

Iterators and Ranges for numerical problems

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Outline

- 1 Motivation and introduction
- 2 Problem 1 – Numerical sequences
- 3 Problem 2 – Dynamical systems
- 4 Problem 3 – Convergence methods
- 5 Conclusion

Motivation

Problem: Find the root of a function $0 = f(x)$

Newtons algorithm: $x_{n+1} = x_n - f(x)/f'(x)$

```
auto newton( auto x , auto f , auto df ) {  
    while( std::abs( f(x) ) > 1.0e-12 )  
        x = x - f(x) / df( x );  
    return x;  
}  
  
double x = 1.0;  
auto f = []( auto x ) { return exp( -x*x ) - 0.5 ; };  
auto df = []( auto x ) { return -2.0*x * exp( -x*x ); };  
double root = newton( x , f , df );
```

Motivation

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double x = 1.0;  
auto f = []( auto x ) { return exp( -x*x ) - 0.5 ; };  
auto df = []( auto x ) { return -2.0*x * exp( -x*x ); };  
double root = newton( x , f , df );
```

Idea – Return a range, that the user can iterate:

```
auto newton( auto x , auto f , auto df ) { ... }  
double x = 1.0;  
auto range = newton( x , f , df );  
for( auto x : range ) cout << x << endl;  
cout << "Final value: " << range.value() << endl;
```

Motivation

Use iterators and ranges for three problems:

- Numerical Sequences
- Dynamical systems
- Convergence algorithms

The range is here a proxy for the algorithm!

The user can look inside the algorithm!

→ Debugging, logging, combine with other algorithms, ...

Iterators – Overview

Operations

- Increment, dereference, assign, copy, decrement, ...

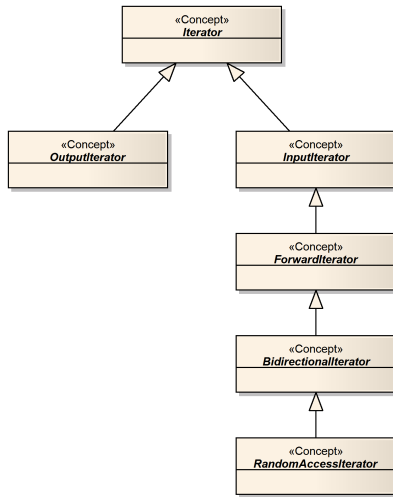
Use cases

- Traverse containers, IO, expressing algorithms

Special iterators

- `zip_iterator`, `transform_iterator`, ...

Iterator concepts



Ranges

- Simplify the usage of iterators
- Generalization of iterators
- Ranges in boost:
 - Ranges are pairs of iterators.
 - Ranges can be adapted/decorated.

```
vector< double > values;  
// fill values  
boost::for_each( values , []( auto x ) {  
    cout << x << endl; } );
```


Ranges for the C++ standard library

Eric Niebler: N4128: Ranges for the Standard Library.

- Ranges are based on iterators
- New concepts:
 - Iterable – Container, holding the elements
 - Range – Lightweight adapters (decorators)
- Three kinds of ranges
 - Iterator pairs, Iterator and a count, Iterator and a predicate
- Variants of each algorithm
 - `sort(in);`
 - `sort(in.begin() , in.end());`
 - `in | view::transform(op);`
 - `in | cont::sort(op);`

Numerical sequences

Numerical sequences

In numerical algorithms one needs often sequences of numerical values

- As part of an algorithm
- Reference data
- Test data

Numerical sequences

```
int n = 1024;  
auto seq = boost::counting_range( 0 , n );  
for( auto x : seq )  
    cout << x << " ";
```

Output

0 1 2 3 ...

Numerical sequences

Range is a proxy object for the sequence

```
using namespace boost::adaptors;

auto seq = boost::counting_range( 0 , n );
auto seq2 = seq | transformed( []( auto x ) {
    return 0.1 * static_cast< double >( x ); } );

for( auto x : seq2 )
    cout << x << " ";
```

Output

0 0.1 0.2 0.3 ...

Numerical sequences

Range is a proxy object for the sequence

```
auto seq = boost::counting_range( 0 , n );  
auto seq2 = seq | transformed( []( auto x ) {  
    return 0.01 * static_cast< double >( x ); } );  
auto seq3 = seq2 | transformed( []( auto x ) { return sin(  
    2.0 * x ) + 0.1; } );  
  
for( auto x : seq3 )  
    cout << x << " ";
```

Output

0.1 0.298669 0.489418 0.664642 ...

Numerical sequences

Use a function

```
auto sequence( int n , double sampling , auto f ) {  
    auto seq = boost::counting_range( 0 , n );  
    return seq | transformed( [sampling,f]( auto x ) {  
        return f(sampling*static_cast<double>( x ) ); } );  
}  
  
auto seq = sequence(1024 ,0.1 ,[]( auto x ) {  
    return sin(2.0*x)+0.1;} );  
for( auto x : seq )  
    cout << x << " ";
```

Output

0.1 0.298669 0.489418 0.664642 ...

Combining numerical sequences

Zip sequences

```
using std::view;
```

Append sequences?

Cartesian sequences?

Numerical ranges and standard C++ Ranges

Infinite sequences:

```
using std::view;
auto sequence( double sampling , auto f ) {
    return iota(0) | transform( [sampling,f]( auto x ) {
        return f( sampling * x ); } );
}

for( auto x : take( sequence( 0.1 , f ) , 10 ) )
    cout << x << endl;
```

Custom break conditions:

```
auto seq = take_while( sequence( 0.1 , f ) , []( auto x ) {
    return x < 1.0; } );
for( auto x : seq )
    cout << x << endl;
```

Dynamical systems

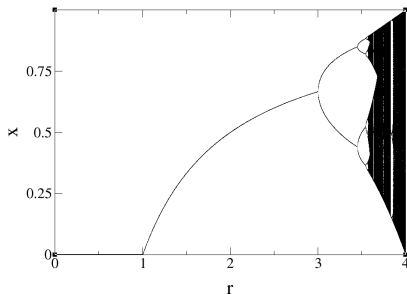
Dynamical systems – Maps

Map – time discrete dynamical system:

$$x_{n+1} = f(x_n)$$

Example: Logistic map

$$x_{n+1} = r x_n (1 - x_n)$$



Map range

Abstraction for $x_{n+1} = f(x_n)$

Two versions:

- 1 `map_range` - **stop predicate**
- 2 `counted_map_range` - iterates n -times

Models the `SinglePassRange` concept

Map range

```
template< typename T , typename F , typename C >
class map_range
{
    struct iterator { ... };

public:
    map_range( T value , F func , C condition )
        : m_value { std::move( value ) }
        , m_func { std::move( func ) }
        , m_condition( condition )
    {}

    iterator begin() const { return iterator( this ); }
    iterator end() const { return iterator( nullptr ); }

private:
    mutable T m_value;
    mutable F m_func;
    C m_condition;
};
```

Map range

```
struct iterator {
    iterator( map_range const* _r ) : r( _r ) {}

    iterator& operator++() {
        r->m_value = r->m_func( r->m_value );
        if( r->m_condition( r->m_value ) ) {
            r = nullptr;
        }
        return *this;
    }

    T& operator*() const {
        return r->m_value; }
    bool operator==( iterator const& o ) const {
        return ( r == o.r ); }
    bool operator!=( iterator const& o ) const {
        return ! ( *this == o ); }
}

map_range const* r;
};
```

Factory functions

```
template< typename T , typename F , typename C >
auto make_map_range( T t , F f , C condition )
{
    return map_range< T , F , C >(
        std::move( t ) ,
        std::move( f ) ,
        std::move( condition ) );
}
```

```
template< typename T , typename F >
auto make_counted_map_range( T t , F f , size_t
    max_iterations )
{
    return counted_map_range< T , F >(
        std::move( t ) ,
        std::move( f ) ,
        max_iterations );
}
```

Example - logistic map

```
double r = 3.2;
auto l = [r]( auto x ) {return r * x * ( 1.0 - x ); };

auto range = make_counted_map_range( 0.5 , 1 , 1000 );
for( auto x : range )
{
    cout << x << endl;
}
```


Dynamical system – cellular automaton

Cellular automaton: Time-discrete and value-discrete

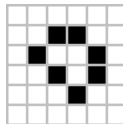
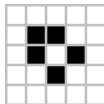
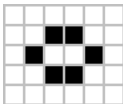
Conway's Game of Life

- Each cell has two states: *alive* or *dead*
- Transition rules
 - Less than two neighbors -> dead (under-population)
 - Two or three neighbors -> alive
 - More than three neighbors -> dead (over-population)
 - Dead cell with three neighbors -> alive (reproduction)

Game of life – patterns

Still lifes:

Oscillators:



Conway's game of life

```
using board = vector< vector< bool > >;

auto show_board = [] ( board const& b ) { ... }
auto next_board = [] ( board const& b ) -> board { ... }

board b;
// initialize b

auto r = make_counted_map_range( b , next_board , 1000 );
for( auto b : r )
{
    show_board( b );
}
```

Map range for time discrete dynamical systems

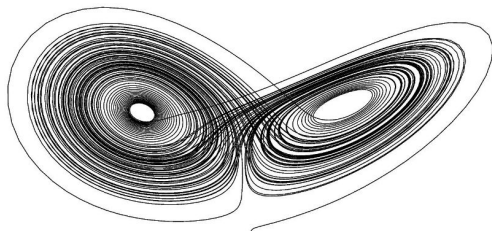
- The range is a proxy for the dynamical system
 - Customizable iteration body
 - Custom stopping criterions
 - *N*-times iteration
- Not optimized - a custom range could be optimized

Dynamical systems – ODEs

$$\frac{dx}{dt} = f(x, t)$$

Example: Lorenz attractor

$$\dot{x} = \sigma(y - x) \quad , \quad \dot{y} = x(\rho - z) - y \quad , \quad \dot{z} = xy - \beta z$$



Numerical solution: $x(t + \Delta t) = F(x(t))$

Example – ODE solver

Solve $\dot{x} = f(x, t)$, Solver $F : x(t + \delta t) = F(x(t))$

Example Boost.Odeint:

```
namespace odeint = boost::numeric::odeint;

auto lorenz = []( auto const& x , auto& dxdt , auto t )
{
    dxdt[0] = 10.0 * ( x[1] - x[0] );
    dxdt[1] = 28.0 * x[0] - x[1] - x[0] * x[2];
    dxdt[2] = -8.0 / 3.0 * x[2] + x[0] * x[1];
};

using state_type = std::array< double , 3 >;
odeint::runge_kutta4< state_type > stepper;

state_type x {{ 10.0 , 10.0 , 10.0 }};
double t = 0.0 , dt = 0.01;
stepper.do_step( lorenz , x , t , dt );
t += dt;
```

Integrate functions:

```
auto obs = []( auto x , auto t ) { std::cout << t << " " << x[0] << "\n"; };
odeint::integrate_const( stepper , lorenz , x , 0.0 , 10.0 , dt , obs );
```

Example – ODE solver

```
auto make_ode_range( auto sys , auto stepper , auto x ,
    auto t0 , auto dt , auto t1 )
{
    auto solve = [sys,stepper,dt]( auto x ) mutable {
        stepper.do_step( sys , x.first , x.second , dt );
        x.second += dt;
        return x; };
    auto cond = [t1]( auto const& x ) { return x.second > t1; };
    auto range = make_map_range( std::make_pair(x,t0) , solver , cond );
    return range;
}
```

Can be used as

```
state_type x {{ 10.0 , 10.0 , 10.0 }};
stepper_type stepper;
auto range = make_ode_range( lorenz , stepper , x , 0.0 , 0.1 , 100.0 );

for( auto r : range )
    std::cout << r.second << " " << r.first[0] << " " << r.first[1] << "\n";
```

ODE ranges

Superior to integrate functions:

- Break conditions are easy
- ODE-Ranges can be used in a natural C++ way, `find`, `transform`, etc.

Map implementation has drawbacks -> custom implementation

- Better performance.
- Step size control – complicated iteration.
- Break condition can use the last two values.

Convergence methods

Newton method

Find the root: $0 = f(x)$

Newtons method

- Choose x_0
- Iterate $x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$

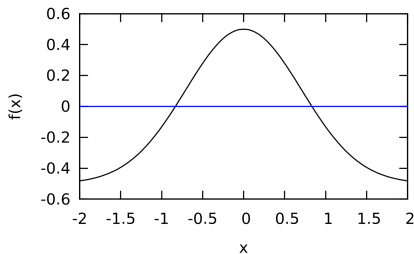
Newton method – Implementation

```
auto newton_range(  
    auto x , auto f , auto df ,  
    auto break_condition )  
{  
    return make_map_range(  
        x ,  
        [f,df]( auto x ) { return x - f( x ) / df( x ); } ,  
        break_condition );  
}
```

Newton method – Example

Solve $\exp(-x^2) - 0.5 = 0$

```
auto f = []( auto x ) { return exp(-x*x) - 0.5; };  
auto df = []( auto x ) { return -2.0*x * exp(-x*x); };  
auto cond = [f]( auto x ) {  
    return std::abs(f(x)) < 1.0e-12; };  
  
auto range = newton_range( 1.0 , f , df , cond );  
  
for( auto r : range )  
    std::cout << r << " : " << f( r ) << std::endl;
```



Similar problems

- Optimizations methods
 - Broyden-Fletcher-Goldfarb-Shanno algorithm (BFGS)
 - Simulated annealing
 - Genetic algorithms
 - Genetic programming
 - ...
- Approximation of functions
- ...

Conclusion

- Iterators and ranges can be used for numerical problems
 - Numerical sequences, dynamical systems, optimization methods, ...
- Range is a proxy for the algorithm
- Custom range implementation needed for optimal performance

Outlook – open points

- Break condition on last two values, e.g. $|v_k - v_{k-1}| < \epsilon$
- More complicated break condition, e.g. count and predicate

References

- `odeint`
- github talk
- github map range

Backup

Example – basic use

```
for( auto iter = values.begin() ;  
    iter != values.end() ;  
    ++iter )  
{  
    cout << *iter << endl;  
}
```

Example – basic use

```
for( auto iter = values.begin() ;  
    iter != values.end() ;  
    ++iter )  
{  
    cout << *iter << endl;  
}
```

C++11 - use range based for

```
for( auto v : values )  
{  
    cout << v << endl;  
}
```

Example – Container traversal

```
list< double > values;  
list< double > values2( values.size() );
```

Can be used in

```
transform( values.begin() , values.end() ,  
           values2.begin() ,  
           []( double x ) {  
               return x * 2.0; } );
```

Example – Container traversal

```
vector< double > values;  
vector< double > values2( values.size() );
```

Can be used in

```
transform( values.begin() , values.end() ,  
           values2.begin() ,  
           []( double x ) {  
               return x * 2.0; } );
```

Examples – IO

Input

```
vector< double > values;  
copy_if( istream_iterator< double >( cout ) ,  
         istream_iterator< double >() ,  
         back_inserter( values ) ,  
         []( double x ) { return x > 0.0; } );
```

Output

```
vector< double > values;  
// fill values  
copy_if( values.begin() , values.end() ,  
         ostream_iterator< double >( std::cout , "\n" ) ,  
         []( double x ) { return x > 0.0; } );
```

Algorithms

I all_of	F remove	I is_partitioned	R is_heap
I any_of	F remove_if	F,B partition	R is_heap_until
I none_of	I,O remove_copy	I,O partition_copy	R make_heap
I for_each	I,O	B stable_partition	R push_heap
I count	remove_copy_if	F partition_point	R pop_heap
I count_if	F replace	F is_sorted	R sort_heap
I mismatch	F replace_if	F is_sorted_until	<u>F max_element</u>
I equal	I,O replace_copy	R sort	F min_element
I find	I,O	R partial_sort	F minmax_element
I find_if	replace_copy_if	I,R partial_sort_copy	I lexicographical_compare
I find_if_not	F swap_ranges	R stable_sort	F is_permutation
F find_end	F iter_swap	<u>R nth_element</u>	B next_permutation
I,F find_first_if	B reverse	<u>F lower_bound</u>	<u>B prev_permutation</u>
F adjacent_find	B,O reverse_copy	F upper_bound	<u>F iota</u>
F search	F rotate	F binary_search	I accumulate
F search_n	F,O rotate_copy	F equal_range	I inner_product
I,O copy	R random_shuffle	I,O merge	I,O adjacent_difference
I,O copy_if	R shuffle	B inplace_merge	I,O partial_sum
I,O copy_n	F unique	I includes	
B,O copy_backward	I,O unique_copy	I,O set_difference	
I,O move		I,O set_intersection	
B,O move_backward		I,O	
F fill		set_symmetric_difference	
F fill_n		I,O set_union	
I,O transform			
F generate			
I generate_n			

Examples – generalized iota

Generalized Iota:

```
size_t n = 10;
auto iota = make_counted_map_range( 1 , [] ( auto x ) {
    return x * 2; } , 10 );

std::vector< int > values;
boost::copy( iota_range , std::back_inserter( values ) );
for( auto i : values ) { cout << i << endl; }
```

Examples – generalized iota

Problem: We can not easily generate a square iota:
1, 4, 9, 16, 25, 36, ...

Examples – generalized iota

Problem: We can not easily generate a square iota:

1, 4, 9, 16, 25, 36, ...

Introduce a projected map range.

```
auto iota_range = make_projected_counted_map_range(  
    1  
    , []( auto x ) { return x+1 ; }  
    , 11  
    , []( auto x ) { return x*x; }  
    );  
for( auto i : iota_range ) { std::cout << i << std::endl; }
```

Map range - applications

- Generalized iota
- Ordinary differential equations
- Maps (dynamical maps)
- Functional random number generators
- Optimization methods
 - Genetic algorithms, Simulated annealing, ...

Map range - applications

- Generalized iota
- Ordinary differential equations
- Maps (dynamical maps)
- Converging algorithms
- Functional random number generators

Iterators for GPUs algorithms

High-level libraries for GPUs

- Thrust
- VexCL
- Boost.Compute
- ViennaCL
- Cuda-MTL

Thrust

Thrust is STL-like library for Cuda – Based on iterators.

```
thrust::host_vector<int> h_vec( 1024 );  
std::generate(h_vec.begin(), h_vec.end(), rand);  
  
thrust::device_vector<int> d_vec = h_vec;  
thrust::sort(d_vec.begin(), d_vec.end());  
  
thrust::copy(d_vec.begin(), d_vec.end(), h_vec.begin());
```

Iterators in Thrust

- `device_vector< T >::iterator`
- `host_vector< T >::iterator`
- **Special (fancy) iterator**
 - `zip_iterator`
 - `transform_iterator`
 - `permutation_iterator`
 - `constant_iterator`, `counting_iterator`,
`discard_iterator`, `reverse_iterator`

Custom algorithms

Special iterators for Thrust

Calculate the norm of a vector

$$||x|| = \sum_{i=1}^N x_i^2$$

```
thrust::device_vector< double > x;  
// fill x  
  
double n = thrust::reduce(x.begin(), x.end(), 0.0); // ?
```


Special iterators for Thrust

Calculate the norm of a vector

$$||x|| = \sum_{i=1}^N x_i^2$$

```
thrust::device_vector< double > x;  
// fill x  
  
auto op = []( auto x , auto y ) { return x + y*y; };  
double n = thrust::reduce(x.begin() , x.end() , 0.0 , op); //  
?
```

Special iterators for Thrust

Calculate the norm of a vector

$$||x|| = \sum_{i=1}^N x_i^2$$

```
thrust::device_vector< double > x;  
// fill x  
  
op = []( auto x ) { return x*x; };  
double n = thrust::reduce(  
    thrust::make_transform_iterator(x.begin(), op) ,  
    thrust::make_transform_iterator(x.end(), op), 0.0);  
// correct
```

SAXPY

$$s = ax + y$$

$$s, x, y \in \mathbb{R}^N, a \in \mathbb{R}$$

Special problems - and solutions

Bucket sort

Solving an ensemble of low-dimensional ODEs

Lorenz example and ODEs