Goals

- Review material from Chapter 7 of Pilone & Miles
  - Testing of Systems
    - unit tests, integration tests, system tests, acceptance tests
  - Testing of Code
    - Black Box
    - Gray Box
    - White Box
    - Code Coverage
  - Continuous Integration
Testing is a critical element of a larger software engineering concern / process known by many names

- software quality control / software quality assurance
- validation and verification
  - **validation**: are we building the right product?
  - **verification**: does “foo” meet its specification?
    - where “foo” can be code, a model, a design diagram, a requirement, …
- At each stage, we need to verify that the thing we produce accurately represents its specification
Terminology

- An *error* is a mistake made by an engineer.
- A *fault* is a manifestation of that error in the code.
- A *failure* is an incorrect output/behavior that is caused by executing a fault.
- Testing attempts to surface failures in our software systems.
  - Debugging attempts to associate failures with faults so they can be removed from the system.
- If a system passes all of its tests, is it free of all faults?
No!

- Faults may be hiding in portions of the code that only rarely get executed
  - “Testing can only be used to prove the existence of faults not their absence” or “Not all faults have failures”
  - Sometimes faults mask each other; this is particularly insidious
- However, if we do a good job in creating a test set that
  - covers all functional capabilities of a system
  - covers all code using a metric such as “branch coverage”
- Then, having all tests pass increases our confidence that our system has high quality and can be deployed
Looking for Faults

All possible states/behaviors of a system
Looking for Faults

Tests are a way of sampling the behaviors of a software system, looking for failures.

As you can see, its not very comprehensive.
The testing literature advocates folding the space into equivalent behaviors and then sampling each partition.
Consider a simple example like the greatest common denominator function

```c
int gcd(int x, int y)
```

At first glance, this function has an infinite number of test cases

But let's fold the space

- `x=6 y=9`, returns 3, tests common case
- `x=2 y=4`, returns 2, tests when `x` is the GCD
- `x=3 y=5`, returns 1, tests two primes
- `x=9 y=0`, returns ?, tests zero
- `x=-3 y=9`, returns ?, tests negative
Completeness

- From this discussion, it should be clear that “completely” testing a system is impossible
  - So, we settle for heuristics
    - attempt to fold the input space into different functional categories
      - then create tests that sample the behavior/output for each functional partition
  - As we will see, we also look at our coverage of the underlying code; are we hitting all statements, all branches, all loops?
Continuous Testing

- Testing is a continuous process that should be performed at every stage of a software development process
  - Recall our requirements gathering process that continually queried the user, “Did we get this right?”
  - Recall our emphasis on iteration throughout the entire development process
    - at the end of each iteration, we check our results to see if what we built is meeting our requirements
Testing the System (I)

- **Unit Tests**
  - Tests that cover low-level aspects of a system
  - For each module, does each operation perform as expected

- **Integration Tests**
  - Tests that check that modules work together in combination
  - Most projects on schedule until they hit this point
    - All sorts of hidden assumptions are surfaced when code written by different developers are used in tandem
  - Lack of integration testing has led to spectacular failures
Testing the System (II)

- **System Tests**
  - Tests performed by the developer to ensure that all major functionality has been implemented
  - Have all user stories been implemented and function correctly?

- **Acceptance Tests**
  - Tests performed by the user to check that the delivered system meets their needs
  - In large, custom projects, developers will be on-site to install system and then respond to problems as they arise
Once we have code, we can perform three types of tests:

- **Black Box Testing**
  - Does the system behave as predicted by its specification

- **Grey Box Testing**
  - Having a bit of insight into the architecture of the system, does it behave as predicted by its specification

- **White Box Testing**
  - Since, we have access to most of the code, lets make sure we are covering all aspects of the code: statements, branches, …
A black box test passes input to a system, records the actual output and compares it to the expected output.
Results

- if actual output == expected output
  - TEST PASSED
- else
  - TEST FAILED

Process
- Write at least one test case per functional capability
- Iterate on code until all tests pass
- Need to automate this process as much as possible
Functionality

- User input validation (based off specification)
- Output results
- State transitions
  - are there clear states in the system in which the system is supposed to behave differently based on the state?
- Boundary cases and off-by-one errors
Grey Box Testing

- Use knowledge of system’s architecture to create a more complete set of black box tests
  - Verifying auditing and logging information
    - for each function is the system really updating all internal state correctly
  - Data destined for other systems
  - System-added information (timestamps, checksums, etc.)
  - “Looking for Scraps”
    - Is the system correctly cleaning up after itself
      - temporary files, memory leaks, data duplication/deletion
White Box Testing

- Writing test cases with complete knowledge of code
  - Format is the same: input, expected output, actual output
- But, now we are looking at
  - code coverage (more on this in a minute)
  - proper error handling
  - working as documented (is method “foo” thread safe?)
  - proper handling of resources
    - how does the software behave when resources become constrained?
A criteria for knowing white box testing is “complete”

- statement coverage
  - write tests until all statements have been executed
- branch coverage (aka edge coverage)
  - write tests until each edge in a program’s control flow graph has been executed at least once (covers true/false conditions)
- condition coverage
  - like branch coverage but with more attention paid to the conditionals (if compound conditional ensure that all combinations have been covered)
A criteria for knowing white box testing is “complete”

- path coverage
  - write tests until all paths in a program’s control flow graph have been executed multiple times as dictated by heuristics, e.g.,
  - for each loop, write a test case that executes the loop
    - zero times (skips the loop)
    - exactly one time
    - more than once (exact number depends on context)
A Sample Ada Program to Test

function P return INTEGER is
begin
   X, Y: INTEGER;
   READ(X); READ(Y);
   while (X > 10) loop
      X := X – 10;
      exit when X = 10;
   end loop;
   if (Y < 20 and then X mod 2 = 0) then
      Y := Y + 20;
   else
      Y := Y – 20;
   end if;
   return 2 * X + Y;
end P;
P’s Control Flow Graph (CFG)
White-box Testing Criteria

- **Statement Coverage**

  Select a test set $T$ such that, by executing $P$ for each $d$ in $T$, each elementary statement of $P$ is executed at least once.
All-Statements Coverage of P
All-Statements Coverage of P

Example all-statements-adequate test set:
All-Statements Coverage of P

Example all-statements-adequate test set:
(X = 20, Y = 10)
All-Statements Coverage of P

Example all-statements-adequate test set:
$(X = 20, Y = 10)$
$(X = 20, Y = 30)$
White-box Testing Criteria

- **Edge Coverage**
  
  Select a test set $T$ such that, by executing $P$ for each $d$ in $T$, each edge of $P$’s control flow graph is traversed at least once.
All-Edges Coverage of $P$
All-Edges Coverage of P

Example all-edges-adequate test set:
All-Edges Coverage of P

Example all-edges-adequate test set:
(X = 20, Y = 10)
All-Edges Coverage of P

Example all-edges-adequate test set:
(X = 20, Y = 10)
(X = 15, Y = 30)
White-box Testing Criteria

- Condition Coverage

Select a test set $T$ such that, by executing $P$ for each $d$ in $T$, each edge of $P$’s control flow graph is traversed at least once and all possible values of the constituents of compound conditions are exercised at least once.
All-Conditions Coverage of P
All-Conditions Coverage of P

Example all-conditions-adequate test set:
All-Conditions Coverage of P

Example all-conditions-adequate test set:

$(X = 20, Y = 10)$
Example all-conditions-adequate test set:

\((X = 20, Y = 10)\)

\((X = 5, Y = 30)\)
All-Conditions Coverage of P

Example all-conditions-adequate test set:

(X = 20, Y = 10)
(X = 5, Y = 30)
(X = 21, Y = 10)
White-box Testing Criteria

- Path Coverage
  
  Select a test set $T$ such that, by executing $P$ for each $d$ in $T$, all paths leading from the initial to the final node of $P$’s control flow graph are traversed at least once.
All-Paths Coverage of P
All-Paths Coverage of P

Example all-paths-adequate test set:
All-Paths Coverage of P

Example all-paths-adequate test set:
$(X = 5, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:  
\((X = 5, Y = 10)\)
All-Paths Coverage of P

Example all-paths-adequate test set: \((X = 5, Y = 10)\)
All-Paths Coverage of P

Example all-paths-adequate test set: 
(X = 5, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
\[(X = 5, Y = 10)\]
All-Paths Coverage of P

Example all-paths-adequate test set: 
$(X = 5, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:
\((X = 5, Y = 10)\)
Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
$(X = 5, Y = 10)$
$(X = 15, Y = 10)$
Example all-paths-adequate test set:

$(X = 5, Y = 10)$

$(X = 15, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:

(X = 5, Y = 10)

(X = 15, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:

(X = 5, Y = 10)

(X = 15, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
$(X = 5, Y = 10)$
$(X = 15, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:
\( (X = 5, Y = 10) \)
\( (X = 15, Y = 10) \)
All-Paths Coverage of P

Example all-paths-adequate test set:

\(X = 5, \ Y = 10\)

\(X = 15, \ Y = 10\)
All-Paths Coverage of P

Example all-paths-adequate test set:

$(X = 5, Y = 10)$

$(X = 15, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:

\( (X = 5, Y = 10) \)

\( (X = 15, Y = 10) \)
All-Paths Coverage of P

Example all-paths-adequate test set:

- \((X = 5, Y = 10)\)
- \((X = 15, Y = 10)\)
- \((X = 25, Y = 10)\)
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
\((X = 5, Y = 10)\)
\((X = 15, Y = 10)\)
\((X = 25, Y = 10)\)
Example all-paths-adequate test set:

- $(X = 5, Y = 10)$
- $(X = 15, Y = 10)$
- $(X = 25, Y = 10)$
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- $(X = 5, Y = 10)$
- $(X = 15, Y = 10)$
- $(X = 25, Y = 10)$
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$(X = 5, Y = 10)$
$(X = 15, Y = 10)$
$(X = 25, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
Example all-paths-adequate test set:

(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:
(X = 5, Y = 10)
(X = 15, Y = 10)
(X = 25, Y = 10)
All-Paths Coverage of P

Example all-paths-adequate test set:

- $(X = 5, Y = 10)$
- $(X = 15, Y = 10)$
- $(X = 25, Y = 10)$
All-Paths Coverage of P

Example all-paths-adequate test set:

\((X = 5, Y = 10)\)
\((X = 15, Y = 10)\)
\((X = 25, Y = 10)\)
\((X = 35, Y = 10)\)
\(\ldots\)
Doing this by hand would be hard!

- Fortunately, there are tools that can track code coverage metrics for you
  - typically just statement and branch coverage

- The book covers one tool that is part of a larger system called Cruise Control

- These systems typically generate reports that show the percentage of the metric being achieved
  - they will also typically provide a view of the source code annotated to show which statements and conditions were “hit” by your test suite
Testing Automation (I)

- It is important that your tests be automated
  - More likely to be run
  - More likely to catch problems as changes are made
- As the number of tests grow, it can take a long time to run the tests, so it is important that the running time of each individual test is as small as possible
  - If that’s not possible to achieve then segregate long running tests from short running tests
    - execute the latter multiple times per day, execute the former at least once per day (they still need to be run!!)
It is important that running tests be easy

- testing frameworks allow tests to be run with a single command
  - often as part of the build management process (as shown in last lecture)
- The book presents details on JUnit (but there are lots of testing frameworks out there)
Since test automation is so critical, systems known as continuous integration frameworks have emerged. The book covers one called CruiseControl:

- <http://cruisecontrol.sourceforge.net/>

Continuous Integration (CI) systems wrap version control, compilation, and testing into a single repeatable process:

- You create/debug code as usual;
  - You then check your code and the CI system builds your code, tests it, and reports back to you.
Wrapping Up

- Testing is one element of software quality assurance
  - Verification and Validation can occur in any phase
- Testing of Code involves
  - Black Box, Grey Box, and White Box tests
  - All require: input, expected output (via spec), actual output
  - White box additionally looks for code coverage
- Testing of systems involves
  - unit tests, integration tests, system tests and acceptance tests
- Testing should be automated and various tools exists to integrate testing into the version control and build management processes of a development organization
Coming Up

- Lecture 21: Deadlock
  - Read Chapter 6 of the Concurrency textbook
- Lecture 22: Test-Driven Design / Development
  - Read Chapter 7 of Head First Software Development