Poll Everywhere

pollev.com/cse333

Which concept has given you the most difficulty so far in the context of Homework 2?

A. The data structures
B. C-string manipulations
C. POSIX I/O
D. Dynamic memory allocation
E. GDB
F. Style considerations
G. Prefer not to say

C++ STL

CSE 333 Winter 2023

Instructor: Justin Hsia

Teaching Assistants:

Adina Tung
Danny Agustinus
Edward Zhang
James Froelich
Lahari Nidadavolu
Mitchell Levy
Noa Ferman
Patrick Ho
Paul Han
Saket Gollapudi
Sara Deutscher
Tim Mandzyuk
Timmy Yang
Wei Wu
Yiqing Wang
Zhuochun Liu

Relevant Course Information

- Exercise 7 due next Wednesday
- Homework 2 was due last night
  - Don't forget to clone your repo to double-/triple-/quadruple-check compilation!
  - Use late days if you can't finish & polish your submission! They exist for a reason
- Homework 3 will be released on Monday, due in ***3 weeks***
- Midterm: February 9 - 11
  - Take home (Gradescope) and open notes
  - Individual, but high-level discussion allowed ("Gilligan's Island Rule")
  - No lecture next Friday (Feb. 10)

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
  - http://www.cplusplus.com/reference/stl/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;
}
```

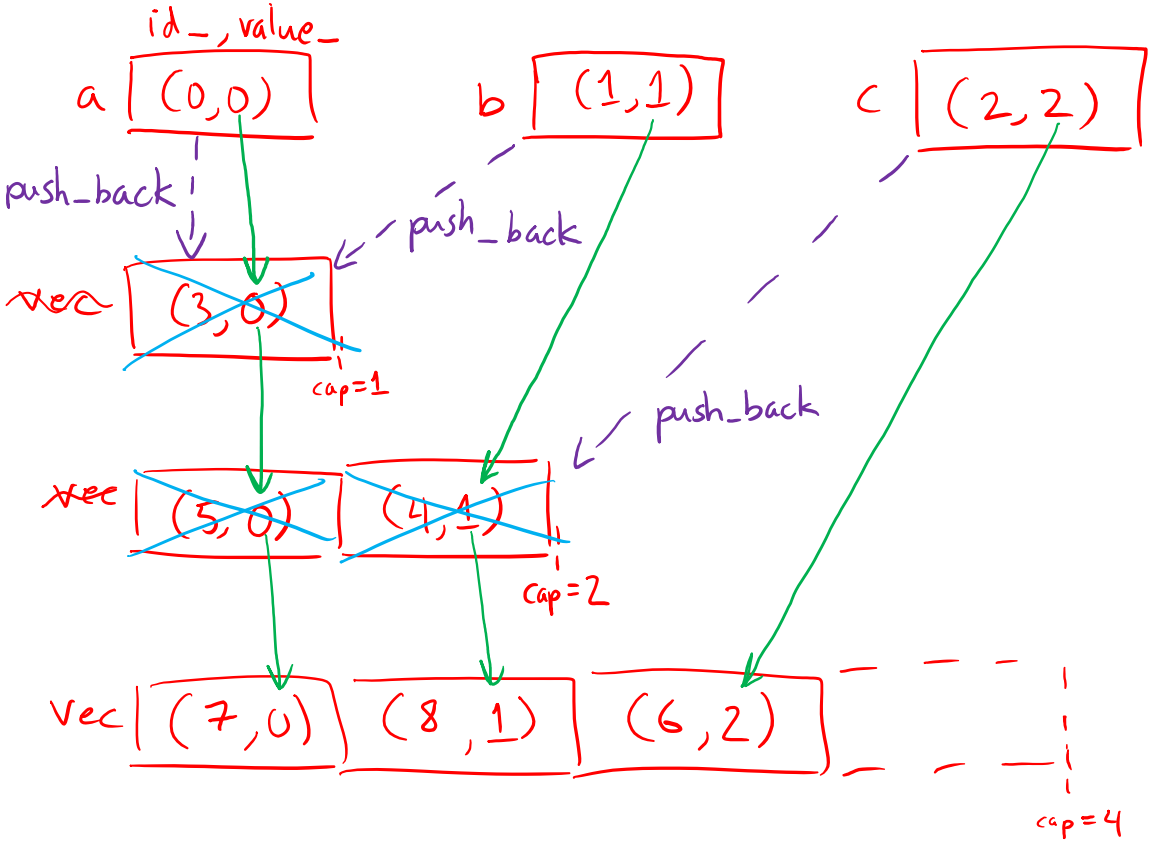
add copies of Tracers to end of container

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
  - http://www.cplusplus.com/reference/std/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
  auto facts2 = Factors(12321);

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

compiler knows the return type of Factors()

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");

for ( auto c : str ) {
  std::cout << c << std::endl;
}
```

char

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 0;
}
```

out of order

sorts elements in range

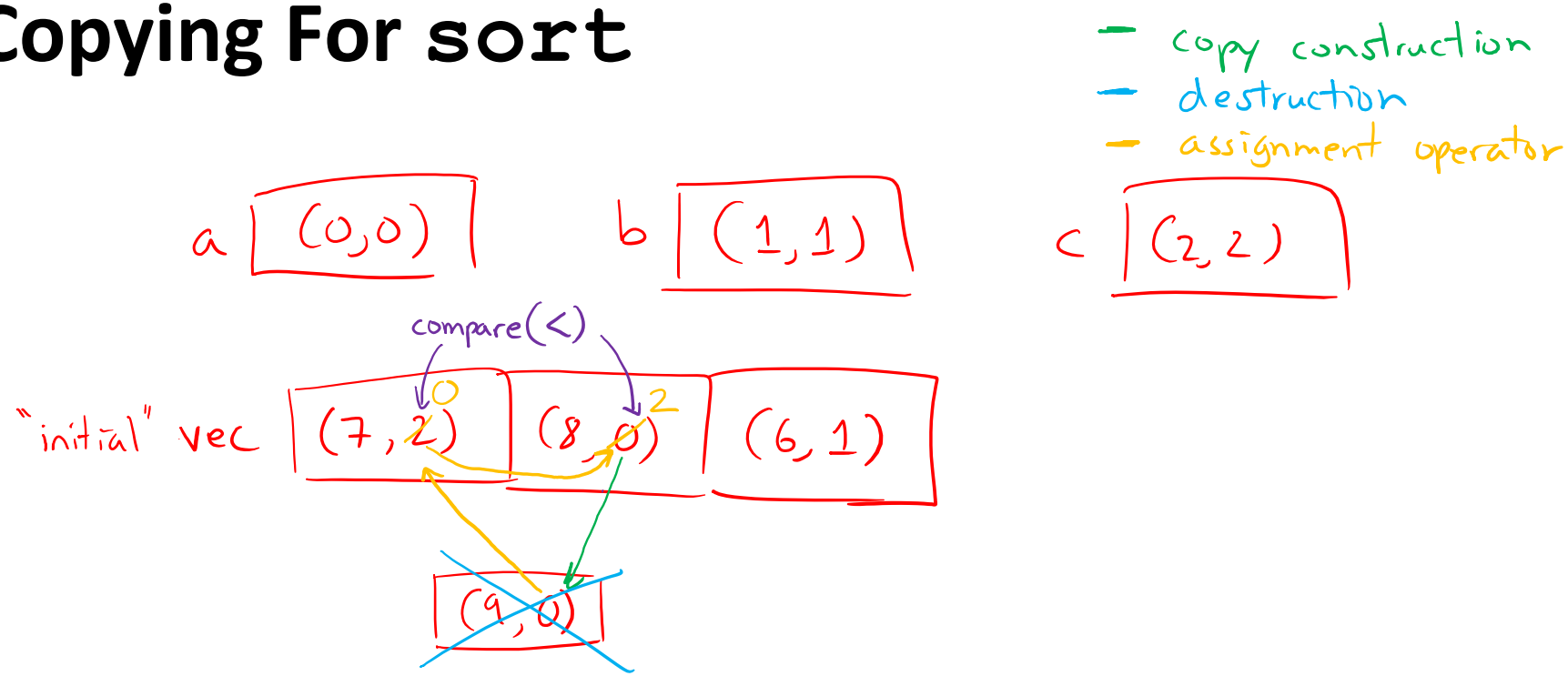
applies function to each element in range

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

sort

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

Copying For `sort`



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