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# Which of the following things have you done in preparation for the Midterm?

A. Found a study group
B. Created a cheat sheet
C. Looked over past lectures
D. Looked over past sections
E. Looked over past assignments (exercise + homework)
F. Looked over past midterms
G. Prefer not to say

# Systems Programming

## C++ Standard Template Library

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# Relevant Course Information

- Exercise 11 released and due **Wednesday** (after Midterm)

- Homework 2 was due last night
  - Don't forget to double-check your `hw2-submit` tag!
  - Use late days if you need to; they exist for a reason!
- Homework 3 will be released on Monday, due in ***3 weeks***
  - Now in C++, but interfacing with the HW1 & HW2 C code!

- Midterm Review tonight @ 4:30 PM (CSE2 G10, Zoom)
- Midterm: February 9 from 5:30—6:40 PM
  - Info: website, Ed post #377
  - No lecture on Monday

# Lecture Outline

- C++ Standard Template Library (STL)

# C++’s Standard Library

- C++’s Standard Library consists of four major pieces:
  1) The entire C standard library
  2) C++’s input/output stream library
     - `std::cin`, `std::cout`, `stringstreams`, `fstreams`, etc.
  3) C++’s standard template library (**STL**) ☜
     - Containers, iterators, algorithms (sort, find, etc.), numerics
  4) C++’s miscellaneous library
     - Strings, exceptions, memory allocation, localization

# STL Containers ☺

- A container is an object that stores (in memory) a collection of other objects (elements)
  - Implemented as class templates, so hugely flexible
  - More info in *C++ Primer* §9.2, 11.2

- Several different classes of container
  - Sequence containers (`vector`, `deque`, `list, ...`) index numerically
  - Associative containers (`set`, `map`, `multiset`, `multimap`, `bitset, ...`) index by key
  - Differ in algorithmic cost and supported operations

# STL Containers ☹

- STL containers store by *value*, not by *reference*
  - When you insert an object, the container makes a *copy*
  - If the container needs to rearrange objects, it makes copies
    - *e.g.*, if you sort a `vector`, it will make many, many copies
    - *e.g.*, if you insert into a `map`, that may trigger several copies
  - What if you don't want this (disabled copy constructor or copying is expensive)?
    - You can insert a wrapper object with a pointer to the object
      - We'll learn about these "smart pointers" soon

# Our Tracer Class

sets unique id_, initial value_ is id_

- Wrapper class for an `unsigned int value_`
  - Also holds unique `unsigned int id_` (increasing from `0`)
  - Default ctor, cctor, dtor, op=, op< defined
  - `friend` function `operator<<` defined
  - Private helper method `PrintID()` to return `"(id_,value_)"` as a string
  - Class and member definitions can be found in `Tracer.h` and `Tracer.cc`

- Useful for tracing behaviors of containers
  - All methods print identifying messages
  - Unique `id_` allows you to follow individual instances

# STL `vector`

- A generic, dynamically resizable array
  - https://cplusplus.com/reference/vector/vector/
  - Elements are store in *contiguous* memory locations
    - Elements can be accessed using pointer arithmetic if you'd like
    - Random access is O(1) time ← calculate address via arithmetic, then access
  - Adding/removing from the end is cheap (amortized constant time)
  - Inserting/deleting from the middle or start is expensive (linear time) must copy all following elements

# vector/Tracer Example

vectorfun.cc

```
#include <iostream>
#include <vector>       // most containers found in libraries of same name
#include "Tracer.h"

using namespace std;

int main(int argc, char** argv) {
  Tracer a, b, c;    // construct 3 Tracer instances
  vector<Tracer> vec;  // new (empty) vector container of Tracers

  cout << "vec.push_back " << a << endl;
  vec.push_back(a);
  cout << "vec.push_back " << b << endl;
  vec.push_back(b);
  cout << "vec.push_back " << c << endl;
  vec.push_back(c);

  cout << "vec[0]" << endl << vec[0] << endl;
  cout << "vec[2]" << endl << vec[2] << endl;

  return EXIT_SUCCESS;
}
```

add copies of Tracers to end of container

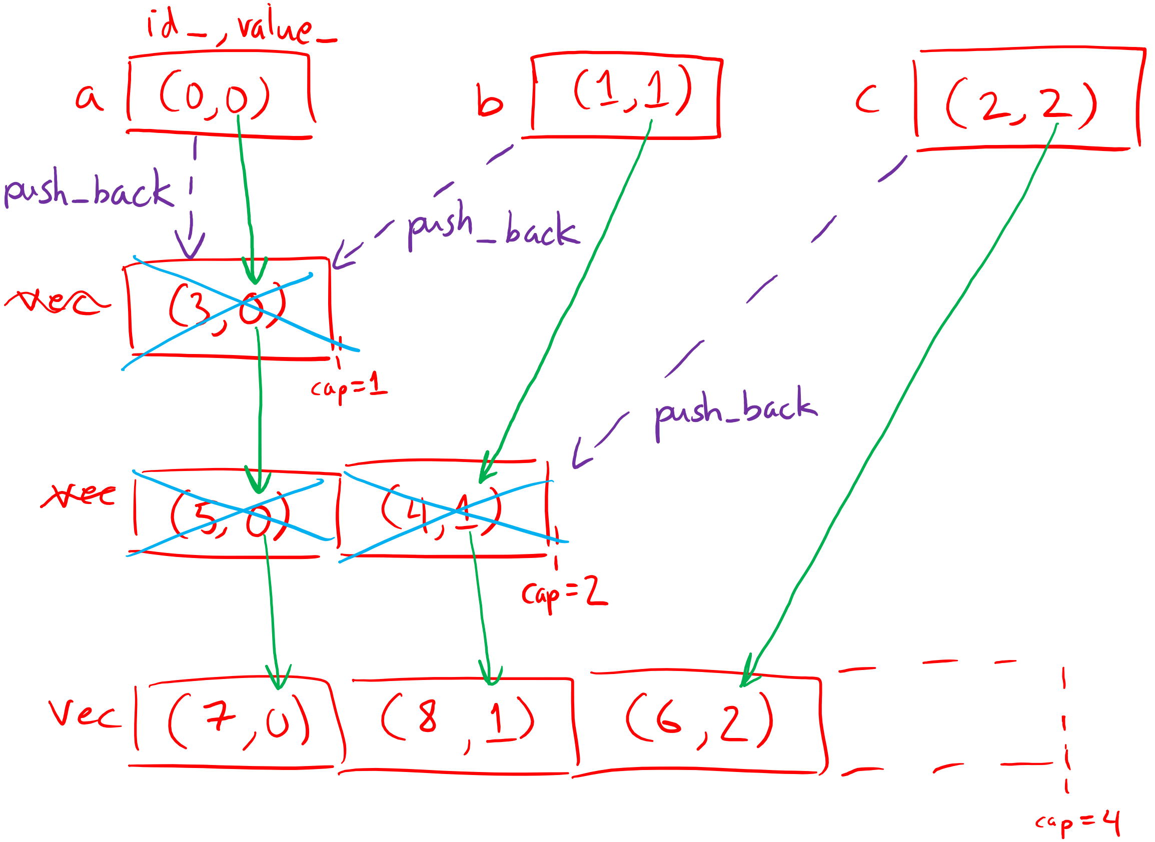
elements can be accessed via subscript notation

verify the stored values are what we expect

# Why All the Copying?

🟩 copy construction

🟦 destruction



| push_back calls | Tracers constructed |
|---|---|
| 0 | 3 (a, b, c) |
| 1 | 4 |
| 2 | 6 |
| 3 | 9 |
| 4 | 10 |
| 5 | 15 |

9 Tracer objects constructed!

Note: capacity doubles here each time (not an important detail)

Note: exact ordering of construction when vec gets moved not important

# STL `iterator`

an iterator specific to the container & element type

- Each container class has an associated iterator class (*e.g.*, `vector<int>::iterator`) used to iterate through elements of the container
  - https://cplusplus.com/reference/iterator/iterator/
  - Iterator range is from `begin` up to `end`, *i.e.*, [`begin` , `end`)
    - `end` is one past the last container element!
  - Some container iterators support more operations than others
    - All can be incremented (`++`), copied, copy-constructed
    - Some can be dereferenced on RHS (*e.g.*, `x = *it;`)
    - Some can be dereferenced on LHS (*e.g.*, `*it = x;`)
    - Some can be decremented (`--`)
    - Some support random access (`[]`, `+`, `-`, `+=`, `-=`, `<`, `>` operators)

# iterator Example

vectoriterator.cc

```
#include <vector>

#include "Tracer.h"

using namespace std;

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(a);
  vec.push_back(b);
  vec.push_back(c);

  cout << "Iterating:" << endl;
  vector<Tracer>::iterator it;
  for (it = vec.begin(); it < vec.end(); it++) {
    cout << *it << endl;
  }
  cout << "Done iterating!" << endl;
  return EXIT_SUCCESS;
}
```

iterator one past last element

incrementing is always legal

iterator of 1st element

"dereference" to get element

# Type Inference (C++11)

- The auto keyword can be used to infer types
  - Simplifies your life if, for example, functions return complicated types
  - The expression using auto must contain explicit initialization for it to work

```
// Calculate and return a vector
// containing all factors of n
std::vector<int> Factors(int n);

void foo(void) {
  // Manually identified type
  std::vector<int> facts1 =
    Factors(324234);

  // Inferred type          compiler knows the
                            return type of Factors()
  auto facts2 = Factors(12321);

  // Compiler error here
  auto facts3; ???
}
```

# auto and Iterators

- Life becomes much simpler!

```
for (vector<Tracer>::iterator it = vec.begin(); it < vec.end(); it++) {
  cout << *it << endl;
}
```

```
for (auto it = vec.begin(); it < vec.end(); it++) {
  cout << *it << endl;
}
```

# Range `for` Statement (C++11)

- Syntactic sugar similar to Java's `foreach`

```
for ( declaration : expression ) {
  statements
}
```

  - *`declaration`* defines loop variable
  - *`expression`* is an object representing a sequence
    - Strings, initializer lists, arrays with an explicit length defined, STL containers that support iterators

sequence of characters

```
// Prints out a string, one
// character per line
std::string str("hello");
      char
for ( auto c : str ) {
  std::cout << c << std::endl;
}
```

# Updated iterator Example

vectoriterator_2011.cc

```
#include <vector>

#include "Tracer.h"

using namespace std;

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(a);
  vec.push_back(b);
  vec.push_back(c);

  cout << "Iterating:" << endl;
  // "auto" is a C++11 feature not available on older compilers
  for (auto& p : vec) {
    cout << p << endl;
  }
  cout << "Done iterating!" << endl;
  return EXIT_SUCCESS;
}
```

greatly simplified!

iterator, begin, end handled for you

# STL Algorithms

- A set of functions to be used on ranges of elements
  - Range: any sequence that can be accessed through *iterators* or *pointers*, like arrays or some of the containers
  - General form: `algorithm(begin, end, ...);`

additional parameters depending on the algorithm

iterators defining a sequence

- Algorithms operate directly on range *elements* rather than the containers they live in
  - Make use of elements' copy ctor, =, ==, !=, <
  - Some do not modify elements
    - *e.g.*, **`find`**, **`count`**, **`for_each`**, **`min_element`**, **`binary_search`**
  - Some do modify elements
    - *e.g.*, **`sort`**, **`transform`**, **`copy`**, **`swap`**

appropriate operator(s) must be defined for element type in order to use STL algorithms

# Algorithms Example

vectoralgos.cc

```
#include <vector>
#include <algorithm>
#include "Tracer.h"
using namespace std;

void PrintOut(const Tracer& p) {
  cout << " printout: " << p << endl;
}

int main(int argc, char** argv) {
  Tracer a, b, c;
  vector<Tracer> vec;

  vec.push_back(c);
  vec.push_back(a);
  vec.push_back(b);
  cout << "sort:" << endl;
  sort(vec.begin(), vec.end());
  cout << "done sort!" << endl;
  for_each(vec.begin(), vec.end(), &PrintOut);
  return EXIT_SUCCESS;
}
```

out of order

sorts elements in range

applies function to each element in range

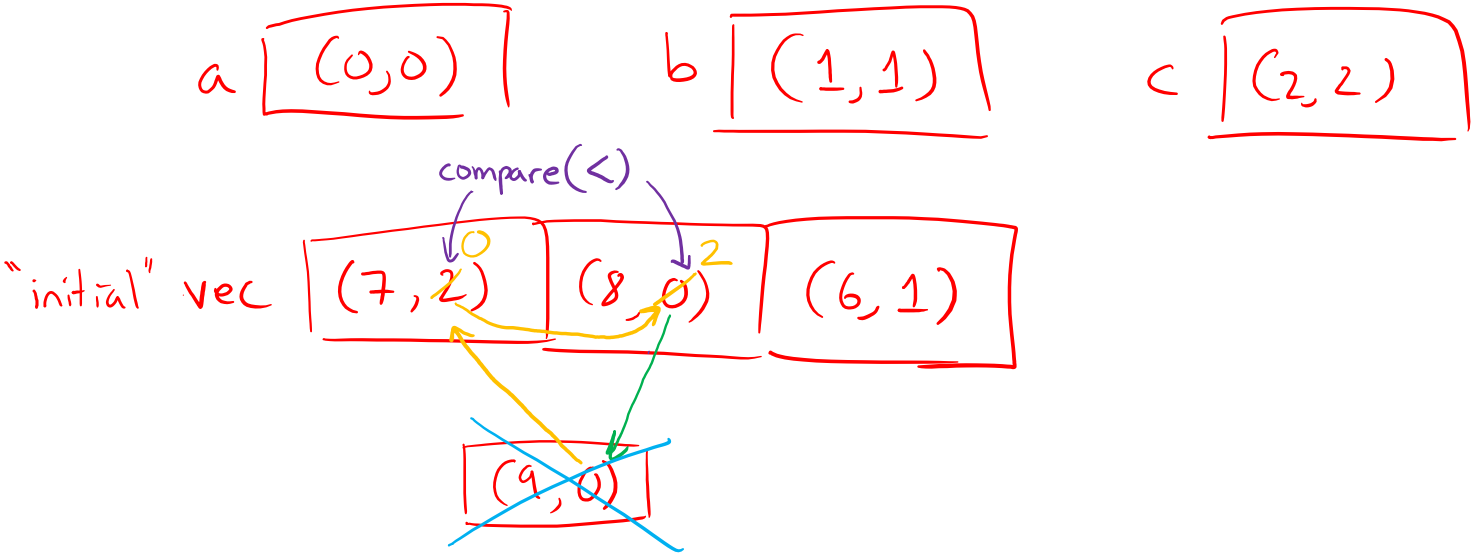
"initial" vec: | (?,2) | (?,0) | (?,1) |

sort

sorted vec: | (?,0) | (?,1) | (?,2) |

# Copying For sort

- 🟩 copy construction
- 🟦 destruction
- 🟨 assignment operator



Note: only first comparison shown here.
more performed to complete swap() algorithm.

# Iterator Question

- Write a function **OrderNext**() that takes a vector<Tracer> iterator and then does the compare-and-possibly-swap operation we saw in **sort**() on that element and the one *after* it
  - Hint: Iterators behave similarly to pointers!
  - Example: **OrderNext**(vec.**begin**()) should order the first 2 elements of vec

```
void OrderNext(vector<Tracer>::iterator it1) {
  auto it2 = it1 + 1;
  if (*it2 < *it1) {
    auto tmp = *it1;
    *it1 = *it2;
    *it2 = tmp;
  }
}
```

vector<Tracer>::iterator

Tracer

Note: there are many equivalent implementations

Note: see the template version (vector<T>) in test.cc

# Extra Exercise #1

- Using the `Tracer.h/.cc` files from lecture:
  - Construct a vector of lists of Tracers
    - *i.e.*, a `vector` container with each element being a `list` of `Tracer`s
  - Observe how many copies happen ☺
    - Use the sort algorithm to sort the vector
    - Use the `list.sort()` function to sort each list