SE 465 Final Review

Faults, Errors & Failures

- **Fault (bug)** – static defect in software; e.g. incorrect lines of code
- **Error** – an incorrect internal state that is the manifestation of some fault; not necessarily observed yet
- **Failure** – external, incorrect behaviour with respect to the expected behaviour; must be visible
- RIP fault model – for a fault to become a failure:
  - Fault must be reachable
  - Program state after reaching fault must be incorrect (i.e. infection)
  - Infected state must propagate to output to cause a visible failure
- Dealing with faults:
  - **Fault avoidance** – not programming in a vulnerable language; better system design, e.g. by making an error state unreachable
  - **Fault detection** – testing; software verification; and repairing detected faults
  - **Fault tolerance** – redundancy (e.g. extra hardware); isolation (e.g. checking preconditions)

Testing

- To test a program, we can:
  - Execute every statement in the program (statement coverage)
  - Feed random inputs
  - Check different values for output conditions (logic coverage)
  - Analyze possible inputs & cover all interesting combinations of input (input space coverage)
- **Static testing** – a.k.a. "ahead of time"
  - E.g. static analysis – runs at compile time, automated
  - E.g. code review
- **Dynamic testing** – a.k.a. "at run-time"
  - Observe program behaviour by executing it
  - E.g. **black-box** (not looking at code) & **white-box** testing (looking at code)

Test Cases & Coverage

- A **test case** consists of:
  - Test case values: input values necessary to complete some execution of the software
  - Expected results: result to be produced if & only if program satisfies intended behaviour
  - Prefix values: inputs to prepare software for test case values
  - Postfix values: inputs for software after test case values
    - Verification values: inputs to show results of test case values
    - Exit commands: inputs to terminate program or to return it to initial state
- **Test requirement (TR)** – a specific element of a (software) artifact that a test case must satisfy or cover
  - E.g. to achieve branch coverage, each branch gives 2 TRs (branch is true; branch is false)
  - Infeasible test requirements – e.g. dead code
- **Coverage level** = # of TRs satisfied by a test set/total # of TRs

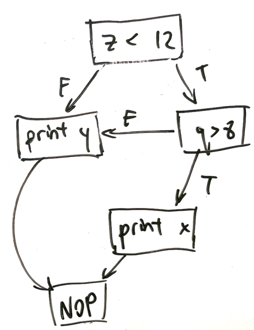
Exploratory Testing

- **Exploratory testing** – "simultaneous learning, test design, and test execution"
  - In contrast: scripted testing – test design happens ahead of time, then execution occurs repeatedly
  - Scenarios where exploratory testing excels:
    - Providing rapid feedback on new product/feature;
    - Learning product quickly;
    - Diversifying testing beyond scripts;
    - Finding single most important bug in shortest time;
    - Independent investigation of another tester's work;
    - Investigating and isolating a particular defect;
    - Investigate status of a particular risk to evaluate need for scripted tests.

Coverage Criteria & CFGs

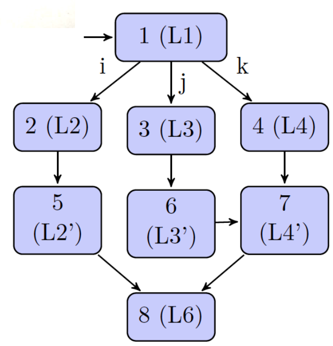
- **Control-flow graphs**
  - Node = zero or more statements (of code)
  - Edge = (s1, s2) → s1 may be followed by s2 in execution
- Examples:
  - Short-circuit conditional:

```
if (z < 12 && q > 8)
    print x
else
    print y
```



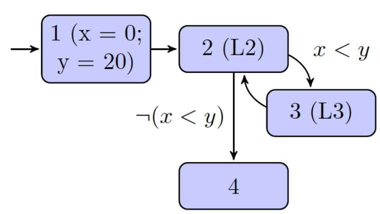
  - Switch statements:

```
1 switch (n) {
2   case `I': ...; break;
3   case `J': ...; // fall thru
4   case `K': ...; break;
5 }
6 // ...
```



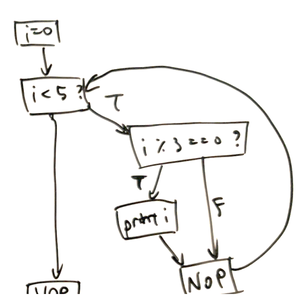
  - While loop:

```
1 x = 0; y = 20;
2 while (x < y) {
3   x ++; y --;
4 }
```



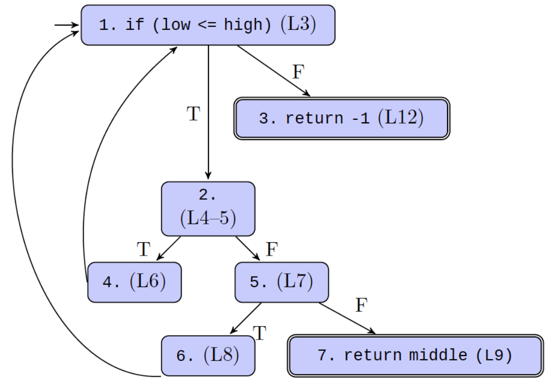
  - For loop:

```
for (i=0 ; i<5 ; i++)
    if (i%3==0)
        print i
```



- Complex example:

```
1   /** Binary search for target in sorted subarray a[low..high] */
2   int binary_search(int[] a, int low, int high, int target) {
3     while (low <= high) {
4       int middle = low + (high-low)/2;
5       if (target < a[middle])
6         high = middle - 1;
7       else if (target > a[middle])
8         low = middle + 1;
9       else
10        return middle;
11    }
12    return -1; /* not found in a[low..high] */
13  }
```



- **Test path** – a path (possibly with length 0) that starts at some initial node (N_0) and ends at some final node (N_f)
  - *path(t)* is the set of test paths corresponding to test case *t*
  - *path(T)* = {*path(t)* | $t \in T$}
  - Each test case gives at least one test path
    - If the program is deterministic, each test case gives exactly one path; i.e. the test case determines the test path
- **Nondeterminism**
  - Caused by dependence on inputs, the thread scheduler, or memory addresses (e.g. Java's hashCode())
  - More than one output might be a valid result of a single input
- **Statement coverage** – for each node n that can be reached by N_0, TR contains a requirement to visit n
  - i.e. T satisfies statement coverage if & only if for every syntactically reachable node n, there is some path in path(T) that visits n
- **Branch coverage** – TR contains each reachable path of length ≤ 1 in G
  - i.e. tests in TR must traverse every possible edge
- In real programs, 80% coverage is usually sufficient
- Impossible to achieve with complete coverage cyclic graphs

Finite State Machines

- FSMs – capture the higher-level design of the software
  - Nodes = software states (e.g. sets of values for key variables)
  - Edges = transitions between software states (e.g. something changes in the environment; someone enters a command)
- **Node/state coverage** – visit every FSM state
- **Edge/transition coverage** – traverse every FSM transition
- **Edge-pair/two-trip coverage** – extend edge coverage of paths with length ≤ 2
- **Round-trip path** – path of nonzero length with no internal cycles that starts and ends at the same node
- **Simple round-trip coverage (SRTC)** – TR contains at least one round-trip path for each reachable node in G that begins and ends a round-trip path
  - i.e. if a node is part of a cycle, cover one of the cycles that the node is in
- **Complete round-trip coverage (CRTC)** - TR contains all round-trip paths for each reachable node in G
  - i.e. if a node is part of a cycle, cover all cycles that the node is in

Syntax-Based Testing

- Context-free grammars can be used to <u>create inputs</u> (both valid and invalid) or <u>modifying programs</u> (mutation testing)
- Using input grammars:
  - **Recognizer** – can include them in a program to validate inputs
  - **Generator** – can create program inputs for testing
    - Begin with the start production and replace non-terminals with their right-hand sides to get (eventually) strings belonging to the input languages
- Example mutation operators:
  - <u>Non-terminal replacement</u>
    dep = "deposit" account amount $\Longrightarrow$ dep = "deposit" amount amount
  - <u>Terminal replacement</u>
    amount = "$" digit$^+$ "." digit { 2 } $\Longrightarrow$ amount = "$" digit$^+$ "$" digit { 2 }
  - <u>Terminal & non-terminal deletion</u>
    dep = "deposit" account amount $\Longrightarrow$ dep = "deposit" amount
  - <u>Terminal & non-terminal duplication</u>
    dep = "deposit" account amount $\Longrightarrow$ dep = "deposit" account account amount
- **Fuzzing**
  - <u>Generation-based fuzzing</u> – starts with a grammar and generates inputs that match the grammar
    - Generate random strings from the grammar $\rightarrow$ feed as input and look for assertion failures
  - <u>Mutation-based fuzzing</u> – starts with existing test cases and randomly modifies them to explore new behaviours
    - E.g. randomly flip bytes, or parse input and change non-terminals
    - A finite given input set can only be fuzzed into a limited set of possibilities & code paths; will need to provide new input sets at that point

Mutation Testing

- **Ground string** – a (valid) string belonging to the language of the grammar
- **Mutation operator** – a rule that specifies syntactic variations of strings generated from a grammar
- **Mutant** – the result of one application of a mutation operator to a ground string
  - Are <u>valid programs</u> that ought to behave differently than the ground string
- Given a mutant M generated from ground string M_0
  - Test case T (strongly) <u>kills</u> M if running T on M gives a <u>different output</u> than on M_0
  - Mutation score = percentage of mutants killed
- Uninteresting mutants:
  - **Stillborn** – cannot compile/immediately crash
  - **Trivial** – killed by almost any test case
  - **Equivalent** – indistinguishable from original program
- **Strong mutation** – fault must be <u>reachable</u>, <u>infect</u> state, and <u>propagate</u> to output (i.e. a failure)
- **Weak mutation** – fault need only be <u>reachable</u> and <u>infect</u> state (i.e. an error)

- **Integration mutation** – mutate interfaces between methods
  - Change calling method by changing actual parameter values
  - Change calling method by changing callee
  - Change callee by changing inputs and outputs

- Example mutation operators
  - $<$ ↔ $\leq$
  - $\leq$ ↔ $>$
  - if (a == b) → if (true)
  - + ↔ –
  - –– ↔ ++
  - true ↔ false
  - 42 ↔ 43
  - return x ↔ return x+1
  - Remove a void method call
  - int x = doSomething() ↔ int x = 1
  - Object y = doSomething() ↔ Object y = null

- Is mutation testing any good?
  - Yes: test suites that kill more mutants are also better at finding real bugs
- Is graph coverage any good?
  - Coverage does not correlate with high quality when it comes to test suites
  - Specifically: test suites that are larger are better because they are larger, not because they have higher coverage
  - Furthermore, stronger coverage (e.g. branch vs statement, logic vs branch) doesn't result in better test suites

Test Design Principles

- Many small tests, not one big test
  - Easier to deal with failures
  - Easier to understand what's being tested
- Make it easy to add new tests
- Unit vs. integration tests
  - Unit tests are more low-level and focus on one particular "class, module, or function"
    - They should execute quickly
  - Integration tests verify end-to-end functionality
- Write some code, write some tests, repeat
- Flaky tests are terrible
  - Timeouts can fail when something takes surprisingly long
  - Iterators can return items in random order
- Look inside the system under test
  - Avoid testing internal state, but rather only what is externally visible

Selenium

- Selenium automates web browsers by using a GUI-less simulator called *HtmlUnit*
- **Page object** – abstraction (interface) of the actions a user can take on a page & queries that can be made
  - Encapsulates UI elements on a page

Coverity

- Coverity is a static analyzer tool which finds bugs in large codebases
- Looks for contradictions & deviance in code
- **Must-beliefs** – inferred from code that has implications/requirements

```
x = *p / z; // MUST: p not null
            // MUST: z != 0
unlock(l); // MUST: l acquired
x++; // MUST: x not protected by l
```

  - Contradictions guarantee errors
  - E.g. redundancy: x = x, y | y, 1 * z
  - E.g. check-then-use: if (!x) x…
  - E.g. use-then-check: x…; if (!x)
- **May-beliefs** – inferences which could be coincidental

```
A();     | A();     |
// ...   | // ...   | // MAY: A() and B() are paired.
B();     | B();     |
```

  - Emit "<u>check</u>" on every belief confirm
  - Emit "<u>error</u>" on every deviation from belief
  - Ranking = check / error (more likely)
  - E.g. use-after-free:
    - foo(p);
      p = 0 → emit check
    - foo(p);
      *p = x → emit error
  - E.g. use-then-check:
    - p = bar();
      if (!p) return;
      *p = x → emit check
    - p = bar();
      *p = x; → emit error

Clones

- **Bellon's Taxonomy:**
  - Type 1 – token streams are identical (may differ in whitespace & comments)
  - Type 2 – literals & identifiers may be different
  - Type 3 – may have extra/missing sections
  - Type 4 – semantically identical
- Clone detection methods
  - Sequence-based approaches
    - String-based
    - Token-based
  - Graph-based approaches
    - AST-based (abstract syntax tree)
    - PDG-based (program dependence graph)
  - Metrics-based approaches
    - Compare measurements instead of structures

Test Engineering Principles

- **Regression tests** should be:
  - Automated (because low yield of finding bugs)
  - Appropriated sized; fast (because should be run continuously)
  - Kept up-to-date; get rid of irrelevant tests over time

- **Test design**
  - Tests can verify state (e.g. calling accessor methods) or verify behaviour (e.g. using mocks)
  - Reduce test code duplication by using:
    - Expected objects
    - Custom asserts
    - Verification methods
  - Avoid logic in tests (e.g. ifs & loops) because tests aren't testable

- Types of **test doubles**:
  - Dummy objects – placeholder objects that don't do anything
  - Fake objects – have actual correct behaviour, unsuitable for use in production
  - Stubs – produces canned answers in response to interactions
  - Mocks – produces canned answers, also check that classic under test makes correct calls
    - Set up/record expectations (which methods are called with what arguments), which are verified as test is executed
  - Spies – wrapper around real object which monitors interactions

- **Flaky tests** – tests sometimes fail non-deterministically
  - Can label flaky tests and re-run them to see if they ever pass; or get rid of them
- Causes of flakiness:
  - Improper waits for async responses – don't hard-code wait durations
  - Concurrency – proper use of concurrency primitives
  - Test order dependency, some tests expect others to be executed first – remove dependencies

- **Continuous integration** – use of a single shared master branch, where changes are merged in continuously
  - Advantages:
    - Software stays in a working state
    - Developers don't take a long time to integrate changes
  - Requires continuous builds & automated testing
  - Broken builds need to be fixed immediately – do not accept commits that don't pass tests
  - Building should be fast; tests should be tiered (fast → slow)
  - Test in prod-like environment (e.g. VMs)

- Anatomy of a **bug report**:
  - Summary/title – one-line recap
  - Description
  - Steps to reproduce – specifically describe each action
  - Expected results
  - Actual results
  - Build date & platform

Static vs. Dynamic Analysis

- **Static analysis** – have partial information about all executions and states
- PMD – a static code analyzer that flags syntax & style issues in code
- XPath – a query language used to navigate through an XML document

Syntax	Description
/	Selects from immediate children
//	Selects from anywhere in the tree
.	Current node
..	Parent node
[...]	Predicate; "such that"
@	Selects attribute
count()	Counts # of occurrences

  - Example:

```
/Function
        [.//Annotation
                /Name[@Image='Test']]
        [count(.//Statement
                [//Prefix
                        /Name[starts-with(@Image, 'assert')]]
                //ArgumentList/Expression//Prefix
                        /Name[@Image='Target'])=1]
```

  - Matches:

```
→ Function
        → Annotation
                → Name 'Test'
        → Statement
                → Prefix
                        → Name 'assertFoobar'
                → ArgumentList
                        → Expression
                                → Prefix
                                        → Name 'Target'
```

- Facebook Infer – open-source static code analyzer
  - *Eradicate* – only references annotated with @Nullable can be assigned null
    - Guarantees no null-pointer exceptions
  - Flags potential resource/memory leaks
  - Flags for exposure of "tainted" values (unsafe or secret data) to outside world or sensitive functions

- **Dynamic analysis** – have complete information about some program states based on observations
  - E.g. Valgrind detects memory errors dynamically
    - Checks by emulating a CPU
    - Illegal reads/writes, reads of uninitialized variables, illegal frees, memory leaks
  - E.g. AddressSanitizer
    - Checks by translating memory calls to its own versions, and using shadow memory
    - Out-of-bounds memory accesses, use-after-free, use-after-return, use-after-scope
  - E.g. Helgrind checks for race conditions
    - Keeps track of which program holds which locks
    - Monitors shared memory