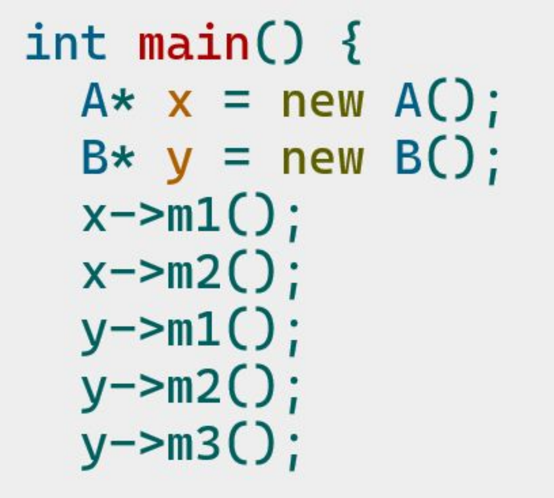
What do you think?

Which functions do we use?

Given that:

```
class A {
public:
  A() { cout << "construct a()" << endl; }  // constructor
  ~A() { cout << "destruct ~a" << endl; }  // destructor
  void m1() { cout << "a:m1" << endl; }
  virtual void m2() { cout << "a:m2" << endl; }
};
// class B inherits from class A
class B : public A {
```



```
int main() {
  A* x = new A();
  B* y = new B();
  x->m1();
  x->m2();
  y->m1();
  y->m2();
  y->m3();
```

CSE 374: Lecture 25

Templates

Thanks to Hannah Tang & Alex Mckinney

Review: `new/delete`

To allocate on the heap using C++, you use the `new` keyword

- You can use new to allocate an object (*e.g.* `new Point`)
- You can use new to allocate a primitive type (*e.g.* `new int`)
- When allocating you can specify a constructor or initial value
    - (e.g. `new Point(1, 2)`) or (e.g. `new int(333)`)
- If no initialization specified, it will use default constructor for objects, garbage for primitives (integer, float, character, boolean, double)
    - You don't need to check that `new` returns `nullptr`

To deallocate a heap-allocated object or primitive, use the `delete` keyword instead of **`free`**`()` from `stdlib.h`

- Don't mix and match!

Review: Dynamically Allocated Arrays

To dynamically allocate an array:

- Default initialize: `type* name = new type[size];`

To dynamically deallocate an array:

- Use `delete[] name;`
- It is an *incorrect* to use “`delete name;`” on an array
  - The compiler probably won’t catch this, though (**!**) because it can’t always tell if `name*` was allocated with `new type[size];` or `new type;`
    - Especially inside a function where a pointer parameter could point to a single item or an array and there’s no way to tell which!
  - Result of wrong `delete` is undefined behavior

Pure virtual methods and interfaces (?)

- A C++ “pure virtual” method is like a Java “abstract” method.
  - Subclass must override because there is no definition in base class
- Makes sense with dynamic dispatch
- Funny syntax in base class; override as usual:

```
class C {
   virtual t0 m(t1,t2,...,tn) = 0;
   ...
};
```

- Side-comment: with multiple inheritance and pure-virtual methods, no need for a separate notion of Java-style interfaces

(Up) casting

- An object of a derived class *cannot* be cast to an object of a base class.
    - For the same reason a `struct T1 {int x,y,z;}` cannot be cast to type `struct T2 {int x,y;}` (different size)
- A pointer to an object of a derived class *can* be cast to a pointer to an object of a base class.
    - For the same reason a `struct T1*` can be cast to type `struct T2*` (pointers to a location in memory)
    - (Story not so simple with multiple inheritance)
- After such an *upcast*, field-access works fine (prefix)
    - but what do method calls mean in the presence of overriding? (see virtual)

(Down) casting

- C pointer-casts: unchecked; be careful
- Java: checked; may raise ClassCastException
- New: C++ has “all the above” (several different kinds of casts)
    - If you use single-inheritance and know what you are doing, the C-style casts (same pointer, assume more about what is pointed to) should work fine for downcasts
    - Worth learning about the differences on your own

Template

Suppose that...

- You want to write a function to compare two `ints`
- You want to write a function to compare two `strings`
    - Function overloading!

```
// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const int& value1, const int& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
int compare(const string& value1, const string& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}
```

Hm…

The two implementations of `compare` are nearly identical!

- What if we wanted a version of `compare` for *every* comparable type?
- We could write (many) more functions, but that's obviously wasteful and redundant
  - Too much repeated code!

What we'd prefer to do is write "*generic code*"

- Code that is type-independent
- Code that is compile-type polymorphic across types

C++ Parametric Polymorphism

C++ has the notion of templates (often referred to as *generics* elsewhere)

- A function or class that accepts a **type** as a parameter
    - You define the function or class once in a type-agnostic way
    - When you invoke the function or instantiate the class, you specify (one or more) types or values as arguments to it

- At **compile-time**, the compiler will generate the “specialized” code from your template using the types you provided
    - Your template definition is NOT runnable code
    - Code is *only* generated if you use your template

Function Templates

Template to **`compare`** two “things”:

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

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>   // <...> can also be written <class T>
int compare(const T& value1, const T& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}

int main(int argc, char **argv) {
  std::string h("hello"), w("world");
  std::cout << compare<int>(10, 20) << std::endl;
  std::cout << compare<std::string>(h, w) << std::endl;
  std::cout << compare<double>(50.5, 50.6) << std::endl;
  return EXIT_SUCCESS;
}
```

Only uses operator < to minimize requirements on T

Explicit type argument

functiontemplate.cc

Compiler Inference

Same thing, but letting the compiler infer the types:

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

// returns 0 if equal, 1 if value1 is bigger, -1 otherwise
template <typename T>
int compare(const T& value1, const T& value2) {
  if (value1 < value2) return -1;
  if (value2 < value1) return  1;
  return 0;
}

int main(int argc, char **argv) {
  std::string h("hello"), w("world");
  std::cout << compare(10, 20) << std::endl; // ok, infers int
  std::cout << compare(h, w) << std::endl;   // ok, infers string
  std::cout << compare("Hello", "World") << std::endl;  // hm…
  return EXIT_SUCCESS;
}
```

Infers char* - does address integer comparison

functiontemplate_infer.cc

Template Non-types

You can use non-types (constant values) in a template:

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

// return pointer to new N-element heap array filled with val
// (not entirely realistic, but shows what’s possible)
template <typename T, int N>
T* valarray(const T& val) {
  T* a = new T[N];
  for (int i = 0; i < N; ++i)
    a[i] = val;
  return a;
}

int main(int argc, char **argv) {
  int* ip = valarray<int, 10>(17);
  string* sp = valarray<string, 17>("hello");
  ...
}
```

Fixed type template parameter

Use comma separated list to specify template arguments

valtemplate.cc

What's Going On?

The compiler doesn't generate any code when it sees the template function

- It doesn't know what code to generate yet, since it doesn't know what types are involved

When the compiler sees the function being used, then it understands what types are involved

- It generates the **instantiation** of the template and compiles it (kind of like macro expansion)
    - The compiler generates template instantiations for *each* type used as a template parameter

Class Templates

Templates are useful for classes as well

- (In fact, that was one of the main motivations for templates!)

Imagine we want a class that holds a pair of things that we can:

- Set the value of the first thing
- Set the value of the second thing
- Get the value of the first thing
- Get the value of the second thing
- Swap the values of the things
- Print the pair of things

Pair Class Definition

Pair.h

```
#ifndef PAIR_H_
#define PAIR_H_

template <typename Thing> class Pair {
 public:
  Pair() { };

  Thing get_first() const { return first_; }
  Thing get_second() const { return second_; }
  void  set_first(Thing& copyme);
  void  set_second(Thing& copyme);
  void  Swap();

 private:
  Thing first_, second_;
};

#include "Pair.cc"
#endif  // PAIR_H_
```

Template parameters for class definition

Could be objects, could be primitives

Included here so that code using Pair can compile the instance; or define all of Pair in header file.

Pair Function Definitions

Pair.cc

```
template <typename Thing>
void Pair<Thing>::set_first(Thing& copyme) {
  first_ = copyme;
}
template <typename Thing>
void Pair<Thing>::set_second(Thing& copyme) {
  second_ = copyme;
}
template <typename Thing>
void Pair<Thing>::Swap() {
  Thing tmp = first_;
  first_ = second_;
  second_ = tmp;
}
template <typename T>
std::ostream &operator<<(std::ostream& out, const Pair<T>& p) {
  return out << "Pair(" << p.get_first() << ", "
             << p.get_second() << ")";
}
```

Definition of member function of template class

member of template class

Non member function to print out data in template class

Using Pair

usepair.cc

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

#include "Pair.h"

int main(int argc, char** argv) {
  Pair<std::string> ps;
  std::string x("foo"), y("bar");

  ps.set_first(x);      // (“foo”, “”)
  ps.set_second(y);     // (“foo”, “bar”)
  ps.Swap();            // (“bar”, “foo”)
  std::cout << ps << std::endl;

  return EXIT_SUCCESS;
}
```

Invokes default ctor, which default constructs members (“”, “”)

Demo: Pair Template

Questions?

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, stringstream, fstream`, 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

Several different classes of container

- Sequence containers (`vector`, `deque`, `list, ...`)
- Associative containers (`set`, `map`, `multiset`, `multimap`, `bitset, ...`)
- 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

Two fields:
value
id (unique to the instance)

Wrapper class for an `int value_`

- Also holds unique `int id_` (increasing from 0)
- Default ctor (set unique `id_` for each instance), 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

Demo: Tracer Walkthrough

STL `vector`

A generic, dynamically resizable array

- https://cplusplus.com/reference/vector/vector/
- Elements are stored in **contiguous** memory locations
  - Like a normal C array, or the ArrayList in Java!
  - Elements can be accessed using pointer arithmetic if you'd like
  - Random access is O(1) time
    - Pointer arithmetic, then access
- Adding/removing from the end is cheap (amortized constant time)
- Inserting/deleting from the middle or start is expensive (linear time)
  - Need to shift all of the elements in the array

`vector/Tracer` Example

vectorfun.cc

```
#include <iostream>
#include <vector>
#include "Tracer.h"

using namespace std;

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

  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;
}
```

Most containers are declared in library of same name

Construct three tracer instances & empty vector

Add tracers to end of vector

Array syntax to access elements

Dynamic Resizing

What’s going on here?

- Answer: a C++ vector (like Java’s ArrayList) is initially small, but grows if needed as elements are added
  - Implemented by allocating a new, larger underlying array, copy existing elements to new array, and then replace previous array with new one
- And vector starts out *really* small by default, so it needs to grow almost immediately!
  - But you can specify an initial capacity if “really small” is an inefficient initial size (use `reserve()` member function)

Demo: Vectors

STL `iterator`

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 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;
}
```

(first element, one past the end, increment to next element)

Dereference to access 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 return value of Factors()

???? No information to infer type

`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

str = sequence of characters

```
// Prints out a string, one
// character per line
std::string str("hello");

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;
  for (auto& p : vec) {    // p is a reference (alias) of vec
    cout << p << endl;     // element here; not a new copy
  }
  cout << "Done iterating!" << endl;
  return EXIT_SUCCESS;
}
```

Look at how much more simplified this is!
No begin(), end(), or dereferencing! **:O**

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, ...);`

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`

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;
}
```

Sort elements from [vec.begin(), vec.end())

Runs function on each element. In this case, prints out each element.

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
        - Backward: --
        - Forward: ++
- Has a built-in sort member function
    - Doesn’t copy! Manipulates list structure instead of element values

`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;
}
```

Use case is similar to vector, but internal implementation is different.

Won’t copy elements, just modifies the next and prev pointers.

STL `map`

One of C++'s *associative* containers: a key/value table, implemented as a search tree

- https://cplusplus.com/reference/map/
- General form: `map<key_type, value_type> name;`
- Keys must be *unique*
  - `multimap` allows duplicate keys
- Efficient lookup (O(log n)) and insertion (O(log n))
  - Access `value` via `name[key]`
    - If key doesn't exist in map, it is added to the map
- 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

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);

  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

Returns iterator (end it not found). Can also use map.count() to see if a key exists.

Unordered Containers (C++11)

`unordered_map`, `unordered_set`

- Average case for key access is O(1)
  - But range iterators can be less efficient than ordered `map/set`
  - Elements are not stored in contiguous order (stored based on the hash).
- See *C++ Primer*, online references for details

Demo: Animals

C++ standard lib is built around templates

Containers store data using various underlying data structures

- The specifics of the data structures define properties and operations for the container

Iterators allow you to traverse container data

- Iterators form the common interface to containers
- Different flavors based on underlying data structure

Algorithms perform common, useful operations on containers

- Use the common interface of iterators, but different algorithms require different ‘complexities’ of iterators

Common C++ STL Containers (and Java equiv)

Sequence containers can be accessed sequentially

- **`vector<Item>`** uses a dynamically-sized contiguous array (like `ArrayList`)
- **`list<Item>`** uses a doubly-linked list (like `LinkedList`)

Associative containers use search trees and are sorted by keys

- **`set<Key>`** only stores keys (like `TreeSet`)
- **`map<Key, Value>`** stores key-value pair<>'s (like `TreeMap`)

Unordered associative containers are hashed

- **`unordered_map<Key, Value>`** (like `HashMap`)