pFUnit 3.0 Tutorial
Advanced

Tom Clune
Advanced Software Technology Group
Computational and Information Sciences and Technology Office
NASA Goddard Space Flight Center

April 10, 2014
Outline

1 Introduction
   • Overview

2 API - Advanced

3 Test-driven development
Outline

1. Introduction
   - Overview

2. API - Advanced

3. Test-driven development
Class Overview

Primary Goals:
- Learn how to use pFUnit 3.0 to create and run unit-tests
- Learn how to apply test-driven development methodology

Prerequisites:
- Access to Fortran compiler supported by pFUnit 3.0
- Familiarity with F95 syntax
- Familiarity with MPI

Beneficial skills:
- Exposure to F2003 syntax - esp. OO features
- Exposure to OO programming in general

\(^1\)MPI-specific sections can be skipped without impact to other topics.
Syllabus

- **Thursday PM - Introduction to pFUnit**
  - Overview of pFUnit and unit testing
  - Build and install pFUnit
  - Simple use cases and exercises
  - Detailed look at framework API

- **Friday AM - Advanced topics (including TDD)**
  - User-defined test subclasses
  - Parameterized tests
  - Introduction to TDD
  - Advanced exercises using TDD

- **Friday PM - Bring-your-own-code**
  - Incorporate pFUnit within the build process of your projects
  - Apply pFUnit/TDD in your own code
  - Supplementary exercises will be available
Materials

1. You will need access to one of the following Fortran compilers to do the hands-on portions
   - gfortran 4.9.0 (possibly available from cloud)
   - Intel 13.1, 14.0.2 (available on jellystone)
   - NAG 5.3.2

2. Last resort - use AWS
   - ssh keys are at ftp://tartaja.com
   - user name: pfunit@tartaja.com passwd: iuse.PYTHON.1969
   - login: ssh -i user1 user1@54.209.194.237

3. You will need a copy of the exercises in your work environment
   - Browser: https://modelingguru.nasa.gov/docs/DOC-2529
   - Jellystone: /picnic/u/home/cacruz/pFUnit.tutorial/Exercises.tar

4. These slides can be downloaded at
   https://modelingguru.nasa.gov/docs/DOC-2528
Outline

1. Introduction

2. API - Advanced
   - API: pFUnit test Hierarchy
   - API: Misc
   - Parser: Advanced

3. Test-driven development
Peeking under the hood - what is inside pFUnit?
Outline

1 Introduction

2 API - Advanced
   - API: pFUnit test Hierarchy
   - API: Misc
   - Parser: Advanced

3 Test-driven development
Test

**Role:** Abstract base class for all test objects.

**Implementation:** Framework provides various subclasses for common/generic cases. Users can define custom subclasses for specific purposes. Provided subclasses include:

- `TestCase`
- `TestMethod`
- `MpiTestCase`
- `MpiTestMethod`
- `TestSuite`
**TestSuite**

**Role:** Aggregates collection of tests into single entity.

**Implementation:** TestSuite objects are simultaneously Test objects and collections of tests. Run() method applies run() to each contained test.
TestCase class

**Role:** Abstract Test subclass that provides some services that are common to most Test subclasses.

**Implementation:**
TestMethod class

Role: Simple concrete Test subclass that supports the common case where test procedure receives no arguments.

Implementation: Constructor stores a procedure pointer to vanilla Fortran subroutine with no arguments. A restricted form of test fixture is permitted by specifying setUp() and tearDown() methods that also have no arguments. (I.e. fixture is not encapsulated.)
TestMethod API

Constructor:

```fortran
function TestMethod(name, method[, setUp, tearDown])
character(len=*) , intent(in) :: name
procedure(empty) :: method
procedure(empty) :: setUp
procedure(empty) :: tearDown
```

Methods:
ParameterizedTestCase class

**Role:** Allows a single test procedure to be execute multiple times with different input values.

**Implementation:** ParameterizedTestCase objects contain an AbstractTestParameter object that encapsulates input. Subclasses of ParameterizedTestCase must generally also subclass AbstractTestParameter.
**MpiTestCase class**

**Role:** *(Abstract)* Extends ParameterizedTestCase with support for MPI.

**Implementation:** MpiTestCase modifies the runBare() launch mechanism to create an appropriately sized MPI group and corresponding subcommunicator. Processes within that group then call the user’s test procedure, while any remaining processes wait at a barrier.

MPI based tests must not use MPI_COMM_WORLD, and must instead obtain MPI context from the passed test object.

The following convenient type-bound procedures are provided:

- `getProcessRank() ! returns rank within group`
- `getNumProcesses() ! returns size of group`
- `getMpiCommunicator() ! returns the bare MPI com.`
MpiTestMethod class

**Role:** Simple concrete Test subclass that supports common MPI cases that just need basic MPI context.

**Implementation:** Analogous to the vanilla TestMethod, except that user test procedures are now passed an object which must be queried for any MPI context that the test needs.
MpiTestMethod API

Constructor:

function MpiTestMethod(name, method, numProcesses, [, setUp)
   character(len=*) , intent(in) :: name
   procedure(empty) :: method
   integer :: numProcesses ! requested
   procedure(empty) :: setUp
   procedure(empty) :: tearDown

Outline

1. Introduction

2. API - Advanced
   - API: pFUnit test Hierarchy
   - API: Misc
   - Parser: Advanced

3. Test-driven development
TestResult class

**Role:** “Scorecard” – accumulates information about tests as they run.

**Implementation:** Each run() method for Test objects has a mandatory TestResult argument. The Visitor pattern is used to allow the TestResult object to manage and monitor the test as it progresses.

**Note:** Visitor is a somewhat advanced pattern and uses OO capabilities in a nontrivial manner. Users should not need to be aware of this, but developers of framework extensions likely will.
Abstract BaseTestRunner class

**Role:** Runs a test (usually a TestSuite).
**Implementation:** Run() method constructs and configures a TestResult object, then runs the passed Test object.
TestRunner class

**Role:** Default Runner for pFUnit.
RobustRunner class

**Role:** Runner subclass that executes tests within a separate process.

**Implementation:** Collaborates with SubsetRunner. RobustRunner restarts SubsetRunner if it detects a hang or a crash. Currently a bit unreliable. (Irony)
Outline

1. Introduction

2. API - Advanced
   - API: pFUnit test Hierarchy
   - API: Misc
   - Parser: Advanced

3. Test-driven development
Annotations: @testCase

@testCase
@testCase(<options>)

- Indicates next line defines a new derived type which extends TestCase.
- All test procedures in file must accept a single argument of that extended type.
- Accepts the following options:
  - `constructor=<name>` Specifies the name of the function to construct corresponding test object. Default is a constructor with same name as derived type²
  - `npes=[<list-of-integers>]` Indicates that extension is a subclass of MpiTestCase, and provides a default set of values for NPES for all test procedures in the file. Individual tests can override.
  - `eaParameters={expr}` Indicates that extension is a subclass of ParameterizedTestCase, and provides a default set of parameters for all tests in the file. Can be overridden by each test.
  - `cases=[<list-of-integers>]` Alternative mechanism for specifying default test parameters where a single integer is passed to the test constructor.

²This F2003 feature is somewhat unreliable, esp. prior to 14.0.2.
Annotations: @testParameter
Encapsulated test fixture

module SomeTests_mod
    use pFUnit_mod
    implicit none
    @testCase
type, extends(TestCase) :: MyTestCase
    real, allocatable :: xInitial(:)
    contains
        procedure :: setUp
        procedure :: tearDown
    end type MyTestCase
    contains
        subroutine setup(this)
            class (MyTestCase), intent(inout) :: this
            xInitial = [1.,3.,5.,3.,1.]
        end subroutine setup
        subroutine tearDown(this)
            class (MyTestCase), intent(inout) :: this
            deallocate(this%xInitial)
        end subroutine tearDown

    ...

Tom Clune (ASTG)
Encapsulated test fixture (cont’d)

```fortran
@test subroutine anotherTest(this)
    class (MyTestCase), intent(inout) :: this
    real, allocatable :: x(:)
    x = oneStep(this%xInitial)
    @assertEqual(...)
end subroutine anotherTest

end module MyTests_mod
```
Encapsulated test fixture (cont’d)

What you need to know:

- Declare derived type that EXTEND’s `TestCase`
- Annotate TestCase extension with `@testCase`
- Declare TYPE-BOUND procedures: `setUp` and `tearDown`
- Annotate test procedure in usual way with `@test`
- Declare single test procedure argument as
  ```
  class (<your type>), intent(inout) :: <dummy>
  ```
MPI test fixture

module SomeMpiTests_mod
  use pFUnit_mod
  implicit none

@testCase(npes=[1,3,5])
type, extends(MpiTestCase) :: MyTestCase
  integer :: rank, npes
  integer :: peEast, peWest
contains
  procedure :: setUp
  procedure :: tearDown
end type MyTestCase

contains

subroutine setup(this)
  class (MyTestCase), intent(inout) :: this
  integer :: rank, npes
  this%rank = this%getProcessRank()
  this%npes = this%getNumProcesses()
  this%peEast = mod(this%rank + this%npes - 1, this%npes)
  this%peWest = mod(this%rank + 1, this%npes)
end subroutine setup

...
MPI test fixture (cont’d)

```fortran
@test subroutine anotherTest(this)
    class (MyTestCase), intent(inout) :: this
    integer :: comm
    real :: x(0:2)

    comm = this%getMpiCommunicator()
    call someMpiProcedure(comm, x)

    @mpiAssertEqual(this%peWest, x(0))
    @mpiAssertEqual(this%rank, x(1))
    @mpiAssertEqual(this%peEast, x(2))
end subroutine anotherTest
end module MyTests_mod
```
MPI test fixture (cont’d)

What you need to know:
- Declare derived type that EXTEND’s MpiTestCase
- Annotate TestCase extention with @testCase
  - Optionally specify default npes list: (npes=[...])
- Declare TYPE-BOUND procedures: setUp and tearDown
- Annotate test procedure in usual way with @test
- Declare single test procedure argument as
  ```
  class (<your type>), intent(inout) :: <dummy>
  ```
- Use @mpiAssert to synchronize returns
Parameterized tests

Suppose you want to test an interface using variant input data:
Parameterized tests

Suppose you want to test an interface using variant input data:
E.g. sorting a list ...

```plaintext
list = sort([1,2,3,4])
list = sort([4,3,2,1])
list = sort([1,4,2,3])
list = sort([1,2,3,1])
```
Parameterized tests

Suppose you want to test an interface using variant input data:
E.g. sorting a list ...

```
list = sort([1,2,3,4])
list = sort([4,3,2,1])
list = sort([1,4,2,3])
list = sort([1,2,3,1])
```
or varying boundary conditions...
```
call solve(x, BC='dirichlet')
call solve(x, BC='neumann')
```
Parameterized tests (cont’d)

One simple strategy is to just duplicate tests:

```plaintext
@test subroutine test1()
    @assertEqual ([1,2,3,4], sort([1,2,3,4]))
end subroutine test1

@test subroutine test2()
    @assertEqual ([1,2,3,4], sort([4,3,2,1]))
end subroutine test2
...
Parameterized tests (cont’d)

One simple strategy is to just duplicate tests:

```fortran
@test subroutine test1()
    @assertEqual([1,2,3,4], sort([1,2,3,4]))
end subroutine test1

@test subroutine test2()
    @assertEqual([1,2,3,4], sort([4,3,2,1]))
end subroutine test2
...
```

This can be quite tedious if there are many cases and/or the tests are more complex.
Parameterized tests (cont’d)

Another approach is to loop within a test

```fortran
@test subroutine test ()

  real , allocatable :: x(:)
  
  call checkDeriv(x, x**0)
  call checkDeriv(x**2, 2*x)
  call checkDeriv(x**3, 3*x**2)
  ...

contains

  subroutine checkDeriv(fx , dfx)
    real , intent(in) :: fx
    real , intent(in) :: dfx
    @assertEqual(dfx, deriv(fx))
  end subroutine checkDeriv

end subroutine test1
```

Tom Clune (ASTG) DUnit 3.0 - API - Advanced - Session II April 10, 2014 50 / 90
Parameterized tests (cont’d)

Another approach is to loop within a test

```fortran
@test subroutine test()
  real, allocatable :: x(:)

  call checkDeriv(x, x**0)
  call checkDeriv(x**2, 2*x)
  call checkDeriv(x**3, 3*x**2)
  ...
contains

  subroutine checkDeriv(fx, dfx)
    real, intent(in) :: fx
    real, intent(in) :: dfx
    @assertEqual(dfx, deriv(fx))
  end subroutine checkDeriv

end subroutine test1
```

Here we lose information about which case(s) failed.
Parameterized tests (cont’d)

pFUnit provides custom support for parameterized tests:
- Exercise tests across list of user-defined parameters
- User EXTEND’s two classes:
  - ParameterizedTestCase (analog of TestCase)
  - AbstractTestParameter
- Annotation argument: testParameters={<expr>}
  - Specifies default parameter list for @testCase
  - Override with argument to @test
- Failures indicate parameter caused failing assert.
  - Provided through type-bound interface toString() on AbstractTestParameter
Example: Parameterized test

```fortran
    @testParameter
    type, extends(AbstractTestParameter) :: StringTestParameter
        character(:), allocatable :: string
        character(:), allocatable :: lowerCase
        character(:), allocatable :: upperCase
    contains
        procedure :: toString
    end type StringTestParameter

    function toString(this) result(string)
      class(StringTestParameter), intent(in) :: this
      character(:), allocatable :: string
      string = '{' // this%string // ',' // this%lowerCase // '
        , // this%upperCase // '}'
    end function toString
```
Example: Parameterized test (cont’d)

```fortran
@testCase(testParameters = {getParams()}, constructor=
new Test_StringUtilities)
type, extends(ParameterizedTestCase) :: Test_StringUtilities
  character(:, allocatable) :: string
  character(:, allocatable) :: lowerCase
  character(:, allocatable) :: upperCase
end type Test_StringUtilities

function getParams() result(params)
  type (StringTestParameter), allocatable :: params(:)
  params = [
    StringTestParameter('a','a','A'), &
    StringTestParameter('b','b','B'), &
    StringTestParameter('A','a','A'), &
    StringTestParameter('1','1','1'), &
    StringTestParameter('+','+','+'), &
    StringTestParameter('a1B2c3D4', 'a1b2c3d4', 'A1B2C3D4')
  ]
end function getParams
```

Example: Parameterized test (cont’d)

...
Example: Parameterized test (cont’d)

To specify a variant list of parameters:

```plaintext
@test(testParameters={getOtherParams()})
subroutine test_toUpperCase(this)
    class (Test_StringUtilities), intent(inout) :: this
    @assertEqual(this%upperCase, toUpperCase(this%string))
end subroutine test_toUpperCase
```
Combining MPI and Parameterized Test
Combining MPI and Parameterized Test

Good news: 
*MpiTestCase* is a subclass of *ParameterizedTest*
Combining MPI and Parameterized Test

Good news:

MpiTestCase is a subclass of ParameterizedTest

- Extend MpiTestCase
Combining MPI and Parameterized Test

Good news:

**MpiTestCase** is a subclass of **ParameterizedTest**

- Extend **MpiTestCase**
- Extend **MpiTestParameter** (invisible with simple MPI)
Combining MPI and Parameterized Test

Good news:

MpiTestCase is a subclass of ParameterizedTest

- Extend MpiTestCase
- Extend MpiTestParameter (invisible with simple MPI)
- Framework augments toString() to ensure that rank/npes is always included in failure messages
Outline

1 Introduction
2 API - Advanced
3 Test-driven development
TDD
Old paradigm:

- Tests written by separate team (black box testing)
- Tests written *after* implementation
Old paradigm:
- Tests written by separate team (black box testing)
- Tests written after implementation

Consequences:
- Testing schedule compressed for release
- Defects detected late in development ($$)
Old paradigm:
- Tests written by separate team (black box testing)
- Tests written after implementation

Consequences:
- Testing schedule compressed for release
- Defects detected late in development ($$)

New paradigm - Test-driven development (TDD)
- Developers write the tests (white box testing)
- Tests written before production code
- Enabled by emergence of strong unit testing frameworks
The TDD cycle

- Focus on interface
  - Extend Tests
  - Refactor

- Focus on algorithm
  - Fix/Extend Production Code
  - Run Tests
  - Success?


Arrows represent the flow of the cycle, with the decision point indicating whether the process should continue with testing or refactoring.
Anecdotal Testimony

- Many professional SEs are initially skeptical
  - High percentage refuse to go back to the old way after only a few days of exposure.
- Some projects drop bug tracking as unnecessary
- Often difficult to sell to management
  - “What? More lines of code?”
Not a panacea
Not a panacea

- Requires training, practice, and discipline
Not a panacea

- Requires training, practice, and discipline
- Need strong tools (framework + refactoring)
Not a panacea

- Requires training, practice, and discipline
- Need strong tools (framework + refactoring)
- Does not invent new algorithms (e.g. FFT)
  - No such thing as magic
Not a panacea

- Requires training, practice, and discipline
- Need strong tools (framework + refactoring)
- Does not invent new algorithms (e.g. FFT)
  - No such thing as magic
- Maintaining tests difficult during a major re-engineering effort.
Not a panacea

- Requires training, practice, and discipline
- Need strong tools (framework + refactoring)
- Does not invent new algorithms (e.g., FFT)
  - No such thing as magic
- Maintaining tests difficult during a major re-engineering effort.
  - But isn't the alternative is even worse?!!
Experience to date

TDD has been used heavily within several projects at NASA
- Mostly for “infrastructure” portions - relatively little numerical
- pFUnit itself
- Snowflake - virtual snowfakes; Multi-lattice Snowfake
- DYNAMO - spectral MHD code on spherical shell
- GTRAJ - offline trajectory integration (C++)
- SpF - OO parallel spectral framework

Observations:
- ~ 1:1 ratio of test code to source code
- Works very well for *infrastructure*
- Learning curve
  - 1-2 days for technique
  - Weeks-months to wean old habits
TDD - Talking Points

- How large of a step at each cycle?
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent than new tests will all pass

- Don’t test constructors and accessors
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent than new tests will all pass

- Don’t test constructors and accessors
- Commit/backup frequently
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent that new tests will all pass

- Don’t test constructors and accessors
- Commit/backup frequently
- Use synthetic data to make results obvious
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent than new tests will all pass

- Don’t test constructors and accessors
- Commit/backup frequently
- Use synthetic data to make results obvious
- Private vs testable
**TDD - Talking Points**

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent than new tests will all pass

- Don’t test constructors and accessors

- Commit/backup *frequently*

- Use synthetic data to make results *obvious*

- Private vs testable
  - One module has everything PUBLIC
  - 2nd module is default private - just export the things you want PUBLIC
  - Tests use first module; application uses 2nd.
TDD - Talking Points

- How large of a step at each cycle?
  - Gauge by time
  - If steps are going quickly try larger changes
  - If iteration > 10 min, start iteration over (repository is your friend)

- Triangulation
  - Start with simple tests
  - Add tests that probe weaknesses in existing implementation
  - Stop when it is apparent than new tests will all pass

- Don’t test constructors and accessors

- Commit/backup frequently

- Use synthetic data to make results obvious

- Private vs testable
  - One module has everything PUBLIC
  - 2nd module is default private - just export the things you want PUBLIC
  - Tests use first module; application uses 2nd.

- Think when writing tests; autopilot when writing implementation
TDD - process reminder

1. Extend test (new test procedure, new assert, etc)
2. Verify test fails Red Light
3. Alter implementation to pass test
4. Refactor to eliminate redundancy Green Light
5. Repeat
TDD Demonstration: Factorial

Instructions:
Use TDD to implement factorial function
To make it interesting, we'll add tests to guard against illegal inputs and overflow.
- Change into the directory ./Exercises/TDD_Warmup
- Set PFUNIT for a serial build
- `% make tests` (ensure that make is working for you)
TDD Demonstration: Dynamical System

Instructions:

We are going to build a set of classes that will integrate a simple dynamical system:

- State of system is specified by a scalar, \( t \), and 2 vectors: \( x \) and \( v \)
- Denote timestep with \( h \)
- Force (\( F \)) on system is any function of \( x, v, t \)
- Initial integration will be via forward Euler: \( Y_{n+1} = Y_n + hF(Y_n, t) \)
- Then we will “upgrade” to RK4
Possible unit tests for Dynamical System

Forward Euler integration

- $F(t) = 0, \nu(t = 0) = 0$ leaves $x_{n+1} = x_0$
- $F(t) = 0, \nu(t = 0) = \nu_0$ has $x_{n+1} = nh\nu_0$
- $F(t) = 0, \nu(t = 0) = \nu_0$ has $\nu_{n+1} = \nu_n$
- $F(t) = F(t = 0) = a$, $\nu(t = 0) = x(t = 0) = 0$ has $\nu_{n+1} = \nu_n + ha$
- $\nu_{n+1} = \nu_n + hF(t_n)$
- $x_{n+1} = x_n + h\nu_n$
- If $h = 0$, $x_n = x_0$ and $\nu_n = \nu_0$ for any $F$
- Vary number of dimensions
• Change into the directory `./Exercises/TDD_DnamicalSystem`
• Set PFUNIT for a serial build
• `% make tests` (ensure that make is working for you)
Runge-Kutta (RK4)

\[ y_{n+1} = y_n + \frac{1}{6}h(k_1 + 2k_2 + 2k_3 + k_4) \]
\[ t_{n+1} = t_n + h \]

\[ k_1 = f(t_n, y_n) \]
\[ k_2 = f(t_n + \frac{1}{2}h, y_n + \frac{h}{2}k_1) \]
\[ k_3 = f(t_n + \frac{1}{2}h, y_n + \frac{h}{2}k_2) \]
\[ k_3 = f(t_n + h, y_n + hk_3) \]
Demo: Build a Linear 1D Interpolator

\[(x, y_{est})\]  \rightarrow  \[(x_i, y_i)\]
Interpolation ...

What are some potential tests?
Interpolation ...

What are some potential tests?
- Bracket: Find $i$ such that $x_i \leq x < x_{i+1}$
Interpolation ...

What are some potential tests?
- Bracket: Find $i$ such that $x_i \leq x < x_{i+1}$
- Computing weights:

$$w_a = \frac{x_{i+1} - x}{x_{i+1} - x_i}$$
$$w_b = 1 - w_a$$
Interpolation ...

What are some potential tests?
- Bracket: Find $i$ such that $x_i \leq x < x_{i+1}$
- Computing weights:
  \[
  w_a = \frac{x_{i+1} - x}{x_{i+1} - x_i}
  \]
  \[
  w_b = 1 - w_a
  \]
- Combining weighted sum: $y = w_a y_i + w_b y_{i+1}$
Tests for finding enclosing bracket

<table>
<thead>
<tr>
<th>{x_1, x_2, x_3}</th>
<th>x</th>
<th>Expect</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>{1.,2.,3.}</td>
<td>1.5</td>
<td>i = 1</td>
<td>vanilla</td>
</tr>
<tr>
<td>{1.,2.,3.}</td>
<td>2.5</td>
<td>i = 2</td>
<td>vary x</td>
</tr>
<tr>
<td>{1.,2.,4.}</td>
<td>3.0</td>
<td>i = 2</td>
<td>irregular spacing</td>
</tr>
<tr>
<td>{1.,2.,4.,5.}</td>
<td>2.5</td>
<td>i = 2</td>
<td>vary # of nodes</td>
</tr>
<tr>
<td>{1.,2.,3.}</td>
<td>2.0</td>
<td>i = 2</td>
<td>edge case</td>
</tr>
<tr>
<td>{1.,2.,3.}</td>
<td>1.0</td>
<td>i = 1?</td>
<td>edge case</td>
</tr>
<tr>
<td>{1.,2.,3.}</td>
<td>3.0</td>
<td>i = 2?</td>
<td>edge case</td>
</tr>
<tr>
<td>{1.,2.,3.}</td>
<td>0.5</td>
<td>exception?</td>
<td>out-of-bounds</td>
</tr>
<tr>
<td>{3.,2.,1.}</td>
<td>1.5</td>
<td>exception?</td>
<td>support inverted order?</td>
</tr>
</tbody>
</table>
Tests for compute weights

<table>
<thead>
<tr>
<th>$x_i$</th>
<th>$x_{i+1}$</th>
<th>$x$</th>
<th>expected</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2.</td>
<td>1.0</td>
<td>$w_a = 1.0$</td>
<td>left end</td>
</tr>
<tr>
<td>1.</td>
<td>2.</td>
<td>2.0</td>
<td>$w_a = 0.0$</td>
<td>right end</td>
</tr>
<tr>
<td>1.</td>
<td>2.</td>
<td>1.5</td>
<td>$w_a = 0.5$</td>
<td>middle</td>
</tr>
<tr>
<td>1.</td>
<td>3.</td>
<td>1.5</td>
<td>$w_a = 0.75$</td>
<td>vary interval</td>
</tr>
<tr>
<td>1.</td>
<td>2.</td>
<td>0.0</td>
<td>$w_a = ?$</td>
<td>out-of-bounds</td>
</tr>
<tr>
<td>1.</td>
<td>1.</td>
<td>1.0</td>
<td>?</td>
<td>duplicate node</td>
</tr>
</tbody>
</table>
Tests for combine weights

<table>
<thead>
<tr>
<th>$w_a$</th>
<th>$y_a$</th>
<th>$y_b$</th>
<th>expected</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1.</td>
<td>2.</td>
<td>$y = 1.0$</td>
<td>left end</td>
</tr>
<tr>
<td>0.</td>
<td>1.</td>
<td>2.</td>
<td>$y = 2.0$</td>
<td>right end</td>
</tr>
<tr>
<td>0.5</td>
<td>1.</td>
<td>2.</td>
<td>$y = 1.5$</td>
<td>middle</td>
</tr>
<tr>
<td>0.5</td>
<td>3.</td>
<td>2.</td>
<td>$y = 2.5$</td>
<td>vary data</td>
</tr>
</tbody>
</table>
Live Demo: Cross Fingers
References

- pFUnit: http://sourceforge.net/projects/pfunit/
- Tutorial materials
  - https://modelingguru.nasa.gov/docs/DOC-1982
  - https://modelingguru.nasa.gov/docs/DOC-1983
  - https://modelingguru.nasa.gov/docs/DOC-1984
- TDD Blog
  - https://modelingguru.nasa.gov/blogs/modelingwithtdd
- Test-Driven Development: By Example - Kent Beck
- Refactoring: Improving the Design of Existing Code - Martin Fowler
- JUnit http://junit.sourceforge.net/
Acknowledgements

- This work has been supported by NASA’s High End Computing (HEC) program and Modeling, Analysis, and Prediction Program.
- Many thanks to team members Carlos Cruz and Mike Rilee for helping with implementation, regression testing and documentation.
- Special thanks to members of the user community that have made contributions.
  - Sean Patrick Santos
  - Matthew Hambley
  - Evan Lezar