6.005 Elements of Software Construction
Fall 2008

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Today's Topics

why testing is important and hard

choosing inputs
➢ input space partitioning
➢ boundary testing

how to know if you've done enough
➢ coverage

testing pragmatics
➢ stubs, drivers, oracles
➢ test-first development
➢ regression testing

Real Programmers Don’t Test!(?)

top 5 reasons not to test

5) I want to get this done fast – testing is going to slow me down.
4) I started programming when I was 2. Don’t insult me by testing my perfect code!
3) testing is for incompetent programmers who cannot hack.
2) we’re not Harvard students – our code actually works!
1) “Most of the functions in Graph.java, as implemented, are one or two line functions that rely solely upon functions in HashMap or HashSet. I am assuming that these functions work perfectly, and thus there is really no need to test them.” – an excerpt from a 6.170 student’s e-mail

WHY TESTING MATTERS
Who Says Software is Buggy?
Ariane 5 self-destructed 37 seconds after launch

reason: a control software bug that went undetected
- conversion from 64-bit floating point to 16-bit signed integer caused an exception
  - because the value was larger than 32767 (max 16-bit signed integer)
- but the exception handler had been disabled for efficiency reasons
- software crashed ... rocket crashed ... total cost over $1 billion

Another Prominent Software Bug
Mars Polar Lander crashed

- sensor signal falsely indicated that the craft had touched down when it was still 130 feet above the surface.
- the descent engines shut down prematurely... and it was never heard from again
the error was traced to a single bad line of code
- Prof. Nancy Leveson: these problems "are well known as difficult parts of the software-engineering process"... and yet we still can't get them right

The Challenge
we want to
- know when product is stable enough to launch
- deliver product with known failure rate (preferably low)
- offer warranty!

but
- it's very hard to measure or ensure quality in software
- residual defect rate after shipping:
  - 1 - 10 defects/kloc (typical)
  - 0.1 - 1 defects/kloc (high quality: Java libraries?)
  - 0.01 - 0.1 defects/kloc (very best: Praxis, NASA)
- example: 1Mloc with 1 defect/kloc means you missed 1000 bugs!

Testing Strategies That Don’t Work
exhaustive testing is infeasible
- space is generally too big to cover exhaustively
- imagine exhaustively testing a 32-bit floating-point multiply operation, a*b
  - there are 2^64 test cases!
statistical testing doesn’t work for software
- other engineering disciplines can test small random samples (e.g. 1% of hard drives manufactured) and infer defect rate for whole lot
- many tricks to speed up time (e.g. opening a refrigerator 1000 times in 24 hours instead of 10 years)
- gives known failure rates (e.g. mean lifetime of a hard drive)
- but assumes continuity or uniformity across the space of defects, which is true for physical artifacts
- this is not true for software
  - overflow bugs (like Ariane 5) happen abruptly
  - Pentium division bug affected approximately 1 in 9 billion divisions
Two Problems

often confused, but very different
(a) problem of finding bugs in defective code
(b) problem of showing absence of bugs in good code

approaches
- testing: good for (a), occasionally (b)
- reasoning: good for (a), also (b)

theory and practice
- for both, you need grasp of basic theory
- good engineering judgment essential too

Aims of Testing

what are we trying to do?
- find bugs as cheaply and quickly as possible

reality vs. ideal
- ideally, choose one test case that exposes a bug and run it
- in practice, have to run many test cases that “fail” (because they don’t expose any bugs)

in practice, conflicting desiderata
- increase chance of finding bug
- decrease cost of test suite (cost to generate, cost to run)

Practical Strategies

design testing strategy carefully
- know what it’s good for (finding egregious bugs) and not good for (security)
- complement with other methods: code review, reasoning, static analysis
- exploit automation (e.g. JUnit) to increase coverage and frequency of testing
- do it early and often

Basic Notions

what’s being tested?
- unit testing: individual module (method, class, interface)
- subsystem testing: entire subsystems
- integration, system, acceptance testing: whole system

how are inputs chosen?
- random: surprisingly effective (in defects found per test case), but not much use when most inputs are invalid (e.g. URLs)
- systematic: partitioning large input space into a few representatives
- arbitrary: not a good idea, and not the same as random!

how are outputs checked?
- automatic checking is preferable, but sometimes hard (how to check the display of a graphical user interface?)
Basic Notions

**how good is the test suite?**
- coverage: how much of the specification or code is exercised by tests?

**when is testing done?**
- test-driven development: tests are written first, before the code
- regression testing: a new test is added for every discovered bug, and tests are run after every change to the code

**essential characteristics of tests**
- modularity: no dependence of test driver on internals of unit being tested
- automation: must be able to run (and check results) without manual effort

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### Example: Thermostat

**specification**
- user sets the desired temperature $T_d$
- thermostat measures the ambient temperature $T_a$
- want heating if desired temp is higher than ambient temp
- want cooling if desired temp is lower than ambient temp

```
if T_d > T_a, turn on heating
if T_d < T_a, turn on air-conditioning
if T_d = T_a, turn everything off
```

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### How Do We Test the Thermostat?

**arbitrary testing is not convincing**
- “just try it and see if it works” won’t fly

**exhaustive testing is not feasible**
- would require millions of runs to test all possible $(T_d, T_a)$ pairs

**key problem: choosing a test suite systematically**
- small enough to run quickly
- large enough to validate the program convincingly
Key Idea: Partition the Input Space

**input space is very large, but program is small**

- so behavior must be the “same” for whole sets of inputs

**ideal test suite**

- identify sets of inputs with the same behavior
- try one input from each set

If \( T_d > T_a \), turn on heating
If \( T_d < T_a \), turn on air-conditioning
If \( T_d = T_a \), turn everything off

More Examples

**java.math.BigInteger.multiply(BigInteger val)**

- has two arguments, this and val, drawn from BigInteger
- partition BigInteger into:
  - BigNeg, SmallNeg, -1, 0, 1, SmallPos, BigPos
- pick a value from each class
  - -265, -9 -1, 0, 1, 9, 265
- test the 7 × 7 = 49 combinations

**static int java.Math.max(int a, int b)**

- partition into:
  - a < b, a = b, a > b
- pick value from each class
  - (1, 2), (1, 1), (2, 1)

More Examples

**Set.intersect(Set that)**

- partition Set into:
  - ∅, singleton, many
- partition whole input space into:
  - this ≠ that, this \( \subseteq \) that, this \( \supseteq \) that, this \( \cap \) that ≠ ∅, this \( \cap \) that = ∅

- pick values that cover both partitions
  - {}, {}, {2}, {2}, {2,3,4}
  - {5}, {}, {5}, {2}, {4}, {2,3,4}
  - {2,3}, {}, {2,3}, {2}, {1,2}, {2,3}

Boundary Testing

- include classes at boundaries of the input space
  - zero, min/max values, empty set, empty string, null
- why? because bugs often occur at boundaries
  - off-by-one errors
  - forget to handle empty container
  - overflow errors in arithmetic
Exercise

**recall our quiz grammar**
- partition the input space of quizzes
- devise a set of test quizzes

Option ::= Value? Text
Value ::= [ digit+ ]
Text ::= char*

Rule ::= Range Message
Range ::= digit+ - digit+ :Message
Message ::= char*

- what important class of inputs are we leaving out?

Coverage

how good are my tests?
- measure extent to which tests ‘cover’ the spec or code

**spec coverage for state machines**
- state machine being tested
- kinds of coverage
  - all actions
  - all states
  - all transitions
  - all paths
- all-actions, all-states ≤ all-transitions ≤ all-paths

State Diagram for Thermostat

- a test case is a trace of (Td,Ta) pairs
- all actions: (Td<Ta), (Td=Ta), (Td>Ta)
  - e.g., using actual temperatures: (67, 70), (67, 67), (70, 67)
- all states: the same trace would cover all states
- all transitions: (Td<Ta), (Td = Ta), (Td > Ta)
  - e.g.: (67, 70), (67, 67), (70, 67), (70, 70)
Code Coverage

- view control flow graph as state machine
- and then apply state machine coverage notions
- example
  
  ```
  if (x < 10) ++;
  ```

How Far Should You Go?

- for spec coverage
  - all-actions: essential
  - all-states, all-transitions: if possible
  - all-paths: generally infeasible, even if finite

- for code coverage
  - all-statements, all-branches: if possible
  - all-paths: infeasible

industry practice

- all-statements is common goal, rarely achieved (due to unreachable code)
- safety critical industry has more arduous criteria (eg. "MCDC", modified decision/condition coverage)

A Typical Statement Coverage Tool

- EclEmma Eclipse plugin

black box vs. glass box testing

- black box testing
  - choosing test data only from spec, without looking at implementation

- glass box (white box) testing
  - choosing test data with knowledge of implementation
    - e.g. if implementation does caching, then should test repeated inputs
    - if implementation selects different algorithms depending on the input, should choose inputs that exercise all the algorithms
  - must take care that tests don’t depend on implementation details
    - e.g. if spec says “throws Exception if the input is poorly formatted”, your test shouldn’t check specifically for a NullPointerException just because that’s what the current implementation does
  - good tests should be modular -- depending only on the spec, not on the implementation

Courtesy of The Eclipse Foundation. Used with permission.
### Black Box vs. Glass Box Testing

**best practice**
- generate black-box test cases until code coverage is sufficient

![Diagram showing the process of generating black-box test cases and measuring code coverage](image)

- too low
- OK

### Testing Framework

**driver**
- just runs the tests
- must design unit to be drivable!
- e.g. program with GUI should have API

**stub**
- replaces other system components
- allows reproducible behaviours (esp. failures)

**oracle**
- determines if result meets spec
- preferably automatic and fast
- varieties: computable predicate (e.g. is the result odd?), comparison with literal (e.g. must be 5), manual examination (by a human)
- in regression testing, can use previous results as "gold standard"

### Example: the Quote Generator

- QuoteApp
- QuoteFormatter
- Generator
- HTMLGenerator
- RTFGenerator
- Yahoo

- need an oracle for testing generators
- want a stub for the network, to test without live server

![Diagram showing the components and interactions of the Quote Generator](image)
Test-First Development

write tests before coding
➤ specifically, for every method or class:
    1) write specification
    2) write test cases that cover the spec
    3) implement the method or class
    4) once the tests pass (and code coverage is sufficient), you’re done

writing tests first is a good way to understand the spec
➤ think about partitioning and boundary cases
➤ if the spec is confusing, write more tests
➤ spec can be buggy too
    • incorrect, incomplete, ambiguous, missing corner cases
    • trying to write tests can uncover these problems

Regression Testing

whenever you find and fix a bug
➤ store the input that elicited the bug
➤ store the correct output
➤ add it to your test suite

why regression tests help
➤ helps to populate test suite with good test cases
    • remember that a test is good if it elicits a bug – and every regression
test did in one version of your code
➤ protects against reversion that reintroduce bug
➤ the bug may be an easy error to make (since it happened once already)
test-first debugging
➤ when a bug arises, immediately write a test case for it that elicits it
➤ once you find and fix the bug, the test case will pass, and you’ll be done

Summary

testing matters
➤ you need to convince others that your code works
➤ testing generally can’t prove absence of bugs, but can increase quality by
    reducing bugs

test early and often
➤ unit testing catches bugs before they have a chance to hide
➤ automate the process so you can run it frequently
➤ regression testing will save time in the long run

be systematic
➤ use input partitioning, boundary testing, and coverage
➤ regard testing as a creative design problem

use tools and build your own
➤ automated testing frameworks (JUnit) and coverage tools (EclEmma)
➤ design modules to be driven, and use stubs for repeatable behavior