Data Structures and Algorithms Lab Sessions

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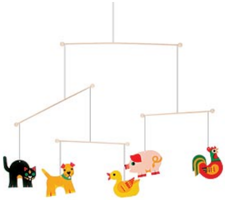

Briefing

- We use the *Jutge* (`https://jutge.org`), a virtual learning environment for computer programming
- Use your institutional email (`@est.fib.upc.edu`) and the *Racó* password to access your *Jutge* account; you should have received an email to enroll in the course EDA Curs 2016/2017 Q2
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- Data Structures and Algorithms course webpage: `www.cs.upc.edu/eda`
- Access lecture notes, exams, problem sets, etc. from Material Docent. Most of the documents and other materials are available in English
- A brief cheatsheet on STL is available there
- We encourage you to take the Self-Assessment Lab Test. It has 11 questions, if you have problems to answer correctly too many of these or you do not understand the "solution" check with your lab prof
- A guide to programming style is available in Catalan in the website and an English translation can be downloaded from here: `http://www.cs.upc.edu/pro1/data/uploads/normeseng.pdf`

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1. The Standard Template Library

The Standard Template Library

- The Standard Template Library (STL, for short) is a fundamental component of the C++ Standard Library
- STL **is not** part of the C++ language, but virtually all, except the most trivial programs, use it
- The evolution of the STL has gone hand in hand with the evolution of C++; its design and use has shaped the language itself
- There are full specifications of the STL (functional and non-functional requirements); each compiler-vendor has freedom to implement it as they want as long as all requirements are met

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The Standard Template Library

- The STL provides a rich number of general-purpose algorithms and data structures: vectors, lists, queues, sorting, . . .
- STL design and implementation heavily relies on templates (compile-time genericity) as opposed to inheritance (run-time genericity)
- STL offers highly-tuned, state-of-the-art implementations for common algorithms and data structures; check if it provides a solution to your problem, don't reinvent the wheel!

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Templates

Example

```
// Pre: v.size() > 0, T has a total order <
// Post: min(v) returns the minimum element in v
template <typename T>
T minimum(const vector<T>& v) {
  T the_min = v[0];
  for (int i = 1; i < v.size(); ++i)
     if (v[i] < the_min) the_min = v[i];
  return the_min;
}
```

Templates

Example

```
vector<double> w;
...
// instatiates minimum with T = double
double m = minimum(w);
vector<string> words = read_words();
// instatiates minimum with T = string
string lexmin = minimum(words);
```

Templates

Example

```
template <typename T>
class BoundedStack {
private:
  vector<T> cont;
  int num_elems;
public:
  const int DEFAULT_MAX_ELEMS = 100;
  BoundedStack(int max_elems = DEFAULT_MAX_ELEMS) :
       cont(max_elems), num_elems(0) {};
  ...
  void push(const T& x) {
    if (num_elems < max_elems) {
      cont[num_elems] = x;
      ++num_elems;
    } else { ... }
  }
  T pop() {
    if (num_elems > 0) {
      --num_elems;
      return cont[numelems];
    } else { // error, empty stack!
    }
  }
```

Templates

Example

```
BoundedStack<double> S1(100);
double x;
while (cin >> x) S1.push(x);
...
// creates a vector of 30 bounded stacks, each of size 10
vector< BoundedStack<int> > S2(30, 10);
...
for (int i = 0; i < 30; ++i) {
  cout << "Stack " << i << ":" << endl;
  while (not S2[i].empty())
     cout << S2[i].pop() << endl;
}
// creates a bounded stack of 30 vectors, each holding 10 ints
BoundedStack< vector<int> > S2(30, 10);
...
```

Containers, Iterators, Algorithms

The three fundamental concepts in the STL are:

1. Containers: a container is a collection or set of objects where we can perform different operations such as adding new objects, removing objects, examine the objects and perform some computation on each of them, etc.
2. Iterators: an iterator is an abstraction for a pointer to an object, they allow us to access, move around and *iterate* over the objects in a container
3. Algorithms: general-purpose algorithms to make some computation or update the contents of a container, e.g., copying, finding an element that satisfies a property, sorting, mapping a function on each object of a container, etc.

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Containers, Iterators, Algorithms

You are already familiar with several STL containers:

- `vector<T>`
- `list<T>` (doubly-linked lists)
- `stack<T>`
- `queue<T>`

Typical operations included in (almost) all containers:

- `size`: returns the number of objects in the collection
- `push/push_back`: adds a new element at the end of the collection
- `pop/pop_back`: removes first/last element inserted
- `empty`: returns true iff the collection contains no object
- `begin`: returns an iterator to the first object in the container
- `end`: returns a fictious iterator past-the-end of the container

Using Containers and Iterators

Example

```
#include <algorithm>
#include <list>
...
string w;
list<string> L;
while (cin >> w) L.push_back(w);
vector<string> v(L.size());
int k = 0;
for (list<string>::const_iterator it = L.begin();
     it != L.end(); ++it) {
       // ++it advances the iterator to the successor
       // *it accesses the string it points to
   v[k] = *it;
   ++k;
}
// copy(L.begin(), L.end(), v.begin()) does the same as loop above
sort(v.begin(), v.end());
L.sort(); // sort(L.begin(), L.end()) does not work
```

Generic Algorithms with Iterators

Example

```
// Pre: [beg, end) contains at least one element, comp
// Post: min(v) returns the minimum element in range
template <typename Iterator,
          typename T, typename Comparator = less<T>>
T minimum(Iterator beg, Iterator end, Comparator smaller) {
  T the_min = *beg;
  for (Iterator it = beg; it != end; ++it)
  if (smaller(*it, the_min))
     the_min = *it;
  return the_min;
}

struct Person {
  int age;
  ...
};
bool is_younger(const Person& a, const Person& b) {
  return a.age < b.age;
}
...
vector<Person> P;
Person benjamin = minimum(v.begin(), v.end(), is_younger);
...
```

Using Containers and Iterators

- The new standard C++11 introduces a new handy syntax to iterate through a container:

```
vector<string> words;
...
for (string w : words) {
  // w iterates through all the values in the
  // vector 'words'
  cout << ' ' << w;
}
```

- C++11 also introduces the keyword **auto** which will be substituted by a typename deduced by the compiler from the context

```
// auto => list<string>::const_iterator
for (auto it = L.begin(); it != L.end(); ++it) {
   v[k] = *it;
   ++k;
}
// auto => string
for (auto w : words) {
  ...
}
```

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for (auto w : words) {
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```

Priority Queues

- A priority queue is a collection of objects which can accessed in (descending) order of priority; each element is "identified" with its priority, so we access elements from largest to smallest.
- Technically speaking `priority_queue` is a container adaptor built on top of a container with random access iterators, e.g., `vector`
- Operations:

Method	Description	Method	Description
`empty`	returns true iff PQ is empty	`size`	returns number of elems
`pop`	remove and return elem of largest priority	`ctor()`	creates empty PQ
`push`	add new elem	`ctor(beg, end)`	creates PQ with elems in the range [beg,end)
`top`	return most prioritary elem		

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Priority Queues

Example

```
#include <queue>
struct ChemElement {
  string symbol;
  double atomic_weight;
}
bool smaller_weight(...) { return X.atomic_weight < Y.atomic_weight; }

// new initialization syntax in C++11
vector<ChemElement> AllChemElements = { {"H", 1.008}, {"He", 4.003},
                                        ..., {"U", 238.03}};

priority_queue<ChemElement, vector<ChemElement>, by_weight> PT;
for (auto e : AllChemElements)
PT.push(e);

while (not PT.empty()) { // print from highest atomic weight ("U")
                         // to lowest ("H")
  ChemElement e = PT.pop();
  cout << e.symbol << " (" << e.atomic_weight << ")" << endl;
}
// it is significantly more efficient to fill PT with:
priority_queue<ChemElement, vector<ChemElement>,
               smaller_weight> PT(AllChemElements.begin(),
                                  AllChemElements.end());
```

Priority Queues

- Priority queues are usually implemented in C++ with heaps (to be explained in detail in theory lectures).
- Cost of the operations:

Method	Cost	Method	Cost
`empty`	$O(1)$	`size`	$O(1)$
`pop`	$O(\log n)$	`ctor()`	$O(1)$
`push`	$O(\log n)$	`ctor(beg, end)`	$O(n)$
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- Notice that n insertions (with `push`) into an initially empty priority queue have cost $O(n \log n)$; inserting n elems with `priority_queue(beg, end)` has cost $O(n)$

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Sets

- A `set<T>` is a finite set of objects in which we can efficiently add new elements, remove exisiting elements and search if a given element is or not in the set. Moreover, we can iterate through all elements of the set in ascending order.
- Operations:

Method	Description	Method	Description
`empty`	returns true iff set is empty	`size`	returns number of elems
`erase(it)`	remove element pointed to by `it`	`ctor()`	creates empty set
`insert`	add new elem	`ctor(beg, end)`	creates set with elems in the range [beg,end)
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Sets

Example

```
#include <set>
#include <cstdlib>
...
Set<int> generate_random_subset(int n, int k) {
  Set<int> C;
  while (C.size() != k) {
    int r = rand() \% n + 1; // r = random number in 1..n
    C.insert(r); // does nothing if r already in C
  }
}
...
Set<int> lotto = generate_random_subset(49, 6);
cout << "Winning numbers:" << endl;
// prints the k selected integers in ascending order
for (int x : lotto) {
  cout << ' ' << x;
  cout << endl;
...
```

Sets

- Sets are usually implemented in C++ with some variant of balanced search trees, for instance, red-black trees (they'll be explained in theory lectures).
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`begin`	$O(\log n)$	`end`	$O(1)$
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Intermezzo: Pairs

The STL provides the convenient class `pair`, which is used by several other classes and fucntions in order to input or output information.

Example

```
template <typename T1, typename T2>
struct pair {
  T1 first;
  T2 second;
};

pair<int,string> p = {3, "hello"};
pair<double, int> q = make_pair(3.14, 7);
cout << "(" << p.first << "," << p.second << ")";
```

Maps

- A `map<K,V>` is a finite set of pairs $\langle$ key,value $\rangle$ such that no two pairs have the same key, in which we can efficiently add new pairs, remove exisiting pairs, update the value associated to a key and search for a key and retrieve its associated value if present. Moreover, we can iterate through all pairs in the map in ascending order of keys.
- Operations:

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`empty`	returns true iff set is empty	`size`	returns number of elems
`erase(it)`	remove pair pointed to by `it`	`ctor()`	creates empty set
`insert(p)`	add new pair p=<k,v>	`ctor(beg, end)`	creates set with elems in the range [beg,end)
`begin`	returns iterator to pair with smallest key	`end`	returns iterator past-the-end
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Maps

Example

```
#include <map>
...
map<string,int> word_freqs;
string w;

while (cin >> w)
  ++word_freqs[w];

// print the list of words in the input
// in alphabetical order and their frequencies
for (auto p : word_freqs)
cout << p.first << ": " << p.second << endl;

auto it = word_freqs.find("abracadabra");
if (it != word_freqs.end()) {
    cout << "this was a magic text!" << endl;
    word_freqs.remove(it);
}
```

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`insert`	$O(\log n)$	`ctor(beg, end)`	$O(n \log n)$
`begin`	$O(\log n)$	`end`	$O(1)$
`find`	$O(\log n)$	`operator[]`	$O(\log n)$

- As in sets, n iterator increments have total cost $O(n)$, amortized cost of `++it` is $O(1)$

More on Containers

- The containers discussed here offer a very rich set of methods, we have described here just a few
- `multiset`, `multimap`: like sets and maps, but duplicities (of elements, of keys) are allowed
- The order used in sets and maps can be changed by supplying a specific parameter when instatiating the container

Example

```
set< double, greater<double> > S;
double x;
while (cin >> x) S.insert(x);
for (auto it = S.begin(); it != S.end(); ) {
  auto next = ++it;
  if (next != S.end())
    if (*next - *it > 0.01)
      cout << ' ' << *it;
    it = next;
}
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- The newest standards (2011, 2014) introduce `unordered_set` and `unordered_map` (and the multi-$*$ variants). These offer almost the same functionality as `set`s and `map`s, except that iteration in order of elements/keys is not possible, but the average cost of insertions, deletions and searches is $O(1)$.
- For instance, our example of counting word frequencies has cost $O(N \log n)$, where n is the number of distinct words in the text and N the length of the text; if we replace `map` by `unordered_map` the average cost drops down to $O(N)$, but the output comes in no paticular order
- Unordered sets and maps are implemented with hash tables; basic hashing schemes will be explained in theory.

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- Read carefully each exercise statement
- Identify which is the most suitable container to efficiently solve the problem
- Write a draft of your solution, do not care about the syntax at this point

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Resources

- A very handy and convenient on-line reference manual for C++ in general (and the STL in particular)
  `http://www.cplusplus.com/reference`
  Other documents, tutorials, etc. can also be found at `www.cplusplus.com`
- The most authoritative reference on the STL is the book "*The C++ Standard Library 2nd ed.*" by Nicolai M. Josuttis
- Another important reference for the C++ is "*The C++ Programming Language 3rd ed.*" by Bjarne Stroustrup (creator of C++)