

# Standard Template Library

Victor Eijkhout, Susan Lindsey

Fall 2022

last formatted: August 24, 2022

# 1. Standard Template Library

- C++ is language syntax plus STL:  
headers such as *vector*
- Some people (read: large companies) write their own STL.
- Here are some useful bits from the STL;  
there are many more.

# 1: Random number generation

## 2. What are random numbers?

- Not really random, just very unpredictable.
- Often based on integer sequences:

$$r_{n+1} = ar_n + b \mod N$$

- $\Rightarrow$  they repeat, but only with a long period.
- A good generator passes statistical tests.

### 3. Random generators and distributions

- Random device

```
std::default_random_engine generator;  
% random seed:  
std::random_device r;  
std::default_random_engine generator{ r() };
```

- Distributions:

```
std::uniform_real_distribution<float> distribution(0.,1.);  
std::uniform_int_distribution<int> distribution(1,6);
```

- Sample from the distribution:

```
std::default_random_engine generator;  
std::uniform_int_distribution<> distribution(0,nbuckets-1);  
random_number = distribution(generator);
```

- Do not use the old C-style random!

## 4. Why so complicated?

- Large period wanted; C random has  $2^{15}$ .
- Multiple generators, guarantee on quality.
- Simple transforms have a bias:

```
int under100 = rand() % 100
```

Simple example: period 7, mod 3



## 5. Dice throw

```
// set the default generator
std::default_random_engine generator;

// distribution: ints 1..6
std::uniform_int_distribution<int> distribution(1,6);

// apply distribution to generator:
int dice_roll = distribution(generator);
    // generates number in the range 1..6
```

## 6. Poisson distribution

Another distribution is the Poisson distribution:

```
std::default_random_engine generator;  
float mean = 3.5;  
std::poisson_distribution<int> distribution(mean);  
int number = distribution(generator);
```



# 7. Global engine

Wrong approach:

Code:

```
int nonrandom_int(int max) {  
    std::default_random_engine engine;  
    std::uniform_int_distribution<>  
        ints(1,max);  
    return ints(engine);  
};
```

Output

[rand] nonrandom:

Three ints: 15, 15,  
15.

Good approach:

Code:

```
int realrandom_int(int max) {  
    static std::default_random_engine  
        static_engine;  
    std::uniform_int_distribution<>  
        ints(1,max);  
    return ints(static_engine);  
};
```

Output

[rand] truerandom:

Three ints: 15, 98,  
70.

## 2: Time

## 8. Chrono

```
#include <chrono>

// several clocks
using myclock = std::chrono::high_resolution_clock;

// time and duration
auto start_time = myclock::now();
auto duration = myclock::now()-start_time;
auto microsec_duration =
    std::chrono::duration_cast<std::chrono::microseconds>
        (duration);
cout << "This took "
    << microsec_duration.count() << "usec\n"
```

### 3: More

## 9. Complex numbers

```
#include <complex>

complex<float> f;
f.re = 1.; f.im = 2.;
complex<double> d(1.,3.);

using std::complex_literals::i;
std::complex<double> c = 1.0 + 1i;

conj(c); exp(c);
```

## 10. Example usage

Code:

```
vector< complex<double> > vec1(N,  
    1.+2.5i );  
auto vec2( vec1 );  
/* ... */  
for ( int i=0; i<vec1.size(); i++ ) {  
    vec2[i] = vec1[i] * ( 1.+1.i );  
}  
/* ... */  
auto sum = accumulate  
    ( vec2.begin(),vec2.end(),  
      complex<double>(0.) );  
cout << "result: " << sum << "\n";
```

Output

[complex] vec:

result:

(-1.5e+06,3.5e+06)

## 4: Tuples; Union-like stuff

## 11. C++11 style tuples

```
#include <tuple>

std::tuple<int,double,char> id = \
    std::make_tuple<int,double,char>( 3, 5.12, 'f' );
// or:
std::make_tuple( 3, 5.12, 'f' );
double result = std::get<1>(id);
std::get<0>(id) += 1;

// also:
std::pair<int,char> ic =
    make_pair( 24, 'd' );
```

Annoyance: all that 'get'ting.



## 12. Function returning tuple

Return type deduction:

```
auto maybe_root1(float x) {  
    if (x<0)  
        return make_tuple  
            <bool,float>(false,-1);  
    else  
        return make_tuple  
            <bool,float>(true,sqrt(x));  
};
```

Alternative:

```
tuple<bool,float>  
    maybe_root2(float x) {  
    if (x<0)  
        return {false,-1};  
    else  
        return {true,sqrt(x)};  
};
```

## 13. Catching a returned tuple

The calling code is particularly elegant:

Code:

```
auto [succeed,y] = maybe_root2(x);  
if (succeed)  
    cout << "Root of " << x  
          << " is " << y << "\n";  
else  
    cout << "Sorry, " << x  
          << " is negative" << "\n";
```

Output

[stl] tuple:

```
Root of 2 is 1.41421  
Sorry, -2 is negative
```

This is known as structured binding.

## 14. Returning two things

simple solution:

```
bool RootOrError(float &x) {  
    if (x<0)  
        return false;  
    else  
        x = sqrt(x);  
    return true;  
};  
/* ... */  
for ( auto x : {2.f,-2.f} )  
    if (RootOrError(x))  
        cout << "Root is " << x << "\n";  
    else  
        cout << "could not take root of " << x << "\n";
```

other solution: tuples

## 15. Tuple solution

```
tuple<bool,float> RootAndValid(float x) {  
    if (x<0)  
        return {false,x};  
    else  
        return {true,sqrt(x)};  
};  
  
/* ... */  
for ( auto x : {2.f,-2.f} )  
    if ( auto [ok,root] = RootAndValid(x) ; ok )  
        cout << "Root is " << root << "\n";  
    else  
        cout << "could not take root of " << x << "\n";
```

## 5: Variants

# 16. Variant

```
#include <variant>
```

```
variant<int,double,string> union_ids;
```

```
union_ids = 3.5;
```

```
switch ( union_ids.index() ) {
```

```
case 1 :
```

```
    cout << "Double case: " << std::get<double>(union_ids) << "\n";  
}
```

```
union_ids = "Hello world";
```

```
if ( auto union_int = get_if<int>(&union_ids) ; union_int )
```

```
    cout << "Int: " << *union_int << "\n";
```

```
else if ( auto union_string = get_if<string>(&union_ids) ; union_string  
    )
```

```
    cout << "String: " << *union_string << "\n";
```

# Exercise 1

Write a routine that computes the roots of the quadratic equation

$$ax^2 + bx + c = 0.$$

The routine should return two roots, or one root, or an indication that the equation has no solutions.

Code:

```
for ( auto coefficients :  
    { make_tuple(2.0, 1.5, 2.5),  
      make_tuple(1.0, 4.0, 4.0),  
      make_tuple(2.2, 5.1, 2.5)  
    } ) {  
    auto result =  
        compute_roots(coefficients);
```

Output

[union] quadratic:

With a=2 b=1.5 c=2.5

No root

With a=2.2 b=5.1  
c=2.5

Root1: -0.703978

root2: -1.6142

With a=1 b=4 c=4

Single root: -2

## 17. Problem setup

Represent the polynomial

$$ax^2 + bx + c$$

as

```
using quadratic = tuple<double,double,double>;
```

Unpack:

```
auto [a,b,c] = coefficients;
```

assert something here?



## Exercise 2

Write a function

```
double discriminant( quadratic coefficients );
```

that computes  $b^2 - 4ac$ , and test:

```
TEST_CASE( "discriminant" ) {  
    REQUIRE( discriminant( make_tuple(0., 2.5, 0.) )  
        ==Catch::Approx(6.25) );  
    REQUIRE( discriminant( make_tuple(1., 0., 1.5 ) )  
        ==Catch::Approx(-6.) );  
    REQUIRE( discriminant( make_tuple(.1, .1, .1*.5 ) )  
        ==Catch::Approx(-.01) );  
}
```

## Exercise 3

Write a function

```
bool discriminant_zero( quadratic coefficients );
```

that passes the test

```
quadratic coefficients = make_tuple(a,b,c);  
d = discriminant( coefficients );  
z = discriminant_zero( coefficients );  
INFO( a << ", " << b << ", " << c << " d=" << d );  
REQUIRE( z );
```

Using for instance the values:

```
a = 2; b = 4; c = 2;  
a = 2; b = sqrt(40); c = 5; // !!!  
a = 3; b = 0; c = 0.;
```

## Exercise 4

Write the function *simple\_root* that returns the single root. For confirmation, test

```
auto r = simple_root(coefficients);  
REQUIRE( evaluate(coefficients,r)==Catch::Approx(0.).margin(1.e-14) );
```

## Exercise 5

Write a function that returns the two roots as a `indexcstdpair`:

```
pair<double,double> double_root( quadratic coefficients );
```

Test:

```
quadratic coefficients = make_tuple(a,b,c);  
auto [r1,r2] = double_root(coefficients);  
auto  
    e1 = evaluate(coefficients,r1),  
    e2 = evaluate(coefficients,r2);  
REQUIRE( evaluate(coefficients,r1)==Catch::Approx(0.).margin(1.e-14) );  
REQUIRE( evaluate(coefficients,r2)==Catch::Approx(0.).margin(1.e-14) );
```

# Exercise 6

Write a function

```
variant< bool,double, pair<double,double> >  
    compute_roots( quadratic coefficients);
```

Test:

```
TEST_CASE( "full test" ) {  
    double a,b,c; int index;  
    SECTION( "no root" ) {  
        a=2.0; b=1.5; c=2.5;  
        index = 0;  
    }  
    SECTION( "single root" ) {  
        a=1.0; b=4.0; c=4.0;  
        index = 1;  
    }  
}
```

```
SECTION( "double root" ) {  
    a=2.2; b=5.1; c=2.5;  
    index = 2;  
}  
quadratic coefficients =  
    make_tuple(a,b,c);  
auto result =  
    compute_roots(coefficients);  
REQUIRE( result.index()==index );  
}
```

## 6: Optional

## 18. Optional results (C++17)

The most elegant solution to 'a number or an error' is to have a single quantity that you can query whether it's valid.

```
#include <optional>

optional<float> MaybeRoot(float x) {
    if (x<0)
        return {};
    else
        return sqrt(x);
};

/* ... */
for ( auto x : {2.f,-2.f} )
    if ( auto root = MaybeRoot(x) ; root.has_value() )
        cout << "Root is " << root.value() << "\n";
    else
        cout << "could not take root of " << x << "\n";
```

## Exercise 7

Write a function *first\_factor* that optionally returns the smallest factor of a given input.

```
auto factor = first_factor(number);  
if (factor.has_value())  
    cout << "Found factor: " << factor.value() << "\n";
```



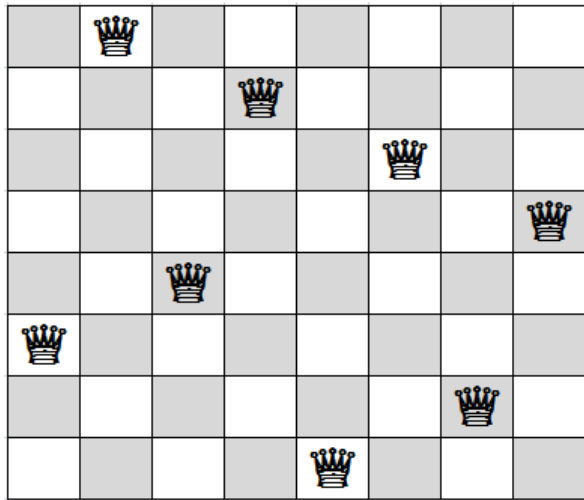
## 19. Any

If you want a variant that can be anything,  
use `std::any`.

## 7: Eight queens problem

## 20. Classic problem

Can you put 8 queens on a board so that they can't hit each other?



## 21. Statement

- Put eight pieces on an  $8 \times 8$  board, no two pieces on the same square; so that
- no two pieces are on the same row,
- no two pieces are on the same column, and
- no two pieces are on the same diagonal.

## 22. Not good solution

A systematic solution would run:

1. put a piece anywhere in the first row;
2. for each choice in the first row, try all positions in the second row;
3. for all choices in the first two rows, try all positions in the third row;
4. when you have a piece in all eight rows, evaluate the board to see if it satisfies the condition.

Better: abort search early.

## Exercise 8: Board class

Class *board*:

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

Method to keep track how far we are:

```
int next_row_to_be_filled()
```

Test:

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

## Exercise 9: Place one queen

Method to place the next queen,  
without testing for feasibility:

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

This test should catch incorrect indexing:

```
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 );
```

Without this test, would you be able to cheat?

## Exercise 10: Test if we're still good

Feasibility test:

```
bool feasible()
```

Some simple cases:

(add to previous test)

```
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() );
```



## Exercise 11: Test collisions

```
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 12: Test a full board

Construct full solution

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

Test:

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

# Exercise 13: Exhaustive testing

This should now work:

```
// loop over all possibilities first queen
auto firstcol = GENERATE_COPY( range(1,n) );
ChessBoard place_one = empty;
REQUIRE_NOTHROW( place_one.place_next_queen_at_column(firstcol)
    );
REQUIRE( place_one.feasible() );

// loop over all possibilities second queen
auto secondcol = GENERATE_COPY( range(1,n) );
ChessBoard place_two = place_one;
REQUIRE_NOTHROW( place_two.place_next_queen_at_column(secondcol)
    );
if (secondcol < firstcol-1 or secondcol > firstcol+1) {
    REQUIRE( place_two.feasible() );
} else {
    REQUIRE( not place_two.feasible() );
}
```

## Exercise 14: Place if possible

You need to write a recursive function:

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

- place the next queen.
- if stuck, return 'nope'.
- if feasible, recurse.

```
class board {  
    /* stuff */  
    optional<board> place_queens() const {  
        /* stuff */  
        board next(*this);  
        /* stuff */  
        return next;  
    };  
};
```

## Exercise 15: Test last step

Test *place\_queens* on a board that is almost complete:

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

Note the new constructor! (Can you write a unit test for it?)

## Exercise 16: Sanity tests

```
TEST_CASE( "no 2x2 solutions", "[8]" ) {  
    ChessBoard two(2);  
    auto solution = two.place_queens();  
    REQUIRE( not solution.has_value() );  
}
```

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

## Exercise 17: 0

ptional: can you do timing the solution time as function of the size of the board?