

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.

1: 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:

$$\text{Exception} \equiv \left\{ \begin{array}{l} \text{'this should not happen'} \\ \text{but we can handle it} \end{array} \right.$$

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.

2: 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) { /* .... */ }
```

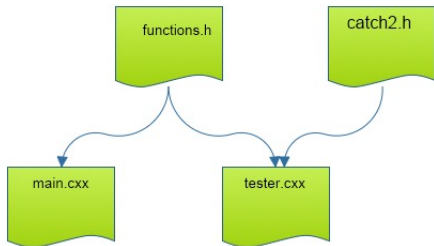
with values in the range $(0, 1)$.

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 input  
    // 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

Suppose 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_NO_THROW( 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

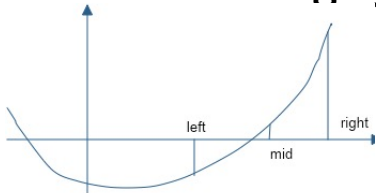
Use SECTION if tests have intro/outtro in common:

```
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)

3: TDD example: Bisection

29. Root finding by bisection



- Start with bounds where the function has opposite signs.

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

- 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

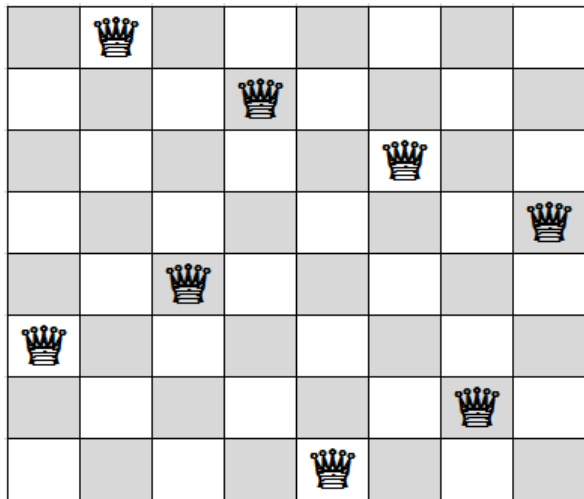
```
coe_bisection -d yourprogram.cc
```

with the -d flag for 'debug'.

4: Eight queens problem

32. Problem statement

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

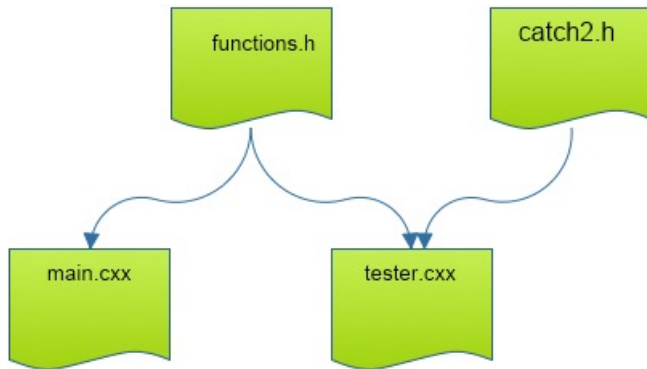


33. Sort of test-driven development

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() );  
}
```