Definition of Testing

- What is “testing”?  
  - A process whereby we increase our confidence in an implementation by observing its behavior

- Fundamental point:
  - Testing can detect the presence of mistakes, never their absence!

- Fail a test case ==> 
- Pass all test cases ==>
Importance of Testing

- Despite limitations, testing is the most practical approach for large systems
- Donald Knuth quotation:
  “Warning: I’ve only proven this algorithm is correct... I haven’t tested it!”
Theory

- 3 levels of abstraction in functionality

- Want: the idea

- Have: an implementation

- “Testing” requires comparing it against something, but what?
Theory (II)

- Ideal: test against our "idea"
  - But the idea is usually too fuzzy
- So make it concrete by writing a **specification**
  - Defines desired mapping from input to output

![Diagram](image)
Example: Sorting a List

- Idea: Function takes a list and puts it in order
- Too fuzzy!
- Questions:
  - Does it modify the list or return a new one?
  - Does it require the list to be non-empty?
  - Does it sort in increasing or decreasing order?
  - What kind of items can be in the list?
Example: Sorting a List

- Specification: Describe how inputs map to outputs
- Recall software I/II contracts
  requires
  \[ |list| \leq 65535 \]
  ensures
  \[ \forall i: 0 \leq i < \text{list.length}: list[i] \leq list[i + 1] \]
Example: Sorting a List

- Specification: Describe how inputs map to outputs
- Recall software I/II contracts
  
  requires
  
  \[|list| \leq 65535\]

  ensures
  
  \[\forall i: 0 \leq i < list.length - 1: list[i] \leq list[i + 1]\]
Example: Sorting a List

- Specification: Describe how inputs map to outputs
- Recall software I/II contracts
  
  requires
  
  \[ |\text{list}| \leq 65535 \]

  ensures
  
  \[ \forall i: 0 \leq i < \text{list.length} - 1: \text{list}[i] \leq \text{list}[i + 1] \]

  \[ \text{list} = \text{permutation}(\#\text{list}) \]
Initial and Final Values

- Often the final value of a parameter depends on its initial value
  - SW I/II: "Updates" parameter mode
  - Example: mutator method sort!

- Consequence: Specification includes old value (eg #list) in ensures clause

- Sometimes the final value is independent of its initial value
  - "Replaces" and "Clears" parameter modes
  - Example: mutator methods fill, clear
Relational Specifications

- A function maps each element in its domain to a *single* element in its range.

- A relation maps each element in its domain to *at least* one elt in its range.

- For specifications:
  - Function = deterministic behavior
  - Relation = nondeterministic behavior

- Examples
  - `find_factor n` returns *some* prime factor
  - `shuffle` scrambles elements of array
Frame of Mind for Validation

- Tests should be written to *break* a program
  - Not to show it works!
- When a test reveals an error, that’s *success*!
  - Failed test case is a *positive* thing
- Good approach: have *someone else* test your code
Importance of Indep't Testing

- See IEEE Computer, Oct ‘99
  - study at NASA Langley
  - had two groups working in parallel
- The group with independent testers found:
  - *more* faults overall (critical and non-critical)
  - found these faults *earlier* in the process
  - fixed these faults with *less effort*
Figure 1 from Arthur article

- **Requirements**: 16 (IV&V), 0 (Non-IV&V)
- **HLD**: 20 (IV&V), 2 (Non-IV&V)
- **LLD**: 31 (IV&V), 8 (Non-IV&V)
- **Code/UT**: 24 (IV&V), 34 (Non-IV&V)
- **I&T**: 6 (IV&V), 14 (Non-IV&V)
- **Total**: 97 (IV&V), 58 (Non-IV&V)
Figure 2 from Arthur article
Writing Good Tests (Inputs)

- Too many possible inputs to test them all
  - Space is defined by requires clause
  - Choose inputs wisely
- Test boundary conditions
  - eg 0, empty array, empty string
- Test different categories of input
  - eg positive, negative, and zero
- Test different categories of behavior
  - eg each menu option, each error message
- Test “unexpected” input
  - eg nil, last name includes a space
- Test representative “normal” input
  - eg random, reasonable values
How To Create Expected Output

- **By hand**
  - Error-prone and tedious

- **With another program**
  - Also error-prone
  - Often just redoing the implementation, and making the same mistakes!

- **Work backwards**
  - Inverse may be easier to calculate
  - Eg start with a sorted list then permute it
Alternative: Validating Output

- **Steps:**
  - Keep a copy of the input
  - Run the program
  - Validate the actual output against input

- **Example: sorting**
  - write two helper functions:
    - 1.
    - 2.
  - copy the input
  - run program and check

- **Helper functions may be easier to get right than the unit under test**
Dangers with Testing

- “Expected output” is wrong
- Testing program is wrong
  - Extra code means more chances to make mistakes
  - E.g. `permute(a, b)` always returns true
- With these errors, there are 2 dangers:
  1. Spurious test failures (passes when shouldn't)
  2. False positives (fails when it shouldn't)
- Which is worse?
Another Danger with Testing

- A third, more subtle, potential error: The specification is wrong
- How can this be?

- When testing drives implementation, this kind of error will not be exposed
- To increase the chances of finding these problems, have *someone else* test your code!
Levels of Testing

- Different kinds of testing, aimed at identifying different kinds of errors
  1. Unit tests
  2. Integration tests
  3. System tests
Unit Tests

- Individual components tested in isolation
  - UUT: Unit Under Test

- Often uses a test fixture
  - Configuration, values, objects which are set up before running all the tests

- Flavors of unit testing:
  - *Black box*: testing based *only* on specification (tester does not look at code)
  - *White box*: testing based on code structure (tester looks at code to make sure every branch of a switch statement is followed)
Integration Tests

- Modules tested in combination in order to check the *interfaces*
- Best done incrementally

```
Driver
  └── Initialize
      ├── FileIO
      ├── Header
      └── Reserve
  └── Load
    └── Simulate
  └── Simulate
      └── Reserve
```

SetMemory
Bottom-up vs Top-down Testing

**Bottom-up**
- Start with most basic modules
- Easy to exercise all the features
- Write a “driver” for higher-level modules

**Top-down**
- Start at top (main)
- Test interfaces early
- Write “stubs” for lower level modules

Often these two occur simultaneously, in tandem
System Tests

- Verify that system as a whole meets the requirements and specifications

- Three flavors:
  - alpha: By developers, before release
  - beta: By “friendly customers”, before general release
  - acceptance: By end customer, to decide whether or not to hire you next time!
TDD: Test-Driven Development

- In dynamic languages, testing is even more important
  - Load-time errors << compile-time errors
- Extreme position: "If it isn't tested, assume it doesn't work"
- TDD: Write tests first (before code)
  - Recall "client-view first" in Software I/II
  - Development cycle: "red, green, refactor"
    - Write tests, watch them fail
    - Write (only) enough code for tests to pass (may need to refactor)
    - Repeat
Summary

- Nature of testing
  - Specification, implementation, test cases
  - Initial values matter too

- Importance of the right frame of mind
  - Write tests to break code
  - TDD: write tests to guide development

- Levels of Testing
  - Unit tests
  - Integration tests
  - System tests
To Ponder

1. If buggy code never gets executed, is it still wrong?

2. Evaluate:

```python
assert_equal 129.95 * 100, 12995
```
To Ponder

`@requires 0 < i < 1000`
`@ensures foo > #i`
def foo i
  i + 1
end

Is foo correct?
- if “yes”, why?
- if “no”, what test case reveals the bug?

`@requires 10 < i < 500`
`@ensures bar = #i + 1`
def bar i
  foo i
end

Is bar correct?
- if “yes”, why?
- if “no”, what test case reveals the bug?
Testing Frameworks (MiniTest: Assert & Spec)
MiniTest and RSpec

- Many popular testing libraries for Ruby
  - MiniTest (replaces older Test::Unit)
    - Comes built-in
    - Looks like JUnit (mapped to Ruby syntax)
    - Well-named!
  - RSpec
    - Installed as a library (*i.e.* a gem)
    - Looks different from JUnit (and even Ruby!)
    - Most unfortunate name!
  - RSpec view is that test cases *define* expected behavior—they *are* the spec!
    - What is wrong with that view?
Writing MiniTest Tests

- Require runner and UUT
  ```ruby
  require 'minitest/autorun'  # the test runner
  require 'card'            # the UUT
  ```

- **Test fixture**: subclass of `MiniTest::Test`
  ```ruby
  class TestCard < MiniTest::Test
  ```

- **Test case**: a method in the fixture
  - Method name *must* begin with `test_
  ```ruby
  def test_identifies_set  ...  end
  ```
  - Contains assertion(s) exercising a single piece of code / behavior / functionality
  - Should be *small* (*i.e.* test one thing)
  - Should be *independent* (*i.e.* of other tests)

- **Test Suite**: a collection of fixtures
require 'minitest/autorun'
require 'card' # assume card.rb on load path

class TestCard < MiniTest::Test

  def test_has_number
    assert.respond_to Card.new, :number
  end

  def test_remembers_number
    @card = Card.new 1, "oval", "open", "red"
    assert_equal 1, @card.number
  end
end
Execution Model

TestCard

instance of

has_number()  
remembers()

instance of

@card

has_number()  
remembers()
Execution Model: Implications

- Separate instances of test class created
  - One instance / test case

- Test cases don't have side effects
  - Passing/failing one test does not affect others

- Can not rely on order of tests
  - Randomized order of execution
  - Controllable with --seed command-line option
  - Also controllable by invoking, in test fixture: `i_suck_and_my_tests_are_order_dependent!`

- Fixture: common set-up to all test cases
  - Field(s) for instance(s) of class being tested
  - Factor initialization code into its own method
  - This method must be called `setup`
Good Practice: setup

- Initialize a fixture with a setup method (rather than initialize method)
- Reasons:
  - If the code being tested throws an exception during the setup, the output is much more meaningful
  - Symmetry with teardown method for cleaning up after a test case
Example: test_card.rb

```ruby
require 'minitest/autorun'
require 'card' # assume card.rb is on load path

class TestCard < Minitest::Test

  def setup
    @card = Card.new 1, "oval", "open", "red"
  end

  def test_has_number
    assert.respond_to @card, :number
  end

  def test_remembers_number
    assert_equal 1, @card.number
  end

end
```

Execution Model
MiniTest Assertion Methods

- Most have two versions: `assert` & `refute`
  - Example: `assert_nil, refute_nil`
  - No need for negation (use `refute` instead)

- Most take an optional message
  ```ruby
  assert_empty Library.new, "A new library contains no books"
  ```
  - Message appears when assertion fails

- Specials:
  - `pass/flunk` – always passes/fails
  - `skip` – skips the rest of the test case

- Performance benchmarking also available
Asserting Equality

- Assert two objects are == equal
  ```ruby
  assert_equal expected, actual
  ```
  - Compares object values (i.e. == in Ruby)
  - Failure produces useful output
    ```ruby
    TestCard#test_total_number_of_cards
    Expected: 81
    Actual: 27
    ```
  - Compare with assert exp == actual
    ```ruby
    TestCard#test_shuffle_is_permutation
    Failed assertion, no message given
    ```

- Assert two objects are aliased
  ```ruby
  assert_same @table.north, @players.first
  ```
  - Compares reference values (i.e. .equal?)
Good Practice: Comparing Floats

- Never compare floating point numbers directly for equality
  ```python
  assert_equal 1.456, calculated, "Low-density experiment"
  ```

- Numeric instabilities make exact equality problematic for floats

- Better: Equality with tolerance
  ```python
  assert_in_delta Math::PI, (22.0 / 7.0), 0.01, "Archimedes algorithm"
  assert_in_epsilon Math::PI, (22.0 / 7.0), 0.1, "Archimedes algorithm"
  ```

- Delta for absolute error, epsilon for relative error
Common Assertions

- **Boolean condition:** `assert (refute)`
  
  ```
  assert @books.all {|b| b.available?}
  ```

- **Is nil:** `assert_nil (refute_nil)`
  
  Checks the result of `#nil?`
  
  ```
  refute_nil @library.manager
  # ie refute @library.manager.nil?
  ```

- **Is empty:** `assert_empty (refute_emp)`
  
  Checks the result of `#empty?`
  
  ```
  assert_empty Library.new
  # ie assert Library.new.empty?
  ```
More Assertions

- String matches a regular expression
  ```ruby
  assert_match /CSE.*/, @course.name
  ```

- Collection includes a particular item
  ```ruby
  assert_includes @library, @book
  ```

- Object is of a particular type
  ```ruby
  assert_instance_of String, @book.title
  ```

- Object has a method
  ```ruby
  assert_respond_to @student, :alarm
  ```

- Block raises an exception
  ```ruby
  assert_raises ZeroDivisionError do
    @library.average_book_cost
  end
  ```
Good Practice: Organization

- Keep tests in the same *project* as the code
  - They are part of the build, the repo, *etc.*
  - Helps to keep tests current
- Separate tests and implementation
  - `/set/lib` – contains card.rb (implementation)
  - `/set/tests` – contains test_card.rb (tests)
- Name test classes consistently
  - `TestCard` tests Card
- Test fixture is a Ruby program
  ```bash
  [setapp] $ ruby tests/test_card.rb
  ```
  - Test needs to be able to find UUT (require)
  - Add location of UUT to load path
  ```bash
  [setapp] $ ruby -I lib tests/test_card.rb
  ```
Alternative Syntax:

- Problem: Cumbersome method names
  
  `test_shuffle_changes_deck_configuration`

- Solution: exploit Ruby language flexibility in API of testing library
  - Methods are available that change the syntax and structure of test cases
  - *Domain-specific language* (DSL) for tests

- Result: MiniTest::Spec
  - Notation inspired by RSpec
Writing MiniTest::Spec Tests

☐ Require runner and UUT as usual

☐ Test fixture ("example group") is a `describe` block

`.describe Card "noun being described" do ... end`

- Can be nested, and identified by string
- The block contains `examples`

☐ Test case ("example") is an `it` block

`.it "identifies a set" ... end`

- Contains `expectation(s)` on a single piece of code / behavior / functionality

☐ Expectations are methods on `values of objects`

`.value(@card.number).must_equal 1`

`.expect(@card.number).must_equal 1 # equivalent`

`.__(@card.number).must_equal 1 # equivalent`
require 'minitest/autorun'
require 'card'  # assume card.rb is on load path

describe Card, "game of set" do

  it "has a number" do
    _(Card.new).must_respond_to :number
    # value(Card.new).must_respond_to :number
    # expect(Card.new).must_respond_to :number
  end

  it "remembers its original number" do
    @card = Card.new 1, "oval", "open", "red"
    _(@card.number).must_equal 1
  end
end
Expectations vs. Assertions

- **Similarity: Positive and negative form**
  
  ```
  must_be_empty # like assert_empty
  wont_be_empty # like refute_empty
  ```

- **Difference: Argument order**
  
  ```
  assert_equal expected, actual
  actual.must_equal expected
  ```

- **Difference: No string argument**
  
  Meaningful output comes from group name and example name

  ```ruby
  Card::game_of_set#test_0001_has_a_number [test_card.rb:14]:
  ```

  ```
  Expected #<Card:0x00564f9a00> (Card) to respond to #number.
  ```
_ (object).must_ + ...

- General expectation: Must be
  \_x.must_be :<=, 10

- Many other flavors of expectation...
  \_x.must_equal y
  \_x.must_be_same_as y
  \(@library.manager).must_be_nil
  \@shelf.must_be_empty
  \@library.must_include @book
  \_PI.must_be_within_delta (22.0 / 7.0), .01
  \(@book.title).must_be_instance_of String
  \(@course.name).must_match /CSE.*/
  \@student.must_respond_to :alarm
  proc {
    @library.average_book_cost
  }.must_raise ZeroDivisionError
Setup/Teardown

- Methods before, after
  describe Student do
    before do
      @buck_id = BuckID.new "4328429"
      @s = Student.new buck_id
    end
    it 'should come to class' do ... end
  end

- Independence is good, but
Let: Lazy Initialization

```ruby
describe Student do
  # both defines a method (student)
  # and memoizes its return value!
  let(:student) { Student.new 1234 }

  describe "sleep deprivation" do
    it "misses class" do
      _(student.awake?).must_equal false
    end
  end
end
end
```
RSpec: Set up and Use

- Install the rspec gem locally
  
  ```
  [~] $ gem install rspec
  ```

- Set up your program to use rspec
  
  ```
  [myapp] $ rspec --init
  ```

- Init creates several things in myapp/ spec/  
  
  ```
  # put tests (foo_spec.rb) here
  spec/spec_helper.rb # configures paths .rspec # default command-line args
  ```

- Run tests
  
  ```
  [myapp] $ rspec spec/foo_spec.rb
  ```
Example Groups and Examples

require_relative '../student'

describe Student do
  # example group
  it "can drop a class" do
    ...
  end
  context "when attending lecture" do
    before :each do ... end
    it "stays awake during lecture" do
      ...
    end
    it "stores info until exam" do
      ...
    end
  end
end
RSpec Expectations

- Verb is “should” (or “should_not”)
  ```ruby
  target.should condition # notice space
  ```

- Examples of condition
  - `==`, equal,
    ```ruby
    factor.should equal 34
    ```
  - `be_true`, `be_false`, `be_nil`, `be_empty`
    ```ruby
    list.empty?.should be_true
    ```
  - `have(n).items`, `have_at_most(n).items`
  - `include(item)`
    ```ruby
    list.should include(name)
    ```
  - `match(regex)`
  - `respond_to(method_name)`

- Preferred form: expect().to (or not_to)
  ```ruby
  expect(a_result).to eq "OSU"
  ```
Stubs

- Top-down: testing a class that uses A, B, C
- Problem: We don't have A, B, C
  - Want quick approximations of A, B, C
  - Behave in certain way, returning canned answers
- Solution: Stub method
  - Takes a hash of method names & return values
  - Returns an object with those methods
    ```ruby
    stub_printer = stub :available? => true,
                    :render => nil
    ```
- Another form adds (or changes) a method/return value of an existing object
  ```ruby
  long_str = 'something'
  long_str.stub (:length).and_return(1000000)
  ```
Mocks

- Stubs passively allow the test to go through
- Mocks *monitor* how they are used (and will fail if they aren't used right)

```ruby
it 'should know how to print itself' do
  mock_printer = mock('Printer')
  mock_printer.should_receive(:available?).and_return(true)
  mock_printer.should_receive(:render).exactly(3).times
  @doc.print(mock_printer).should == 'Done'
end
```
Summary

- MiniTest
  - Test fixture: class extending Minitest::Test
  - Test case: method named test_

- Execution model: multiple instances
  - Independence of test cases

- MiniTest::Spec
  - Examples and expectations
  - String descriptions

- RSpec
  - Stubs and mocks