High Level Programming

Programming with the STL

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The algorithm library

- Instead of defining each operation as a part of a container, the standard library defines a set of generic algorithms
  - **Generic:** because they operate on elements of different type
  - **Algorithms:** because they implement classical procedures, like sorting, searching, etc.
- Generic algorithms are included in four headers
  - Algorithm, numeric, memory, cstdlib
  - Algorithm defines the most relevant parts (more than 100 functions) to
    - Find, search, sort, combinatorics functions, set operations, etc.

The algorithm library

For more operations see the reference documentation

Type	Meaning
find	Algorithms to find an object.
binary_search	Algorithms to perform a binary search.
partitioning	Divide elements into two groups; the first group includes elements that satisfy a predicate; the second group those that do not satisfy it.
sort	Several sorting algorithm (stable, non-stable, etc.).
rotate (shuffle)	Rotate (randomly reorder) elements
permutation	Generate lexicographical permutation of a sequence.
set	Set algorithms (inclusion, union, intersection, etc.) on sorted sets.
min (max)	Minimum (maximum) value.
sum (difference)	Numeric algorithms.

The algorithm library

- It is essential to understand the structure of these algorithms rather than memorize their details
- They perform an operation on a range of elements
  - Ranges can be specified using pointers or any appropriate iterator type
  - In all following examples
    - **b** is the begin iterator
    - **e** the end iterator
    - **v** a value

The algorithm library

- Many algorithms require a predicate
  - A predicate is an expression that can be called and returns a value that can be used as a condition
  - The default version of the algorithm usually uses a standard predicate
    - The operator is related to the type of the element, e.g., less than <, equal to ==, etc.
  - The extended version usually supplies its own **predicate** operator
    - In the following examples
      - **up** indicates a unary predicate (with one operand)
      - **bp** indicates a binary predicate (with two operands)

Search

- The library offers a variety of search functions
  - Different operations for sorted and unsorted ranges
    - In general, searching on sorted ranges is faster
    - Sorting will pay off for repeated lookups
- General semantics
  - Search operations return iterators pointing to the result
  - Unsuccessful operations are usually indicated by returning the **end** iterator

Search

- Several variants are possible

Type	Meaning
find(b,e,v)	Return an iterator to the first element in the input range equal to val.
find_if(b,e,up)	Return an iterator to the first element for which the predicate pred succeeds.
count(b,e,v)	Count matching elements.
count_if(b,e,up)	Count how many times pred succeeds.
all_of(b,e,up)	Return a bool if pred succeds for all elements (similarly for any_of and some_of).
search(b1,e1,b2,e2, bp)	Return an iterator to the first position of the input range at which the second range occur as a subsequence.

Examples

```
#include <algorithm>
#include <vector>

std::vector<int> v = {2, 6, 1, 7, 3, 7};

auto res1 = std::find(v.begin(), v.end(), 7);
// res1 refer the first value equal to 7 in the sequence

auto res2 = std::find(v.begin(), v.end(), 9);
// no 9 in the sequence; the end iterator is returned
if(res2 == v.end())
  std::cout << "Not found!";
```

This is a value

Binary search

- On sorted ranges, the library offers binary search operations
  - Require forward iterators but are faster with random iterators
  - These algorithms execute a logarithmic number of comparison
    - Complexity $O(log(N))$
    - However, when use with forward iterators make a linear number of iterator operations
  - They can employ custom comparison function
    - Please, see section of lambda functions

Binary search

- Elements in the input sequence must be sorted

Type	Meaning
lower_bound(b,e,v)	Returns and iterator denoting the first element such that val is not less than that element.
upper_bound(b,e,v)	Returns and iterator denoting the first element such that val is less than that element.
equal_range(b,e,v)	Return a pair: The first member returned by lower_bound and the second by upper_bound.
binary_search(b,e,v)	Return a bool indicating whether the sequence contains a value equal to val.

Examples

```
#include <algorithm>
#include <vector>

vector<int> arr1 = { 10, 15, 20, 25, 30, 35 };
vector<int> arr2 = { 10, 15, 20, 20, 25, 30, 35 };
vector<int> arr3 = { 10, 15, 25, 30, 35 };

// prints 2
cout <<
  lower_bound(arr1.begin(), arr1.end(), 20) - arr1.begin()
  << endl;

// prints 2
cout <<
  lower_bound(arr2.begin(), arr2.end(), 20) - arr2.begin();
  << endl;

// prints 2 (index of next higher)
cout <<
  lower_bound(arr3.begin(), arr3.end(), 20) - arr3.begin();
   << cout;
```

This is a value

Examples

```
#include <algorithm>
#include <vector>

vector<int> arr = { 10, 15, 20, 25, 30, 35 };

// Use binary_search to check if 15 exists
if (binary_search(arr.begin(), arr.end(), 15))
  cout << "15 exists in vector";
else
  cout << "15 does not exist";
cut << endl;

// Use binary_search to check if 23 exists
if (binary_search(arr.begin(), arr.end(), 23))
  cout << "23 exists in vector";
else
  cout << "23 does not exist";
```

This is a value

Sort

- The sort algorithm orders all elements
  - They need a random-access iterator
  - Each algorithms is given in two forms
    - The first one, use the operator "<" to compare elements
    - The second one, takes an extra parameters that specifies an ordering relation
  - Algorithms do not guarantee the order of equal elements
  - Usually, they need $O(N \cdot \log(N))$ comparisons

Sort

- All following functions have two versions
  - The first with a standard comparison function
  - The second with a third parameter (bp, i.e., a binary predicate) to specify the comparison operator

Type	Meaning
sort(b,e,bp)	**Sort** an entire range.
stable_sort(b,e,bp)	As before, bur with a **stable** sorting procedure.
is_sorted(b,e,bp)	Returns a bool to indicate whether the range is sorted.
is_sorted_until(b,e,bp)	Checks if a (partial) range is sorted.
partial_sort(b,mid,e,bp)	Sorts all elements between mid-b and places those elements at the beginning of the range.

Examples

```
#include <algorithm>
#include <vector>

std::vector<unsigned> v={3,4,1,2};
...
std::sort(v.begin(),v.end());
// Now v is 1, 2, 3, 4
```

Sort uses the standard comparison function for integers (<)

```
#include <algorithm>
#include <vector>

std::vector<string> words = {...};

bool isShorter (const string &s1, contr string &s2) {
  return s1.size() < s2.size();
}


sort (words.begin(), words.end(), isShorter);
// Now the array word is alphabetically sorted
```

Ad-hoc comparison function

Sort uses an ad-hoc comparison function (predicate)

Examples

```
#include <vector>
#include <algorithm>
using namespace std;

vector<int> v = { 10, 10, 30, 30, 30, 100, 10,
                  300, 300, 70, 70, 80 };

std::pair<std::vector<int>::iterator,
std::vector<int>::iterator> ip;

// Sorting the vector v
sort(v.begin(), v.end());
// v becomes 10 10 10 30 30 30 70 70 80 100 300 300

// Using std::equal_range to compare elements with 30
ip = std::equal_range(v.begin(), v.begin() + 12, 30);

// Display the subrange bounds
cout << "30 is present in the sorted vector from index "
     << (ip.first - v.begin()) << " till "
     << (ip.second - v.begin());
```

Sort and other function used together

Sort uses the standard comparison function for integers (<)

Permutations

- The permutation algorithms generate lexicographic permutations of a sequence
  - The algorithms reorder a permutation to generate the next or previous permutation in a given sequence
    - The permutation are listed in lexicographical order based on the less than operator
    - Example: abc, acb, bac, bca, cab, cba
  - The algorithm may proceed forward and backward in the permutation
    - It requires a bidirectional iterator
  - A custom comparison function can be supplied (see belove)

Permutations

- The algorithms assume that the element of the sequence are unique
  - Please remind, simple permutation versus permutation with repetition

Type	Meaning
is_permutation(b1,e1,b2,bp)	Return true if there is a permutation of the second sequence with all elements of the first sequence.
next_permutation(b,e,bp)	Tranform the input sequence into the next sequence (or the first one if the input sequence is the last one).
prev_permutation(b,e,bp)	As before, but in reverse order.

Examples

Print all permutation of the string "abc"
abc, acb, bca, cba, bca, cba

```
#include <algorithm>
#include <string>
#include <iostream>

int main() {
  std::string s = "abc";
  std::sort(s.begin(), s.end());
  do {
    std::cout << s << '\n';
  } while(std::next_permutation(s.begin(), s.end()));
}
```

Sort uses the standard comparison function for integers (<)

With the string s="aba" it prints
aba, baa, aab

Set algorithms

- Set operations are possible on a sequence that is in sorted order

Type	Meaning
includes(b1,e1,b2,e2,bp)	Returns true if every element of the second sequence is present in the first sequence.
set_union(b1,e1,b2,e2,bp)	Create a sorted sequence with the elements that are in either sequence.
set_intersection(b1,e1,b2,e2,bp)	Create a sorted sequence with the elements that are in both sequences.
set_difference(b1,e1,b2,e2,bp)	Create a sorted sequence with the elements present in the first sequence but not in the second.
set_symmetric_difference (b1,e1,b2,e2,bp)	Create a sorted sequence of elements present in either sequence but not in both.

Examples

We need to introduce sets to better understand this example !

```
#include <iostream>
#include <algorithm>
#include <iterator>
#include <set>

int main() {
  int a[] = { 1, 3, 5 };
  int b[] = { 0, 2, 4, 6 };
  std::set<int> s;

  std::set_union (std::begin(a), std::end(a),
                  std::begin(b), std::end(b),
                  std::inserter (s, s.begin()));

  for (int x : s)
    std::cout << x << ' ';
  std::cout << std::endl;

  return 0;
}
```

Set union:
$s = a \cup b$

Examples

We need to introduce sets to better understand this example !

```
#include <iostream>
#include <set>
#include <algorithm>
int main() {
  std::set<int> a = {1, 2, 3, 4, 5};
  std::set<int> b = {3, 4, 5, 6, 7};
  std::set<int> in, dif;

  std::set_intersection(a.begin(), a.end(),
                        b.begin(), b.end(),
                        std::inserter(in, in.begin()));
  for (int num : in) {
    std::cout << num << " ";
  }

  std::set_difference(a.begin(), a.end(),
                      b.begin(), b.end(),
                      std::inserter(dif, dif.begin()));
  for (int num : dif)
    std::cout << num << " ";
  return 0;
}
```

Set intersection:
$s = a \cap b$

Set difference:
$s = a - b$

Algorithms and predicates

- In all previous examples, the predicates where
  - Standard or
  - Implemented through an external function
- In general, a predicate can be any callable object, i.e., an object that we can **call**
  - In C++, there are three types of callable objects
    - **Functions**
    - Classes overloading a function
    - **Lambda expressions**
- We need to analyze lambda expressions and see how to use them as an algorithm predicate

Lambda expressions

Lambda expressions

```
[capture_list] (parameter_list) -> return_type {body}
```

- Represent a **callable** unit of code
- It can be thought of as an **unnamed**, **inline function**
- **Like** any other function, a lambda has
  - A parameter list, a return type, and a function body
- **Unlike** any other function, a lambda
  - May be defined **inside** a function
  - Being an **internal** function has a **capture** list

They can also have a name

Lambda expressions

- The capture_list
  - Although a lambda may appear inside a function, it can use variables local to that function **only** if it specifies which variables it intends to use
  - Specifies which local variables will be used by the lambda expression
  - It may be empty

```
[capture_list] (parameter_list) -> return_type {body}
```

The capture list must always be present. It is eventually empty.

Lambda expressions

- Similarly to standard functions, lambdas can capture variables by value or by reference

Type	Meaning
[]	Empty capture list. The lambda use only local variables.
[v1,v2,...]	A comma-separated list of local variables. By default, variables are copied. When preceded by & are captured by reference.
[&]	**All** objects in the enclosing function are passed by reference.
[=]	**All** objects in the enclosing function are passed by value.
[&,v1,v2,…]	**All** variables are captured by reference **but** the ones in the list (captured by value).
[=,&v1,&v2,…]	**All** variables are captured by value **but** the ones in the list (captured by reference).

Lambda expressions

- The parameter_list
  - Is a comma-separated list of function parameters (used in the body)
    - Like any other function, the arguments are used to initialize the lambda's parameters
  - Arguments and parameter types must match
    - A lambda may not have default arguments

```
[capture_list] (parameter_list) -> return_type {body}
```

The parameter list has a standard format (as all other functions). It can be omitted.

Lambda expressions

- The return_type
  - Specifies the type of the object the function returns

```
[capture_list] (parameter_list) -> return_type {body}
```

Unlike other functions, lambda must use a **trailing return**. A trailing return follows the parameter list and is preceded by ->.
It can be omitted.

Lambda expressions

- If the body of a lambda includes
  - **Only** a return statement, the type of the lambda expression is deduced by the return statement
  - Any statement other than a return, that lambda is supposed to return **void**
  - In alll other cases, we need to define a return type using a **trailing return** type

```
[capture_list] (parameter_list) -> return_type {body}
```

Unlike other functions, lambda must use a **trailing return**. A trailing return follows the parameter list and is preceded by ->.
It can be omitted.

Lambda expressions

- The body
  - Includes the function body, i.e., its implementation

```
[capture_list] (parameter_list) -> return_type {body}
```

The body must always be present.

Examples

The parameter list

```
[](const string &a, const string &b)
  { return a.size() < b.size(); }
```

Lambda function to evaluate which string is shorter

This is how we call it within a stable sorting algorithm

```
stable_sort (words.begin(), words,end()
  [](const string &a, const string &b)
    { return a.size() < b.size(); }
  );
```

lambda

Sort a vector of integer values

```
std::vector<unsigned> v = {3, 4, 1, 2};
std::sort(v.begin(), v.end(),
  [](unsigned lhs, unsigned rhs) {return lhs > rhs;});
// v is now {4, 3, 2, 1}
```

lambda

```
[capture_list] (parameter_list) -> return_type {body}
```

Examples

```
#include <algorithm>
#include <vector>

std::vector<int> v = {2, 6, 1, 7, 3, 7};

auto it = std::find(v.begin(), v.end(), 7);
// it points to the first element equal to 7

int a = std::distance(v.begin(), it);
// Now a = 3, i.e., the index distance between
// iterator begin() and it
```

Standard comparison

```
auto it = std::find_if(
  v.begin(), v.end(),
  [](int val) { return (val % 2) == 1; }
);
// it points to the first odd element, i.e., 1
int a = std::distance(vec.begin(), it);
// Now a = 2, i.e., the index distance between
// iterator begin() and it
```

Lambda function

```
[capture_list] (parameter_list) -> return_type {body}
```

Examples

my_size is an object local to the "external" function

```
[my_size](const string &a)
  { return a.size() >= my_size; }
```

Captured value

Used inside the function to compare the string size

This is how we call it within the find_if algorithm to return an iterator to the firsts element that is at least as long as the given size

```
auto wc = find_if (words.begin(); words.end();
  [my_size](const string &a)
    { return a.size() >= my_size; }
  );
```

Examples

Passing a lambda function to a user function

Standard function

```
int callFunc(int (*func)(int, int), int arg1, int arg2) {
  return func(arg1, arg2);
}

auto lambda = [](int arg1, int arg2) {
  return arg1 + arg2;
};


int i = callFunc(lambda, 2, 4);
// Now i = 6


int j = lambda(5, 6);
// Now j = 11
```

Locally defined and **named** lambda function

Calling the standard function with lambda as a parametr

Direct call of a lambda function

```
[capture_list] (parameter_list) -> return_type {body}
```

Examples

Capture list

```
int i = 0;
int j = 42;

auto lambda1 = [i](){};      // i by-copy
auto lambda2 = [&i](){};     // i by-reference

auto lambda3 = [&j, i](){};  // j by-reference, i by-copy
auto lambda4 = [=, &i](){};  // j by-copy, i by-reference

// ERROR: non-diverging capture types
auto lambda5 = [&, &i](){};

// ERROR: non-diverging capture types
auto lambda6 = [=, i](){};
```

Example

- The capture is done at the definition, thus
  - In the capture by value, the **value** is persistent
  - In the capture by reference, the **reference** is persistent (**not** the value)

```
int i = 20;
auto lambda1 = [i]() { return i + 42; };
auto lambda2 = [&i]() { return i + 42; };

i = 0;

int a = lambda1();
// Now a = 20+42 = 62
int b = lambda2();
// Now b = 0+42 = 42
```

The local value of i is retained

The current value of i is retained

Examples

The return type

The algorithm transform takes three iterators:
It transform the values included in the range specified by the first two iterators copying them to the third iterator

```
transform (v.begin(), v.end(), v.begin(),
  [](int i) { return i < 0 ? -i : i; }
);
```

There is only a return statement in the body; the type of the lambda is automatic

```
transform (v.begin(), v.end(), v.begin(),
  [](int i) -> int
    { if (i<0) return -i; else return i; }
);
```

Here, there are other statements, we need to define the return type with the trailing return

C++ versus C

- Which are the main differences between C macros and C++ lambdas

C (preprocessor)

```
#define MAX(A,B) (((A)>(B))?(A):(B))
#define LAMBDA(A,B) ((A)+(B))
```

C++

```
auto lambda = [](int arg1, int arg2) {
  return arg1 + arg2;
};
```

Macros	Lambdas
Are just a brute force text substitution mechanism	Are much less verbose than other library functions
Cannot be passed to as an argument to an algorithm	Are a much more general construct
Are the way to go, to achieve the shortest syntax possible	The preprocessor is strongly discouraged in C++

Exercise

- Which is the output generated b the following program?

Exam 04.09.2023

```
int main() {
  int i, j;
  vector<int> v{0,1,2,3,4,5,6};
  auto l = [&](int i){ swap(v[i], v[v.size()-1-i]); };
    for (i=0, j=v.size()-1; i<j; i++, j--) {
      cout << v[i] << " ";
      l(i);
    }
  cout << "# ";
  for(auto e: v) {
    cout << e << " ";
  }
  return 1;
}
```

Solution

- Which is the output generated b the following program?

Exam 04.09.2023

```
int main() {
  int i, j;
  vector<int> v{0,1,2,3,4,5,6};
  auto l = [&](int i){ swap(v[i], v[v.size()-1-i]); };
    for (i=0, j=v.size()-1; i<j; i++, j--) {
      cout << v[i] << " ";
      l(i);
    }
  cout << "# ";
  for(auto e: v) {
    cout << e << " ";
  }
  return 1;
}
```

```
0 1 2 # 6 5 4 3 2 1 0
```

Exercise

- Which is the output generated b the following program?

Exam 07.07.2023

```
auto lambda = []( std::string h )->bool{
   return ( h != "-" && h != "." );
};
int main() {
  std::string s("123.456.789-00");
  std::vector<std::string> num;
  for (int i = 0; i < s.length() ; i++) {
    num.push_back( s.substr(i, 1) );
  }
  cout << s << "#";
  for( auto z : num ) {
    if (lambda(z)) std::cout << z;
  };
  std::cout << '\n';
  return 0;
}
```

```
123.456.789-00#1234567890
```

Solution

- Which is the output generated b the following program?

Exam 07.07.2023

```
auto lambda = []( std::string h )->bool{
   return ( h != "-" && h != "." );
};
int main() {
  std::string s("123.456.789-00");
  std::vector<std::string> num;
  for (int i = 0; i < s.length() ; i++) {
    num.push_back( s.substr(i, 1) );
  }
  cout << s << "#";
  for( auto z : num ) {
    if (lambda(z)) std::cout << z;
  };
  std::cout << '\n';
  return 0;
}
```

```
123.456.789-00#1234567890
```

Exercise: Sorting Student Records

- Write a C++ program that manages a list of student records and performs the following tasks
  - Allow the user to input student records one by one. Each record should include the student's ID, name, and grade
  - Store the student records in a sequential container
  - Sort the students by
    - ID in ascending order
    - Name in alphabetical order
    - Grade in descending order
  - Use lambda functions to define custom sorting criteria for the sorting function

Example

```
Enter student records (ID, Name, Grade):
1 John 85.5
2 Alice 92.0
3 Bob 78.3
4 Sarah 88.7
5 Mike 75.2

Choose sorting criteria:
1. Sort by ID
2. Sort by Name
3. Sort by Grade

Enter your choice: 3

Sorted Student Records by Grade (descending order):
ID: 2, Name: Alice, Grade: 92.0
ID: 4, Name: Sarah, Grade: 88.7
ID: 1, Name: John, Grade: 85.5
ID: 3, Name: Bob, Grade: 78.3
ID: 5, Name: Mike, Grade: 75.2
```

Input

Output

Solution

```
#include <iostream>
#include <vector>
#include <algorithm>
#include <string>

struct Student {
  int id;
  std::string name;
  double grade;
};

// Function to display student records
void displayRecords(const std::vector<Student>& students) {
  for (const auto& student : students) {
    std::cout << "ID: " << student.id << ", Name: "
              << student.name << ", Grade: "
              << student.grade << std::endl;
  }
}
```

Data structure and output function

Solution

Sorting lambda functions

```
// Sort student records based on ID in ascending order
void sortByID(std::vector<Student>& students) {
  std::sort(students.begin(), students.end(),
    [](const Student& a, const Student& b) {
      return a.id < b.id;
  });
}
// Sort student records based on name in alphabetical order
void sortByName(std::vector<Student>& students) {
  std::sort(students.begin(), students.end(),
    [](const Student& a, const Student& b) {
      return a.name < b.name;
  });
}
// Sort student records based on grade in descending order
void sortByGrade(std::vector<Student>& students) {
  std::sort(students.begin(), students.end(),
    [](const Student& a, const Student& b) {
      return a.grade > b.grade;
  });
}
```

Solution

Main: Part 2

```
int main() {
  std::vector<Student> students;
  int id, choice;
  std::string name;
  double grade;

  std::cout << "Enter student records (ID, Name, Grade):\n";
  while (true) {
    std::cout << "> ";
    std::cin >> id >> name >> grade;
    if (id==0)
      break;
    students.push_back({id, name, grade});
  }

  std::cout << "\nChoose sorting criteria:\n";
  std::cout << "1. Sort by ID\n";
  std::cout << "2. Sort by Name\n";
  std::cout << "3. Sort by Grade\n";
  std::cout << "\nEnter your choice: ";
  std::cin >> choice;
```

Solution

Main: Part 2

```
  switch (choice) {
    case 1:
      sortByID(students);
      std::cout << "ID Sorting:\n";
      break;
    case 2:
      sortByName(students);
      ...
      break;
    case 3:
      sortByGrade(students);
      ...
      break;
    default:
      std::cout << "Invalid choice.\n";
      return 1;
    }
 displayRecords(students);
 return 0;
}
```