# C++ STL (part 2 of 2)

## CSE 333 Fall 2023

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# Relevant Course Information

- Homework 3 released today, due ~~Nov. 16~~ Nov. 23

- Exercise 8 deadline extended to Monday, Nov. 6
  - Use C++ reference material to find useful standard library features

- Midterm Grading Update

# Review from last lecture

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

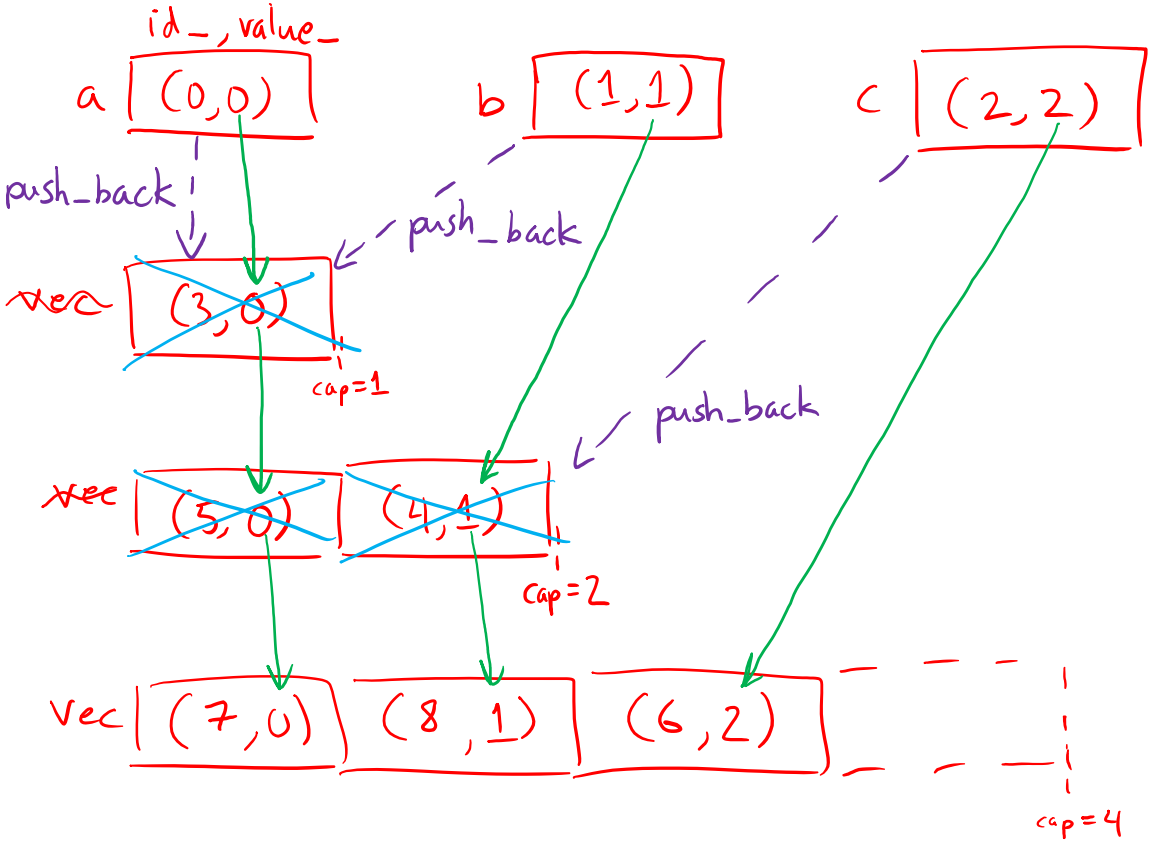
elements can be accessed via subscript notation

verify the stored values are what we expect

# Review from last lecture

- copy construction
- destruction

## Why All the Copying?




| 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

# Lecture Outline

- **STL iterators, algorithms**
- STL (finish)
  - List
  - Map

# 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
  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) |

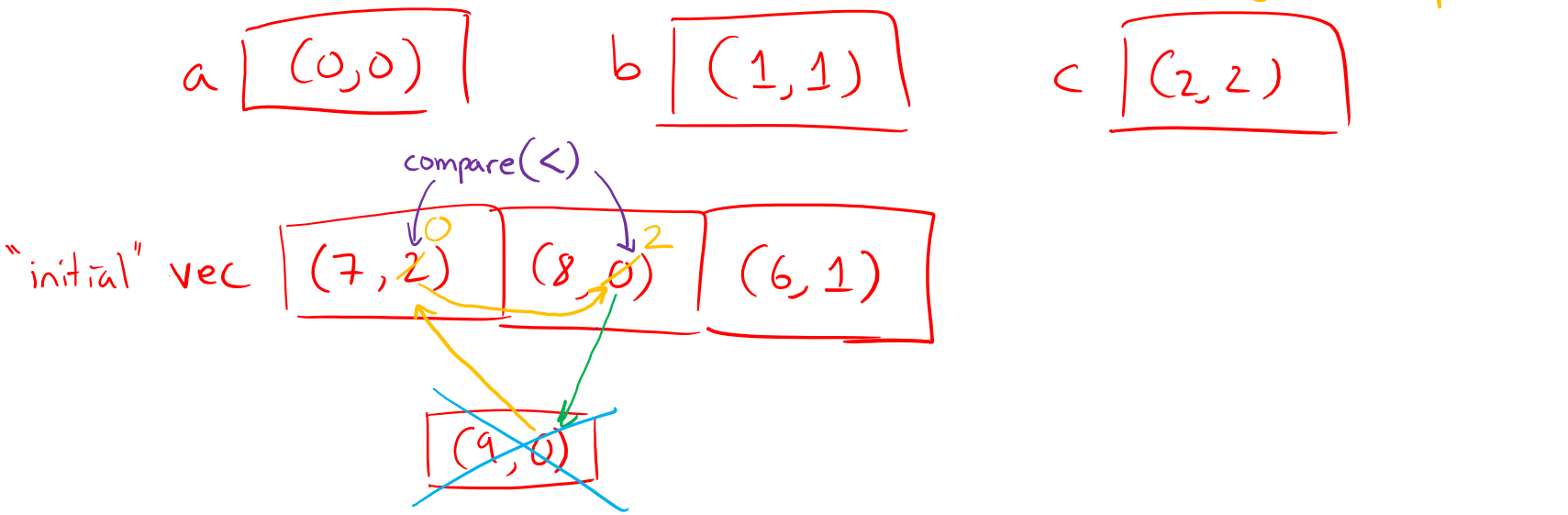
sort

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

# *Attempt on your own after lecture*

## Copying For `sort`

- copy construction
- destruction
- assignment operator




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

# *Attempt on your own after lecture*

## 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

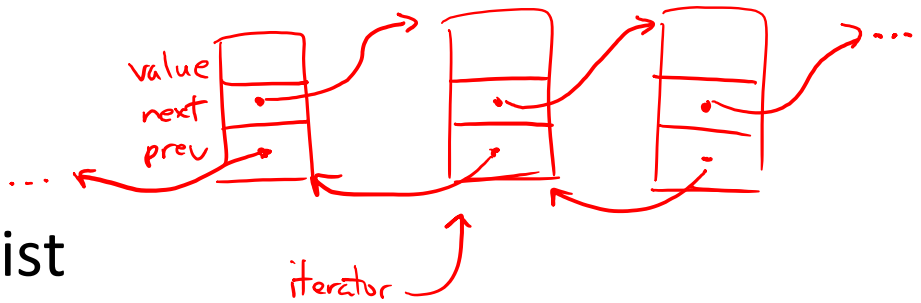
Note: there are many equivalent implementations

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

# Lecture Outline

- STL iterators, algorithms
- **STL (finish)**
  - **List**
  - **Map**

# STL `list`



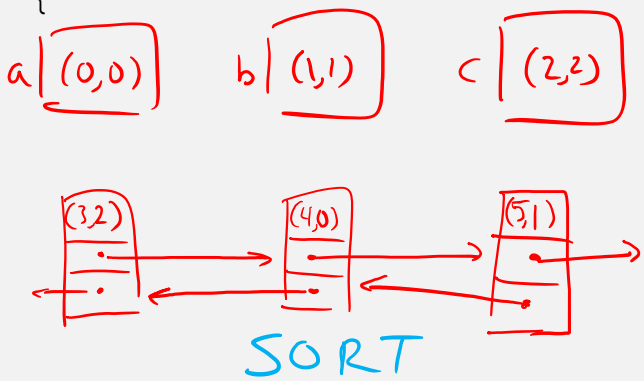

- A generic doubly-linked list
  - https://cplusplus.com/reference/list/list/
  - Elements are ***not*** stored in contiguous memory locations
    - Does not support random access (*e.g.*, cannot do `list[5]`)
  - Some operations are much more efficient than vectors
    - Constant time insertion, deletion anywhere in list
    - Can iterate forward or backwards (++) (--)
  - Has a built-in sort member function
    - Doesn't copy! Manipulates list structure instead of element values

↑ copies pointers instead of list elements

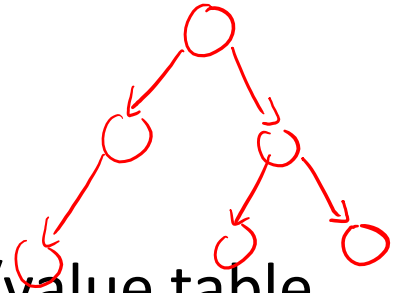
# `list` Example

listexample.cc

```
#include <list>
#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;
  list<Tracer> lst;

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



# STL `map`



- One of C++'s *associative* containers: a key/value table, implemented as a search tree
  - https://cplusplus.com/reference/map/map/
  - General form: `map<key_type, value_type> name;`
  - Keys must be *unique*
    - `multimap` allows duplicate keys
  - Efficient lookup ($\mathcal{O}(\log n)$) and insertion ($\mathcal{O}(\log n)$)
    - Access `value` via `name[key]`
  - Elements are type `pair<key_type, value_type>` and are stored in *sorted* order (key is field `first`, value is field `second`)
    - Key type must support less-than operator (`<`)

# map Example

#include <map>

type of element in map<Tracer,Tracer>

mapexample.cc

```
void PrintOut(const pair<Tracer, Tracer>& p) {
  cout << "printout: [" << p.first << "," << p.second << "]" << endl;
}

int main(int argc, char** argv) {
  Tracer a, b, c, d, e, f;
  map<Tracer, Tracer> table;
  map<Tracer, Tracer>::iterator it;

  table.insert(pair<Tracer, Tracer>(a, b));
  table[c] = d;
  table[e] = f;
  cout << "table[e]:" << table[e] << endl;
  it = table.find(c);   // returns iterator (end if not found)
    // should check if found here before accessing element
  cout << "PrintOut(*it), where it = table.find(c)" << endl;
  PrintOut(*it);

  cout << "iterating:" << endl;
  for_each(table.begin(), table.end(), &PrintOut);

  return EXIT_SUCCESS;
}
```

} equivalent behavior

# Basic map Usage

- animals.cc

# Basic `map` Usage

- `animals.cc`


- https://www.youtube.com/watch?v=jofNR_WkoCE

# Unordered Containers (C++11)

- `unordered_map`, `unordered_set`
  - And related classes `unordered_multimap`, `unordered_multiset`
  - Average case for key access is $\mathcal{O}(1)$
    - But range iterators can be less efficient than ordered `map`/`set`
  - See *C++ Primer*, online references for details

# 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