Error handling and testing

Victor Eijkhout, Susan Lindsey

Fall 2022

last formatted: August 28, 2022

1. Programming and correctness

Find your favorite example of costly programming mistakes . . .

What to do about it?

- Never make mistakes.
- Prove that your program is correct.
- Test your program before deploying it.
- Handle errors as they occur.

Error handling

2. Assertions to catch logic errors

Sanity check on things 'that you just know are true':

```
#include <cassert>
...
assert( bool expression )
```

Example:

```
x = sin(2.81);
y = x*x;
z = y * (1-y);
assert( z>=0. and z<=1. );
```

3. Using assertions

Check on valid input parameters:

```
#include <cassert>

// this function requires x<y
// it computes something positive
float f(x,y) {
  assert( x<y );
  return /* some result */;
}
```

Check on valid results:

```
float positive_outcome = f(x,y);
assert( positive_outcome>0 );
```

4. Example

```
int collatz_next( int current ) {
  assert( current>0 );
  int next{-1};
  if (current%2==0) {
    next = current/2;
    assert(next<current);
  } else {
    next = 3*current+1;
    assert(next>current);
  }
  return next;
}
```

5. Use assertions during development

Assertions are disabled by

```
#define NDEBUG
```

before the include.

You can pass this as compiler flag:
`icpc -DNDEBUG yourprog.cxx`

6. Exceptions

Not every error is fatal:

$$\text{Exception} \equiv \begin{cases} \text{`this should not happen'} \\ \text{but we can handle it} \end{cases}$$

1. recover from the problem
2. graceful exit

7. Exceptions

Have you seen the following?

Code:

```
vector<float> x(5);
x.at(5) = 3.14;
```

Output

```
[except] boundthrow:

libc++abi.dylib: terminating with
    uncaught exception of type
    std::out_of_range: vector
```

The Standard Template Library (STL) can generate many exceptions.

- You can let your program crash, and start debugging
- You can try to catch and handle them yourself.

8. Exception structure

Code with problem:

```
if ( /* some problem */ )
  throw(5);
  /* or: throw("error"); */
```

```
try {
  /* code that can go wrong */
} catch (...) { // literally
    three dots!
  /* code to deal with the
    problem */
}
```

9. Exceptions

Assume a routine only works for certain values, and you want to generate an error if called with an inappropriate value.

```
double compute_root(double x) {
  if (x<0) throw(1);
  return sqrt(x);
}
int main() {
  try {
    y = compute_root(x);
  } catch (...) {
    /* handle error */
    cout << "Root failed, using default\n";
    y = 0;
  }
```

See book for more details.

Unit testing and test-driven development (TDD)

10. Dijkstra quote

> *Today a usual technique is to make a program and then to test it. But: program testing can be a very effective way to show the presence of bugs, but is hopelessly inadequate for showing their absence. (cue laughter)*

Still . . .

11. Types of testing

- *Unit tests* that test a small part of a program by itself;
- *System tests* test the correct behavior of the whole software system; and
- *Regression tests* establish that the behavior of a program has not changed by adding or changing aspects of it.

12. Unit testing

- Every part of a program should be testable
- $\Rightarrow$ good idea to have a function for each bit of functionality
- Positive tests: show that code works when it should
- Negative tests: show that the code fails when it should

13. Unit testing

- Every part of a program should be testable
- Do not write the tests after the program:
  write tests while you develop the program.
- Test-driven development:
  1. design functionality
  2. write test
  3. write code that makes the test work

14. Principles of TDD

Develop code and tests hand-in-hand:

- Both the whole code and its parts should always be testable.
- When extending the code, make only the smallest change that allows for testing.
- With every change, test before and after.
- Assure correctness before adding new features.

15. Unit testing frameworks

Testing is important, so there is much software to assist you.

Popular choice with C++ programmers: Catch2
`https://github.com/catchorg`

16. Toy example

Function and tester:

```
double f(int n) { return n*n+1; }

#define CATCH_CONFIG_MAIN
#include "catch2/catch_all.hpp"

TEST_CASE( "test that f always returns positive" ) {
  for (int n=0; n<1000; n++)
    REQUIRE( f(n)>0 );
}
```

(accept the `define` and `include` as magic)

17. Compiling toy example

```
icpc -o tdd tdd.cxx \
    -I${TACC_CATCH2_INC} -L${TACC_CATCH2_LIB} \
    -lCatch2Main -lCatch2
```

- Files:

  ```
  icpc -o tdd tdd.cxx
  ```

- Path to include and library files:

  ```
  -I${TACC_CATCH2_INC} -L${TACC_CATCH2_LIB}
  ```

- Libraries:

  ```
  -lCatch2Main -lCatch2
  ```

Exercise 1: Extend the toy example

1. Write a function

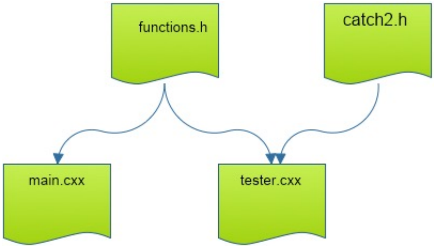
   ```
   double f(int n) { /* .... */ }
   ```

   with values in the range $(0, 1)$.
2. Write a unit test for this.

You can base this off the file `tdd.cxx` in the repository

18. Realistic setup

- All program functionality in a 'library' file
- Main program really short
- Tester file with only tests.
- (Tester also needs the `catch2` stuff included)



19. Slightly realistic example

Example: we use a function that

- only works for positive inputs;
- returns input $+1$.

Program that uses this:

```
#include "functions.h"
int main() {
  for ( int i=10; i>-1; i-- )
    cout << "One more than the positive number "
         << i << " is "
         << increment_positive_only(i)
         << "\n";
```

Note the include file!

20. Function to be developed

We know the structure:

```
int increment_positive_only( int i ) {
  // this function returns one more than the inpuut
  // input has to be positive, error otherwise
  /* ... */
}
```

function body to be developed.

21. Functionality testing

File `tester.cxx`:

Same include file for the functionality;
the testing framework creates its own main.

```
#include "functions.h"

#define CATCH_CONFIG_MAIN
#include "catch2/catch_all.hpp"

TEST_CASE( "test the increment function" ) {
  /* ... */
}
```

22. Compiling the tester at TACC

One-line solution:

```
icpc -o tester test_main.cxx \
    -I${TACC_CATCH2_INC} -L${TACC_CATCH2_LIB} \
    -lCatch2Main -lCatch2
```

Exercise 2: File structure

Make three files:

1. Include file with the functions.
2. Main program that uses the functions.
3. Tester main file, contents to be determined.

23. Correctness through 'require' clause

Tests go in `tester.cxx`:

```
TEST_CASE( "test that f always returns positive" ) {
  for (int n=0; n<1000; n++)
    REQUIRE( f(n)>0 );
}
```

- `TEST_CASE` acts like independent program.
- `REQUIRE` is like `assert` but more sophisticated
- Can contain (multiple) tests for correctness.

24. Tests

Boolean:

```
REQUIRE( some_test(some_input) );
REQUIRE( not some_test(other_input) );
```

Integer:

```
REQUIRE( integer_function(1)==3 );
REQUIRE( integer_function(1)!=0 );
```

Beware floating point:

```
REQUIRE( real_function(1.5)==Catch::Approx(3.0) );
REQUIRE( real_function(1)!=Catch::Approx(1.0) );
```

In general exact tests don't work.

25. Output for failing tests

Run the tester:

```
-------------------------------------------------------------------------------
test the increment function
-------------------------------------------------------------------------------
test.cxx:25
...............................................................................

test.cxx:29: FAILED:
  REQUIRE( increment_positive_only(i)==i+1 )
with expansion:
  1 == 2

===============================================================================
test cases: 1 | 1 failed
assertions: 1 | 1 failed
```

26. Diagnostic information for failing tests

INFO: print out information at a failing test

```
TEST_CASE( "test that f always returns positive" ) {
  for (int n=0; n<1000; n++)
    INFO( "function fails for " << n );
    REQUIRE( f(n)>0 );
}
```

Exercise 3: Positive tests

Continue with the example of slide 23:
add a positive TEST_CASE

```
for (int i=1; i<10; i++)
  REQUIRE( increment_positive_only(i)==i+1 );
```

Make the function satisfy this test.

27. Test for exceptions

Supppose function g(n)

- succeeds for input $n > 0$
- fails for input $n \leq 0$:
  throws exception

```
TEST_CASE( "test that g only works for positive" ) {
  for (int n=-100; n<+100; n++)
    if (n<=0)
      REQUIRE_THROWS( g(n) );
    else
      REQUIRE_NOTHROW( g(n) );
}
```

Exercise 4: Negative tests

Make sure your function throws an exception at illegal inputs:

```
for (int i=0; i>-10; i--)
  REQUIRE_THROWS( increment_positive_only(i) );
```

28. Tests with code in common

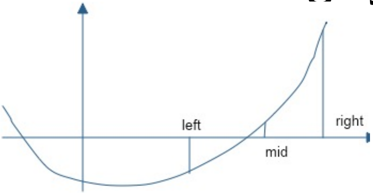
Use SECTION if tests have intro/outtro in common:

```
TEST_CASE( "commonalities" ) {
  // common setup:
  double x,y,z;
  REQUIRE_NOTHROW( y = f(x) );
  // two independent tests:
  SECTION( "g function" ) {
    REQUIRE_NOTHROW( z = g(y) );
  }
  SECTION( "h function" ) {
    REQUIRE_NOTHROW( z = h(y) );
  }
  // common followup
  REQUIRE( z>x );
}
```

(sometimes called setup/teardown)

TDD example: Bisection

29. Root finding by bisection



- Start with bounds where the function has opposite signs.

$$x_- < x_+, \qquad f(x_-) \cdot f(x_+) < 0,$$

- Find the mid point;
- Adjust either left or right bound.

30. Coefficient handling

$$f(x) = c_d x^d + \cdots + c_1 x^1 + c_0$$

We implement this by storing the coefficients in a `vector<double>`.
Proper:

```
TEST_CASE( "coefficients are polynomial","[1]" ) {
  auto coefficients = set_coefficients();
  REQUIRE( coefficients.size()>0 );
  REQUIRE( coefficients.front()!=0. );
}
```

Exercise 5: Proper polynomials

Write a routine *set_coefficients* that constructs a vector of coefficients:

```
vector<double> coefficients = set_coefficients();
```

and make it satisfy the above conditions.

At first write a hard-coded set of coefficients, then try reading them from the command line.

Exercise 6: One test for properness

Write a function `proper_polynomial` as described, and write unit tests for it, both passing and failing.

31. Test on polynomials evaluation

```
// correct interpretation: 2x^2 + 1
vector<double> second{2,0,1};
REQUIRE( proper_polynomial(second) );
REQUIRE( evaluate_at(second,2) == Catch::Approx(9) );
// wrong interpretation: 1x^2 + 2
REQUIRE( evaluate_at(second,2) != Catch::Approx(6) );
```

Exercise 7: Implementation

Write a function `evaluate_at` which computes

$$y \leftarrow f(x).$$

and confirm that it passes the above tests.

For bonus points, look up Horner's rule and implement it.

Exercise 8: Odd degree polynomials only

With odd degree you can always find bounds x_-, x_+.
Reject even degree polynomials:

```
if ( not is_odd(coefficients) ) {
  cout << "This program only works for odd-degree polynomials\n";
  exit(1);
}
```

Gain confidence by unit testing:

```
vector<double> second{2,0,1}; // 2x^2 + 1
REQUIRE( not is_odd(second) );
vector<double> third{3,2,0,1}; // 3x^3 + 2x^2 + 1
REQUIRE( is_odd(third) );
```

Exercise 9: Find bounds

Write a function *find_outer* which computes x_-, x_+ such that

$$f(x_-) < 0 < f(x_+) \quad \text{or} \quad f(x_+) < 0 < f(x_-)$$

(can you write that more compactly?)
Unit test:

```
right = left+1;
vector<double> second{2,0,1}; // 2x^2 + 1
REQUIRE_THROWS( find_initial_bounds(second,left,right) );
vector<double> third{3,2,0,1}; // 3x^3 + 2x^2 + 1
REQUIRE_NOTHROW( find_initial_bounds(third,left,right) );
REQUIRE( left<right );
```

How would you test the function values?

Exercise 10: Put it all together

Make this call work:

```
auto zero = find_zero(coefficients,left,right);
cout << "Found root " << zero
     << " with value " << evaluate_at(coefficients,zero) << "\n";
```

Add an optional precision argument to the root finding function.

Design unit tests, including on the precision attained, and make sure your code passes them.

Turn it in!

- If you think your functions pass all tests, subject them to the tester:

  `coe_bisection yourprogram.cc`

  where '`yourprogram.cc`' stands for the name of your source file.
- Is it reporting that your program is correct? If so, do:

  `coe_bisection -s yourprogram.cc`

  where the `-s` flag stands for 'submit'.
- If you don't manage to get your code working correctly, you can submit as incomplete with

  `coe_bisection -i yourprogram.cc`
- If you want feedback on what the tester thinks about your code do

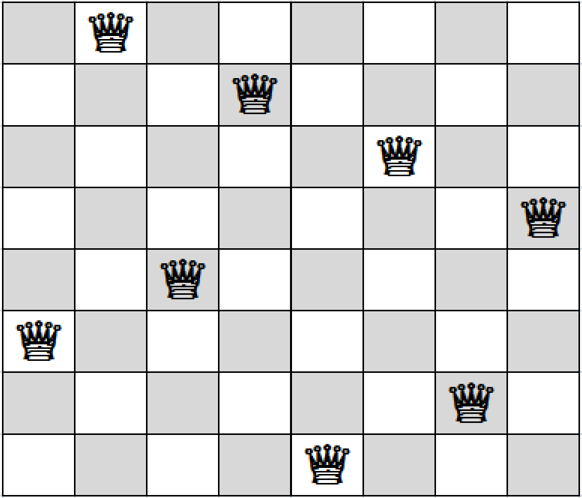
  `coe_bisection -d yourprogram.cc`

  with the `-d` flag for 'debug.

Eight queens problem

32. Problem statement

Can you place eight queens on a chess board so that no pair threatens each other?

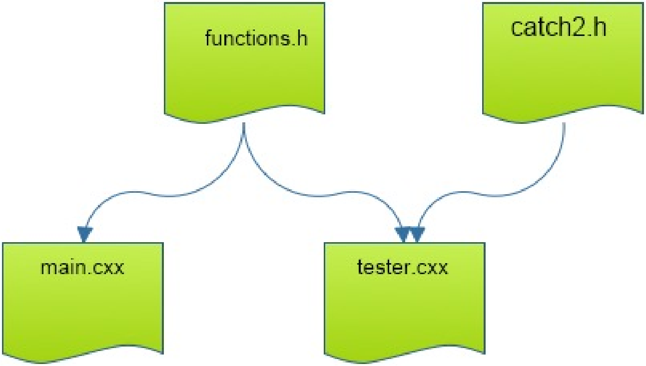


33. Sort of test-driven development

You will solve the ‘eight queens’ problem by

- designing tests for the functionality
- then implementing it

34. File structure



35. Basic object design

Object constructor of an empty board:

```
ChessBoard(int n);
```

Test how far we are:

```
int next_row_to_be_filled()
```

First test:

```
TEST_CASE( "empty board","[1]" ) {
  constexpr int n=10;
  ChessBoard empty(n);
  REQUIRE( empty.next_row_to_be_filled()==0 );
}
```

Exercise 11: Board object

Start writing the `board` class, and make it pass the above test.

Exercise 12: Board method

Write a method for placing a queen on the next row,

```
void place_next_queen_at_column(int i);
```

and make it pass this test (put this in a `TEST_CASE`):

```
REQUIRE_THROWS( empty.place_next_queen_at_column(-1) );
REQUIRE_THROWS( empty.place_next_queen_at_column(n) );
REQUIRE_NOTHROW( empty.place_next_queen_at_column(0) );
REQUIRE( empty.next_row_to_be_filled()==1 );
```

Exercise 13: Test for collisions

Write a method that tests if a board is collision-free:

```
bool feasible()
```

This test has to work for simple cases to begin with. You can add these lines to the above tests:

```
ChessBoard empty(n);
REQUIRE( empty.feasible() );

ChessBoard one = empty;
one.place_next_queen_at_column(0);
REQUIRE( one.next_row_to_be_filled()==1 );
REQUIRE( one.feasible() );

ChessBoard collide = one;
// place a queen in a ‘colliding’ location
collide.place_next_queen_at_column(0);
// and test that this is not feasible
REQUIRE( not collide.feasible() );
```

Exercise 14: Test full solutions

Make a second constructor to 'create' solutions:

```
ChessBoard( int n,vector<int> cols );
ChessBoard( vector<int> cols );
```

Now we test small solutions:

```
ChessBoard five( {0,3,1,4,2} );
REQUIRE( five.feasible() );
```

Exercise 15: No more delay: the hard stuff!

Write a function that takes a partial board, and places the next queen:

```
optional<ChessBoard> place_queens()
```

Test that the last step works:

```
ChessBoard almost( 4, {1,3,0} );
auto solution = almost.place_queens();
REQUIRE( solution.has_value() );
REQUIRE( solution->filled() );
```

Alternative to using `optional`:

```
bool place_queen( const board& current, board &next );
// true if possible, false is not
```

Exercise 16: Test that you can find solutions

Test that there are no 3×3 solutions:

```
TEST_CASE( "no 3x3 solutions","[9]" ) {
  ChessBoard three(3);
  auto solution = three.place_queens();
  REQUIRE( not solution.has_value() );
}
```

but 4×4 solutions do exist:

```
TEST_CASE( "there are 4x4 solutions","[10]" ) {
  ChessBoard four(4);
  auto solution = four.place_queens();
  REQUIRE( solution.has_value() );
}
```