all paths* through the CFG

But: number of program paths usually infinite (loops, recursion)
also: one path, multiple data (proper equivalence classes?)

⇒ must choose modest structural criteria

⇒ but not arbitrary – chosen *judiciously*

Testing axioms (Weyuker)

Antiextensionality:

There are equivalent programs P și Q such that a test suite T is adequate for P but not for Q.

i.e. *semantically* equivalent programs may need different test suites

General Multiple Change:

There are programs P and Q that have the same form (structure) and a test suite T which is adequate for P but not for Q.

i.e. *syntactically* close programs may need different test suites

Criteria: Line coverage

also: statement coverage, basic block coverage

- Sufficient tests to execute each program statement
- Obviously a necessary criterion (not executed = not tested)
- obviously also insufficient

```
char a[5], *s = NULL;
if (len < 5)
  s = a;
*s = 't';
```

Test with `len = 4` covers all statements; misses error

Branch coverage

also: decision coverage

Tests every possible value of a decision (true/false)
more precise definition: also tests every entry and exit from program
  usually implies statement coverage
  (every instruction is on some branch; see exception below)

The following are also decisions / branches
- `switch`/`case` statements (multiple branches)
- *exception handling* (hard to test, often neglected)
  - every *potential* exception is a branching point
  - code that looks straight-line in reality isn't

Caution: functions or side-effects in decisions:

```
if (a && (b || f(x, y))
```

does not call `f` if `a` and `b` both true
⇒ a case where branch coverage does not subsume line coverage

Condition coverage

A *condition* is an *elementary boolean expression* in a *decision*
needs tests for each possible value of a condition
apparently more complex than decision coverage, but does not subsume it

Example

```
if (x > 5 && y == 3) /*some code */
```

Two tests: `x = 6, y = 2` and `x = 4, y = 3`
generate all possible condition values (T and F, F and T)
but follow the same branch (`false`)

Condition/decision coverage

Simultaneously covers *both* criteria
May need more tests than individual methods or just recombining them

Example

```
if (x > 5 && y == 3) /*some code */
```

two tests are still enough: `x = 6, y = 3`, and `x = 4, y = 2`

May be insufficient: the effect of some conditions may *mask* others

Multiple condition coverage

Tests all combinations for the *subexpressions* (conditions) of the decision

Exponential in number of conditions (2^n tests for n conditions)
 ⇒ often too expensive to implement

In pratice, some of the 2^n combinations

- may be irrelevant (for short-circuit evaluation)
- may be infeasible (when conditions are not independent)

⇒ in general, this requirement is not justified

Modified Condition/Decision Coverage

One of the strongest criteria; initially developed at Boeing
is a requirement in avionics/safety-critical systems (standard DO-178B)

Complete requirements for an MC/DC test suite:
- All program entry and exit points covered
- Each decision exercised on both branches
- Each condition takes both values
- *Each condition is shown to affect its enclosing decision*

(keep other conditions fixed, varying condition of interest)

Same tests, whether language has short-circuit evaluation or not.

Constructing an MC/DC test suite

Start from base cases `&&` and `||` with two conditions
AND operator `&&` has a single case (`t t`) with result `t`.
Changing any condition to `f`, result becomes `f`.
Likewise for `||` (dual operator), switching `t` and `f`.

a	b	a && b	
f	t	f	(1)
t	f	f	(2)
t	t	t	(3)

a: (1, 3)
b: (2, 3)

a	b	a || b	
t	f	t	(1)
f	t	t	(2)
f	f	f	(3)

We indicate the pair of tests relevant for each condition:
(1, 3) shows `a` may influence decision; likewise, (2, 3) for `b`.

For *n* conditions: a test with all the same, *n* tests with one each flipped

a	b	c	a && b && c	
f	t	t	f	(1)
t	f	t	f	(2)
t	t	f	f	(3)
t	t	t	t	(4)

a: (1, 4)
b: (2, 4)
c: (3, 4)

MC/DC Construction Example

Consider `a && b && (c || d && e)`

Start from innermost expression(s), `d && e` (watch precedence!)

d	e	d && e	
f	t	f	(1)
t	f	f	(2)
t	t	t	(3)

d: (1, 3)
e: (2, 3)

We then add `c ||`.
Since `||` with `f` does not change truth, add `c=f` to all tests (1-3).
For the new test (4), choose test with `f` result (2) and add `c=t`.

c	d	e	c || d && e	
f	f	t	f	(1)
f	t	f	f	(2)
f	t	t	t	(3)
t	t	f	t	(4)

Now also shows effect of `c`:
c: (2, 4)
d: (1, 3)
e: (2, 3)

MC/DC example (cont.)

Now add `a && b && .` To previous tests, add `a=t`, `b=t`.
Then choose a test with `t` result (4), flip in turm `a` and `b` to `f`, showing `a` and `b` influence decision:

a	b	c	d	e	a && b && (c || d && e)	
t	t	f	f	t	f	(1)
t	t	f	t	f	f	(2)
t	t	f	t	t	t	(3)
t	t	t	t	f	t	(4)
f	t	t	t	f	f	(5)
t	f	t	t	f	f	(6)

a: (4, 5)
b: (4, 6)
c: (2, 4)
d: (1, 3)
e: (2, 3)

Each test pair has one condition shown to influence outcome, all other conditions have the same value in both tests.

By construction, it follows that n variables need $n+1$ tests.

MC/DC coverage: example 2

Consider `a && b || c && d` .
We write tests for both subexpressions (given by precedence)

a	b	a && b	
f	t	f	(1')
t	f	f	(2')
t	t	t	(3')

a: (1', 3')
b: (2', 3')
c: (1", 3")
d: (2", 3")

c	d	c && d	
f	t	f	(1")
t	f	f	(2")
t	t	t	(3")

We combine with `||`. Since `||` with `f` has no effect, choose one `f` test from each group (1' + 1") and combine with all tests in the other group.

a	b	c	d	`a && b || c && d`		
f	t	f	t	f	(1=1'+1")	a: (1, 5)
f	t	t	f	f	(2=1'+2")	b: (4, 5)
f	t	t	t	t	(3=1'+3")	c: (1, 3)
t	f	f	t	f	(4=2'+1")	d: (2, 3)
t	t	f	t	t	(5=3'+1")	

We have thus kept the influence of each individual condition.

MC/DC in real code

The above analysis is valid for *independent conditions*

it's always possible to generate the designed tests

In reality, conditions may be *coupled* (correlated)

Example: `(z - x >= 3 && z - y >= 1 || y < 5) && x <= 3`

To have `z - x >= 3` influence the condition, we'd need

`x <= 3`, and `y >= 5`, and `z - y >= 1`

But from these, we get `z - x >= 3`, thus the condition can't be false, and can't influence the decision!

⇒ trying to get MC/DC coverage, we can detect if a condition is written needlessly complex, or has irrelevant parts (a possible logic error)

In this case, since `z - x < 3` cannt have an effect, the condition can be rewritten setting `z - x >= 3` to *true*:

```
(z - y >= 1 || y < 5) && x <= 3
```

Unique-Cause MC/DC vs. Masking MC/DC

Unique-Cause MC/DC
the initially presented variant: the influence of a condition must be shown keeping all other conditions unchanged
may be impossible to achieve for coupled conditions

Masking MC/DC
a relaxed variant:
in the test pair, not all conditions must have same value,
but both combinations must show the effect of the scrutinized condition

In practice: combination
unique cause for all independent conditions
masking MC/DC for coupled conditions

Predicate coverage

or predicate-complete coverage [T. Ball, 2004]

Previous criteria do NOT correlate multiple decisions
$\Rightarrow$ e.g. combinations of successive `if` statements in the program
$\Rightarrow$ we need a criterion closer to *path coverage*
(which would cover all execution paths)

Approach: identify n relevant *predicates* (conditions) in the program
Try to generate all $S \cdot 2^n$ possible combinations
   S states (program locations), n predicates
$\Rightarrow$ correlates between them all states and predicates in the program

Predicate coverage example [T. Ball]

```
void partition(int a[], int n) { // assume(n>2);
  int pivot = a[0];
  int lo = 1, hi = n-1;
  while (lo <= hi) {
    while (a[lo] <= pivot)
      lo++;
    while (a[hi] > pivot)
      hi--;
  if (lo < hi)
    swap(a,lo,hi);
  }
}
```

Is it correct? Do you detect an error?

Relevant predicates: branch conditions

`lo <= hi, lo < hi, a[lo] <= pivot, a[hi] > pivot`

Coverage criteria for cycles

[Beizer, Software Testing Techniques]

For simple cycles

– zero iterations (cycle is skipped)
  possibly also: negative counter – correct behavior?
– one iteration
– two iterations (may catch *initialization errors)*
– one typical intermediate value
– N-1 iterations
– N iterations
– try to force N+1 iterations (more than assumed max)

For nonzero minimum: try min-1, min, min+1 ...

Coverage for multiple cycles [Beizer]

1. minimal number of outer iterations
   try inner cycle completely (as independent cycle)
2. continue following cycles outwards
   – with inner cycle at typical iteration count
   – vary count for current cycle
3. finally, vary all cycles together from min to max

Other path testing criteria

Boundary interior path testing

- all paths that traverse a cycle once, without repetition (boundary test)
- all paths that repeat a test, at most once (interior test)

Linear Code Sequence and Jump (LCSAJ)

an LCSAJ sequence: straight line code followed by a jump

length N LCSAJ criterion: N such consecutive sequences

N = 1 ensures line coverage

N = 2 ensures branch coverage (even more)

Mutation-based testing

Try changing decisions/statements according to some patterns to detect if the program runs differently

Examples:
– $<$ changed to $<=$, etc.
– $+1$ changed to -1 or ignored
– limits changed by $\pm$ 1
– `a || b` changed to `a`, resp. `b`
(is the test relevant?); same for `a && b`

If a mutation is not caught ("mutant not killed") by any test
$\Rightarrow$ either tests are insufficient
$\Rightarrow$ or program may be wrong (or has irrelevant code)

Dataflow coverage criteria

Criteria so far: linked to program *control flow*
Alternative: criteria linked to *data flow* (*dataflow coverage*)

Key notions:
– variable *definition* (**def**): place where it's assigned
– variable **use**: place where it is read
(used in expression or tested in condition)

Various coverage criteria, e.g.: all-defs, all-uses
def-use coverage: cover each *feasible* pair of def-use with a test case

How relevant is coverage?

Errors increase with complexity

Cyclomatic complexity (of CFG)
$= E - V + 2$ (E = edges, V = nodes)
is a good measure for complexity

We want better coverage for more complex code

But: code coverage is not an absolute measure for test quality
cf. Brian Marick: How to misuse code coverage