Software Verification and Testing

Lecture Notes: Testing I

Motivation

verification:

- powerful method for finding software errors
- mathematical proof of absence of errors in implementations relative to specifications
- formal specification and analysis often very expensive; requires highly qualified engineers
- automated techniques rather limited

testing: (as “poor man’s verification”)

- can only detect presence of errors
- cannot find all errors (induction problem)
- much cheaper than verification
- requires less mathematical skills

Motivation

verification vs testing:

- verification used often in early stages of development; testing in later stages
- but test cases can be developed during the specification phase
- verification presupposes formal program semantics; testing does not
- verification often based on abstraction, thus also only a necessary correctness criterion
- system tests go beyond verification, since real environment is involved
- testing is strongly used in software engineering: up to 40% of software development efforts go into it
- formal verification is rarely used in practice. . .

Motivation

psychology of testing:

- coding is often seen as a “constructive” or “creative” activity; testing as a “destructive” one
- the aim of testing should not be in the verification, but in the falsification of a program
- ideally, development and testing teams should be separate

reality of testing:

- testing can be partially automated (using CASE-tools)
- good testing may require considerable engineering experience
- testing strongly contributes to software quality

Testing Notation

test object: the software component or program to be tested

test case: a collection of test data causing the complete execution of the test object

test datum: input value for an input variable or input parameter of the test object in a particular test case

test driver: frame for interactively calling a test object which is a function or procedure

Testing Notation

instrumentation:

- addition of counters to source code
- either manually or by a tool
- evaluation of counters gives information about commands executed

coverage: describes the degree of completeness of a test procedure

regression tests: automated replay of test cases after code alternations

Classification of Testing Methods

dynamic testing: software component is executed with concrete input values (in a real environment)

- structure testing (white-box testing):
  test cases derived from control flow or data flow of the component
- functional testing (black-box testing):
  test cases derived from (formal) component specification

static testing: code analysis (components are not executed) by code inspections, code reviews, walkthroughs. . .

symbolic execution: (abstract interpretation) execution of source code with abstract symbolic input values by interpreter;
intermediate between testing and verification

Classification of Testing Methods

here: focus on dynamic testing

structure testing:

- control flow oriented:
  statement coverage tests, branch coverage tests, path coverage tests, condition coverage tests
- data flow oriented:
  defs/uses-tests, required k-tuples tests

functional testing: equivalence class tests, boundary value tests, special value tests, random value tests, state automata tests

Control Flow Graphs

example: specification

- the procedure reads input from the keyboard; it stops when some input is not an upper case character or some upper value `MaxSize` has been reached
- if the input an upper case character, then the counter `InCount` is incremented; if it is a vowel, then the counter `VoCount` is incremented
- both counters are input and output parameters
- the invariant `VoCount <= InCount` holds

Control Flow Graphs

example: implementation

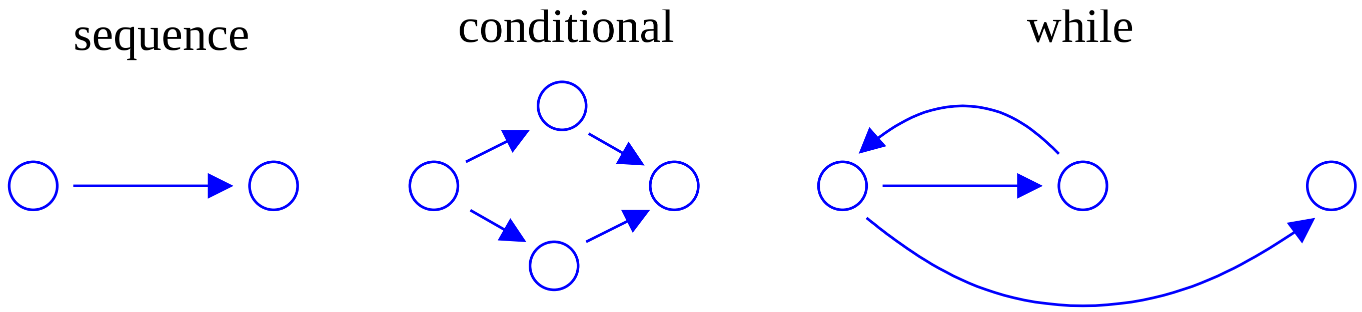
```
void CountDigits(int &VoCount, int &InCount)
{
   char Digit
   cin >> Digit        //read Digit from input stream
   while ((Digit >= ’A’) && (Digit <= ’Z’) && (InCount < MaxSize))
      {
         InCount++;
         if ((Digit == ’A’) || (Digit == ’E’) || (Digit == ’I’) ||
             (Digit == ’O’) || (Digit == ’U’))
         {
            VoCount++;
         }// end if
         cin >> Digit;
      }//end while
}
```

Control Flow Graphs

control flow graph: directed graph (transition system) with start and end vertex

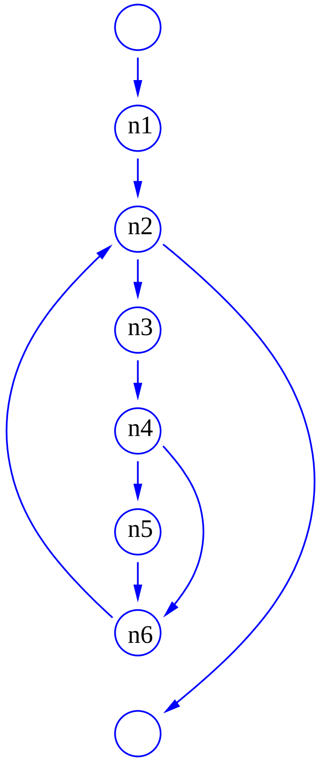
- nodes labelled by executable commands
- edges represent control flow between nodes

basic flow graphs:



Control Flow Graphs

example:



```
cin >> Digit;

while ((...))

InCount++;

if ((...))

VoCount++;

cin >> Digit;
```

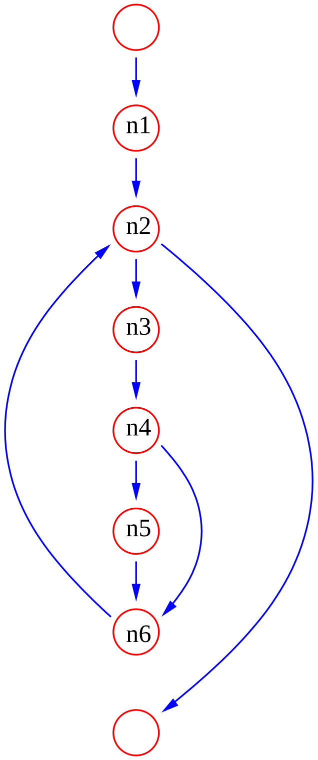
Control Flow Oriented Structure Testing

here: we consider

- statement coverage test:
  test case must cover all nodes, i.e., all possible commands must be executed at least once
- branch coverage test:
  test case must cover all edges, i.e., all possible choices must be explored at least once
- path coverage test:
  test case must cover all different traces of a program,
  i.e., paths in the flow graph
- condition coverage test:
  test case for complex conditions/tests

Statement Coverage

example:



```
cin >> Digit;

while ((...))

InCount++;

if ((...))

VoCount++;

cin >> Digit;
```

Statement Coverage

test case: call `CountDigits` with `InCount` $= 0 =$ `VoCount`

- input from keyboard: 'A', '1'
- test path: $n_i, n_1, n_2, n_3, n_4, n_5, n_6, n_2, n_o$

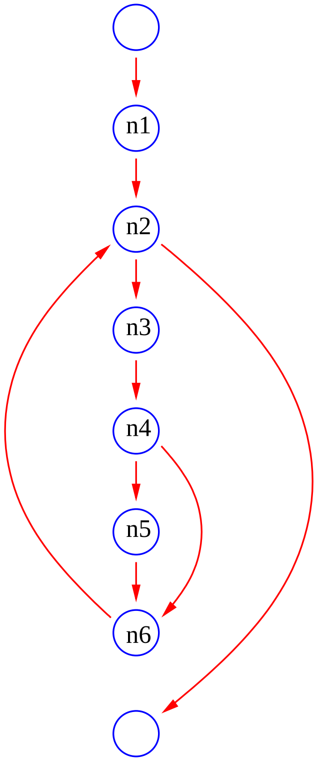
remark: edge from n_4 to n_6 is not considered

evaluation:

- non-executable code can be found
- not a stand-alone testing technique

Branch Coverage

example:



cin >> Digit;

while ((...))

InCount++;

if ((...))

VoCount++;

cin >> Digit;

Branch Coverage

test case: call `CountDigits` with `InCount` $= 0 =$ `VoCount`

- input from keyboard: 'A', 'B','1'
- test path: $n_i, n_1, n_2, n_3, n_4, n_5, n_6, n_2, n_3, n_4, n_6, n_2, n_o$

remarks: branch coverage

- subsumes statement coverage
- is a minimal testing technique
- helps to identify and optimise strongly used program parts

problems: branch coverage does not

- suffice for loop testing
- consider dependencies between branches
- resolve complex conditions/tests

Path Coverage

example:

- define the paths

$$c_1 = (n_i, n_1) \cdot (n_1, n_2) \qquad c_2 = (n_2, n_3) \cdot (n_3, n_4) \qquad c_3 = (n_4, n_5) \cdot (n_5, n_6)$$
$$c_4 = (n_5, n_6) \qquad c_5 = (n_6, n_2) \qquad c_6 = (n_2, n_6)$$

- then the set of all paths can be described by the regular expression

$$c_1 \cdot (c_2 \cdot (c_3 \cup c_4) \cdot c_5)^* \cdot c_6$$

- it can be obtained by unwinding the control flow graph

Path Coverage

question: how many paths are in $(c_1 \cup c_2)^*$ (when the maximal length of paths is bounded by n)?

answer: exponentially many (2^n)!

consequence: it is not feasible to test all possible execution paths of a component

heuristics:

- boundary-interior path test:
  1. consider all paths that enter, but do not repeat a loop (boundary test)
  2. consider all paths that repeat a loop, restricted to two repetitions (interior test)
- structured path test: generalisation of the above (discussion later)

Boundary-Interior Path Test

example: consider again `CountDigits`

1. outside of loop:
   call with `InCount` $=$ `MaxSize`
   input from keyboard: whatever
   test path: $c_1 \cdot c_6$

Boundary-Interior Path Test

example: consider again `CountDigits`

2. boundary test:

   (a) call with `InCount` $= 0$
   input from keyboard: 'A', '1'
   test path: $c_1 \cdot c_2 \cdot c_3 \cdot c_5 \cdot c_6$

   (b) call with `InCount` $= 0$
   input from keyboard: 'B', '1'
   test path: $c_1 \cdot c_2 \cdot c_4 \cdot c_5 \cdot c_6$

Boundary-Interior Path Test

example: consider again `CountDigits`

3. interior test:

   (a) call with $\texttt{InCount} = 0$
   input from keyboard: 'A', 'U', '1'
   test path: $c_1 \cdot (c_2 \cdot c_3 \cdot c_5)^2 \cdot c_6$

   (b) call with $\texttt{InCount} = 0$
   input from keyboard: 'U', 'K' '!'
   test path: $c_1 \cdot c_2 \cdot c_3 \cdot c_5 \cdot c_2 \cdot c_4 \cdot c_5 \cdot c_6$

Boundary-Interior Path Test

example: consider again `CountDigits`

3. interior test:

   (c) call with `InCount` $= 0$
   input from keyboard: 'C', 'A' 'n'
   test path: $c_1 \cdot c_2 \cdot c_4 \cdot c_5 \cdot c_2 \cdot c_3 \cdot c_5 \cdot c_6$

   (d) call with `InCount` $= 0$
   input from keyboard: 'G', 'B' 'DD'
   test path: $c_1 \cdot (c_2 \cdot c_4 \cdot c_5)^2 \cdot c_6$

Structured Path Test

idea: extend boundary-interior path tests to depth k

properties: for some k

- do not explore paths $c_i \cdot c_j^{>k} \cdot c_l$
- explore all paths $c_i \cdot c_j^{\leq k} \cdot c_l$

Condition Coverage Test

example: `CountDigits` contains two conditions/tests

```
...
((Digit >= ’A’) && (Digit <= ’Z’) && (InCount < MaxSize))
...
((Digit == ’A’) || (Digit == ’E’) || (Digit == ’I’) ||
 (Digit == ’O’) || (Digit == ’U’))
...
```

observation: path coverage tests do not analyse these conditions

Condition Coverage Test

variations:

- simple condition coverage: every atomic condition must be at least once true and once false
- multiple condition coverage: considers full truth table
- minimal multiple condition coverage: every condition (atomic or composite) must be at least once true and once false

Condition Coverage Tests

discussion:

- simple condition coverage subsumes not even statement coverage: not an applicable technique
- multiple condition coverage considers exponentially many cases; many of them not reachable because of dependencies
- minimal multiple condition coverage is more difficult to establish

Control Flow Testing: Empirical Data

error identification:

- statement coverage: 18%
- branch coverage: 34% (79% control flow errors, 20% computation errors)
- path testing techniques: no reliable data found
- condition coverage: no reliable data found

Data Flow Oriented Testing

idea: use definitions and accesses to variables for defining test cases

applications: this is useful for testing

- data structures
- data types
- objects

variants:

- defs/uses procedures
- required k-tuples testing
- data context covering

Defs/Uses Procedures

variables: they are used essentially in three different ways in programs

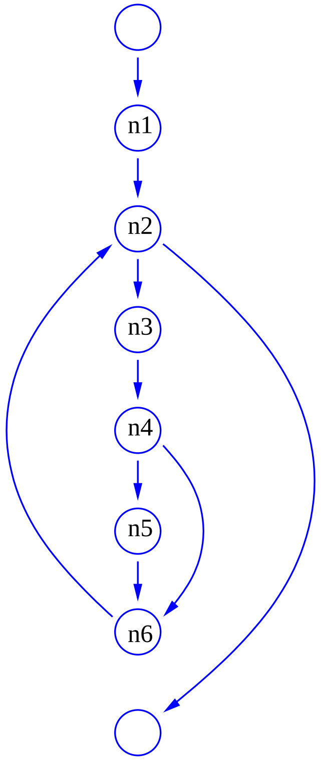
- assignments of values/definitions (defs)
- computations (c-uses)
- conditions/propositions (p-uses)

example: in if $z > 1$ then $y = x + 1$ else skip

- z is p-used
- y is defed
- x is c-used

Defs/Uses Procedures

example:



```
cin >> Digit;
while ((...))
InCount++;
if ((...))
VoCount++;
cin >> Digit;
```

Defs/Uses Procedures

example:

- n_i: def `InCount`, `VoCount`
- n_1: def `Digit`
- n_2: p-use `Digit`, `InCount`
- n_3: c-use `InCount`, def `InCount`
- n_4: p-use `Digit`
- n_5: c-use `VoCount`, def `VoCount`
- n_6: def `Digit`
- n_o: c-use `InCount`, c-use `VoCount`

Defs/Uses Procedures

terminology:

- a def of x in n_i precedes a c-use or p-use of x in n_j
  if there is a path c with source n_i and target n_j and
  x is defined nowhere on c
- conversely, the c-use or p-used succeeds the def
- a p-use or c-use of a variable is local if it is preceeded by a def
  in the same block
- it is called global if it is preceeded by a def not in the same block
- a def of a variable is local if it precedes a p-use or c-use in the same block
- it is called global if it does not precede a use in the same block

Criteria

all defs:

- test case contains for every globally defined variable at some node a path to some succeeding c-use or p-use
- subsumes neither statement nor branch coverage

all p-uses:

- test case contains for every globally defined variable at some node a path to all succeeding p-uses
- subsumes branch coverage

all c-uses:

- test case contains for every globally defined variable at some node a path to all succeeding c-uses
- subsumes neither statement nor branch coverage

Criteria

all c-uses/some p-uses:

1. try all c-uses
2. if there is no c-use, test some succeeding p-use

all p-uses/some c-uses: dual to above

all uses: combine all c-uses and all p-uses

example: in exercises. . .

Data Flow Testing: Empirical Data

study:

- all defs, all p-uses and all c-uses together found 70% of program errors
- all c-uses found 48% of errors, first of all computation errors
- all p-uses found 34% of errors, first of all control flow errors
- all defs found 24% of errors, no control flow errors

Alternatives

required k-tuples:

- test alternating sequences of definitions and uses
- different bounds on sequence length yield different procedures

data context coverage: for each program variable, test each possible assignment of value