CS100
Introduction to Programming

Lectures 23-24. Lambda functions
(Or: “New” features of C++11/14)

`auto` Variables

- Implicit variable declaration: the compiler knows what you mean
  - (Almost) necessary for anonymous types
  - Very convenient for complex templates
  - Easily abused by lazy programmers!

```
std::map<int, std::list<string>> M;
auto iter = M.begin(); //what’s the type of iter?
auto pair = std::make_pair(iter, M.key_range(...));
auto ptr = condition ? new class1 : new class2; //ERROR
auto x = 15; auto s = (string)"Hello";
```

Taking It Further…

- Some people now use auto ***exclusively***
  - Beauty is in the eyes of the beholder…

```
auto flags = DWORD { FILE_FLAG_NO_BUFFERING };
auto numbers = std::vector<int> { 1, 2, 3 };
auto event_handle = HANDLE {};

// You can consistenly use ‚auto‘ with functions, too:
auto is_prime(unsigned n) -> bool;
auto read_async(HANDLE h, unsigned count) -> vector<char>;
```

Today’s learning objectives

- Functional programming
- Introduction to Lambda functions
- Playing with Lambda functions
- ”New” features of C++11
- What’s new in C++ 14?

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Two types of programming paradigms

- Imperative programming
  - Based on *von Neumann* architecture
  - Efficiency is primary concern, rather than suitability of language for software development

- Functional programming
  - Based on mathematical functions
  - Solid theoretical basis close to user
  - Unconcerned with architecture of machines

Example: Imperative programming

- Statements, not just expressions
  - Change the state of the code

- Examples
  - Assignment:

    ```
    int y;
    y = someFunction(x);
    ```

  - Non-const member function

    ```
    SomeClass class;
    class.someMethod(x);
    ```

Call is changing internal state of class

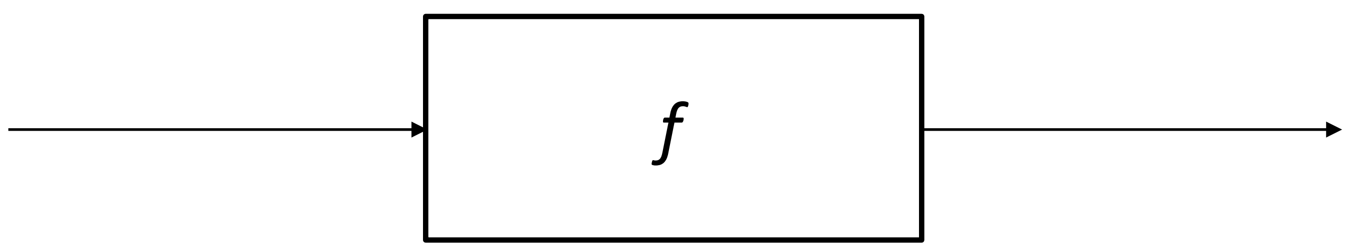
Function without return value!

Imperative programming

- Drawbacks:
  - Depends on local/global state
  - May produce different result everytime a function is run
  - No transparency
  - Difficult to understand/predict the behavior of code

Functional programming

- Declarative programming paradigm
  - Uses expressions or declarations instead of statements
  - Avoids changing state/mutable data
  - Function output depends only on passed input variables
  - Function result is always the same



Origins: mathematical functions

- A mathematical function is a *mapping* of members of one set, called the *domain set*, to another set, called the *range set*

- A *lambda expression* specifies the parameter(s) and the mapping of a function in the following form

```
λ(x) x * x * x
```

for the function `cube (x) = x * x * x`

Lambda expressions

- Lambda expressions describe nameless functions
- Lambda expressions are applied to parameter(s) by placing the parameter(s) after the expression

e.g., `(λ(x) x * x * x)(2)`

which evaluates to `8`

Functional forms

- A higher-order function, or *functional form*, is one that
  - takes functions as parameters
  - yields a function as its result
  - Both
- Example: Functional composition
  - Takes two functions as parameters
  - Yields function whose value is first actual parameter function applied to the application of the second
  - Form: $h \equiv f \circ g$, means $h(x) \equiv f(g(x))$

  For $f(x) \equiv x + 2$ and $g(x) \equiv 3 * x$,
  $h \equiv f \circ g$ yields $(3 * x) + 2$

Functional Programming is really out There

- Functional Programming eXchange
- Strange Loop
- ReactConf
- LambdaConf
- LambdaJam
- CraftConf
- MSFT MVP Summit
- Qcon NYC/SF/London
- Closure West
- Spring into Scala
- Progressive F#
- FP Days
- SkillsMatter

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Lambda Functions

```
int main() {
  [](){}();
  []{}();
} //this is legal C++,
  //although not useful
```

Lambda Cometh to C++

- Lambda Expressions
  - **`expr.prim.lambda`**
- Anonymous functions

```
void abssort(float* x, unsigned N) {
  std::sort( x, x + N,
      [](float a, float b) {
        return std::abs(a) < std::abs(b);
      });
}
```

Good Old C++

```
class Comp {
  float a;
public:
  Comp(float x) {
    a = x;
  }

  bool compare(float b) const {
    return std::abs(a) < std::abs(b);
  }
};

float array[5] = { 0, 1, 2, 3, 4 };
float a = 3;
Comp f(a);
for(float item : array)
  std::cout << std::boolalpha << f.compare(item);
```

Still, Good Old C++

```
class Comp {
  float a;
public:
  Comp(float x) {
    a = x;
  }

  bool operator () (float b) const {
    return std::abs(a) < std::abs(b);
  }
};

float array[5] = { 0, 1, 2, 3, 4 };
float a = 3;
Comp f(a);
for(float item : array)
  std::cout << std::boolalpha << f(item);
```

Not Valid C++

```
class ##### {
  float a;
public:
  Foo(float x) {
    a = x;
  }

  bool operator () (float b) const {
    return std::abs(a) < std::abs(b);
  }
};

float array[5] = { 0, 1, 2, 3, 4 };
float a = 3;
auto f = #####(a);
for(float item : array)
  std::cout << std::boolalpha << f(item);
```

In C++, Lambda are just function objects

```
class ##### {
  float a;
public:
  Foo(float x) {
    a = x;
  }
  bool operator () (float b) const {
    return std::abs(a) < std::abs(b);
  }
};

float array[5] = { 0, 1, 2, 3, 4 };
float a = 3;
auto f = #####(a);
auto f = [a](float b) {return std::abs(a) <std::abs(b)};
for(float item : array)
  std::cout << std::boolalpha << f(item);
```

Lambdas in C++11/14

- Anonymous functions
- Written exactly in the place where it's needed
- Can access the variables available in the enclosing scope (closure)
- May maintain state (mutable or const)
- Can be passed to a function
- Can be returned from a function
- Deduce return type automatically
- Accept generic parameter types (only in C++14)

```
[a](auto b) { return std::abs(a) < std::abs(b) };
```

Write Lambda function

- Write an Identity function that takes an argument and returns the same argument.

```
Identity(3)   //3
```

```
auto Identity = [](auto x) {
  return x;
};
```

Write Lambda function

- Write 3 functions **`add`**, **`sub`**, and **`mul`** that take 2 parameters each and return their sum, difference, and product respectively.

```
add(3,4) //7
sub(4,3) //1
mul(4,5) //20
```

Write Lambda function

```
auto add = [](auto x, auto y) {
    return x + y;
};
auto sub = [](auto x, auto y) {
    return x - y;
};
int mul (int x, int y) {
    return x * y;
};
```

Capturing

- Capturing external local variables
  - Compiled to a function object with fields

```
int fib1 = 1, fib2 = 1;
auto next_step = [&]() {      //capture by reference
   int temp = fib2; fib2 = fib2 + fib1; fib1 = temp;
};
for (int i = 0; i < 20; ++i) next_step();

std::thread t([=]() {          // capture by value
    std::cout << fib1 << std::endl;
});
t.join();
```

Write Lambda function

- Write a function *identityf* that takes an argument and returns a callable that returns that argument.

```
auto idf = identityf(5);
idf() //5
```

Using an Inner Class

```
auto identityf = [](auto x) {
  class Inner {
    int x;
    public: Inner(int i): x(i) {}
    int operator() () { return x; }
  };
  return Inner(x);
};
auto idf = identityf(5);
idf() //5
```

Using a Closure

```
auto identityf = [](auto x)
  return [](){ /* must remember x*/};
};

auto identityf = [](auto x) {
  return [=]() { return x; };
};

auto idf = identityf(5);
idf() //5
```

A closure is a lambda expression paired with an environment
that binds each of its free variables to a value

Closure != Lambda

- A lambda is just an anonymous function.
- A closure is a function which closes over the environment in which it was defined.
- Not all closures are lambdas and not all lambdas are closures.
- Closures are just function objects in C++
- C++ closures **do not extend the lifetime of their context** (If you need this use shared_ptr)

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Write Lambda function

- Write a function that produces a function that returns values in a range.

```
fromto(0, 10)
```

Write Lambda function

```
auto fromto = [](auto start, auto finish){
  return [=]() mutable {
    if(start < finish)
      return start++;
    else
      throw std::runtime_error("Complete");
    };
};

auto range = fromto(0, 10)
range() //0
range() //1
```

mutable: state can be changed!!

Write Lambda function

- Write a function that adds from two invocations

```
addf(5)(4) //9

auto addf = [](auto x){
  return [=](auto y) {
    return x+y;
  };
};
```

Write Lambda function

- Write a function swap that swaps the arguments of a binary function.

```
swap(sub)(3, 2) //-1
```

Write Lambda function

```
auto sub = [](auto x, auto y) {
   return x - y;
};

auto swap =[](auto binary) {
   return [=](auto x, auto y) {
     return binary(y, x);
   };
};

swap(sub)(3, 2) //-1
```

Write Lambda function

- Write a function twice that takes a binary function and returns a unary function that passes its argument to the binary function twice.

```
twice(add)(11) // 22
```

Write Lambda function

```
auto twice =[](auto binary) {
   return [=](auto x) {
     return binary(x, x);
   };
};

twice(add)(11) // 22
```

Write Lambda function

- Write a function that takes a binary function and makes it callable with two invocations.

```
applyf(mul)(3)(4) // 12
```

Write Lambda function

```
auto applyf = [](auto binary) {
   return [binary](auto x) {
     return [binary,x](auto y) {
       return binary(x, y);
     };
   };
};

auto a = applyf(mul);
auto b = a(3);
auto c = b(4) // 12
```

Write Lambda function

- Write a function that takes a function and an argument and returns a function that takes the second argument and applies the function.

```
curry(mul,3)(4)    // 12
```

Write Lambda function

```
auto curry = [](auto binary, auto x) {
   return [=](auto y) {
     return binary(x, y);
   };
};

curry(mul,3)(4) // 12
```

Currying

- Currying is the technique of transforming a function that takes multiple arguments in such a way that it can be called as a chain of functions, each with a single argument.
- In lambda calculus functions take a single argument only.
- Must know Currying to understand Haskell.
- Currying != Partial function application.

Partial Function of Application

```
auto addFour = [](auto a, auto b,
                  auto c, auto d) {
   return a+b+c+d;
};
auto partial = [](auto func, auto a,
                  auto b) {
   return [=](auto c, auto d) {
     return func(a, b, c, d);
   };
};

partial(addFour,1,2)(3,4); //10
```

Write Lambda function

- Without creating a new function show 3 ways to create the inc function.

```
inc(4) // 5
```

Write Lambda function

```
auto inc = curry(add,1);
auto inc = addf(1);
auto inc = applyf(add)(1);

inc(4) // 5
```

Write Lambda function

- Write a function composeu that takes two unary functions and returns a unary function that calls them both.

```
composeu(inc, curry(mul, 5))(3) // 20
```

Write Lambda function

```
auto composeu =[](auto f1, auto f2) {
   return [=](auto x) {
     return f2(f1(x));
   };
};

composeu(inc1, curry(mul, 5))(3) // 20
```

Write Lambda function

- Write a function that returns a function that allows a binary function to be called exactly once.

```
once(add)(3, 4) // 7
once(add)(3, 4) // error
```

Write Lambda function

```
auto once = [](auto binary) {
   bool done = false;
   return [=](auto x, auto y) mutable {
     if(!done) {
       done = true;
       return binary(x, y);
     }
     else
       throw std::runtime_error("once!");
     };
   };
once(add)(3, 4) // 7
once(add)(3, 4) // exception
```

Write Lambda function

- Write a function that takes a binary function and returns a function that takes two arguments and a callback and invokes the callback on the result of the binary function.

Write Lambda function

```
auto binaryc = [](auto binary) {
   return [=](auto x, auto y, auto callbk){
     return callbk(binary(x,y));
   };
};

binaryc(mul)(5, 6, inc) // 31
binaryc(mul)(5,6,[](int a) {
  return a+1;
});
```

Write 3 functions

- Unit
  - same as identityf
- Stringify
  - that stringifies its argument and applies unit to it.
- Bind
  - that takes a result of unit and returns a function that takes a callback and returns the result of callback applied to the result of unit

Write 3 functions

```
auto unit = [](auto x) {
   return [=]() { return x; };
};

auto stringify = [](auto x) {
   std::stringstream ss;
   ss << x;
   return unit(ss.str());
};

auto bind = [](auto u) {
   return [=](auto callback) {
      return callback(u());
   };
};
```

Verify

```
std::cout << "Left Identity "
          << stringify(15)()
          << "=="
          << bind(unit(15))(stringify)()
          << std::endl;

std::cout << "Right Identity "
          << stringify(5)()
          << "=="
          << bind(stringify(5))(unit)()
          << std::endl;
```

Applying Lambdas

- Design your APIs with lambdas in mind
  - Usually through template parameters
- Invest in re-learning STL algorithms

```
template <typename Callback>
void enum_windows(const string& title, Callback callback) {
  . . . callback(current_window);
}

template <typename RAIter, typename Comparer>
void superfast_sort(RAIter from, RAIter to, Comparer cmp);
```

Lambdas and Function Pointers

- Stateless lambdas are convertible to function pointers!
  - Useful for interop with C-style APIs that take function pointers (e.g., Win32)

```
ReadFileEx(file, buffer, 4096, &overlapped,
  [](DWORD ec, DWORD count, LPOVERLAPPED overlapped) {
     // process the results
  }
);
```

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Range-Based for Loop

- Automatic iterator over arrays and STL collections
  - Your collection will work – provide begin(), end(), and an input iterator over the elements
  - Can also specialize global std::begin(), std::end() if you don’t control the collection class

```
int numbers[] = ...;
for (int n : numbers) std::cout << n;
std::map<std::string,std::list<int>> M;
for (const auto& pair : M)
  std::cout << pair.first << " ";
  for (auto n : pair.second)
    std::cout << n << " ";
```

Initializer Lists

- Initialize arrays, lists, vectors, other containers— and *your own* containers—with a natural syntax
- Also applies to structs/classes!

```
vector<int> v { 1, 2, 3, 4 };
list<string> l = { "Tel-Aviv", "London" };
my_cont c { 42, 43, 44 };
point origin { 0, 0 }; //not a container, but has ctor taking two ints

class my_cont {
  public: my_cont(std::initializer_list<int> list) {
    for (auto it = list.begin(); it != list.end(); ++it) . . .
  }
};
```

Modern C++ Style

- Use auto, for, initializer lists ubiquitously
- OK to design algorithms that require predicates, projections, and other functors
  - They will be easy to use—with lambda functions
- Use STL algorithms more widely with lambdas

Delegating Constructors

- No more `init()`-functions! You can now call a constructor from another constructor

```
class file {
public:
  file(string filename) : file(filename.c_str()) {}
  file(const char* filename) : file(open(filename)) {}
  file(int fd) {
    // Actual initialization goes here
  }
};
```

Alias Templates

- typedefs can now be templates
- The using keyword can replace typedef completely

```
template <typename K, typename V, typename Alloc>
class map;

template <typename T>
using simple_set<T> = map<T, bool, DefaultAllocator>;

using thread_func = DWORD(*)(LPVOID);
```

Non-Static Data Member Initializers

- Data members can be initialized inline
- The compiler adds the appropriate code prior to each constructor

```
class counter {
  int count = 0;
  SRWLOCK lock { SRWLOCK_INIT };
 public:
  // ...
};
```

More Miscellaneous Features

- Explicit conversion operators
- Raw string literals
- Custom literals

```
auto utf8string  = u8"Hello";
auto utf16string = u"Hello";
auto utf32string = U"Hello";

auto raw = R"(I can put " here and also \)";
auto break_time = 5min; // in the STL as of C++14
```

New Smart Pointers

- STL now has three types of smart pointers, eliminating the need to ever use delete
  - If you are the sole owner of the object, use unique_ptr to make sure it's deleted when the pointer dies (RAII)
  - If you want to share the object with others, use shared_ptr—it will perform smart reference counting
  - If you got yourself a cycle, use weak_ptr to break it!

unique_ptr

- Sole owner of an object
  - Moveable, not copyable
- Replaces auto_ptr (which can be copied, but leads to problems)

```
unique_ptr<expensive_thing> create() {
  unique_ptr<expensive_thing> p(new expensive_thing);
  // ...do some initialization, exceptions are covered by RAII
  return p;
}

unique_ptr<expensive_thing> p = create();  // move constructor used!

//another example is storing pointers in containers:
vector<unique_ptr<string>> v = { new string('A'), new string('B') };
```

shared_ptr

- Thread-safe reference-counted pointer to an object with shared ownership
  - When the last pointer dies, the object is deleted

```
struct file_handle {
  HANDLE handle;
  file_handle(const string& filename) ...
  ~file_handle() ... //closes the handle
};
class file {
  shared_ptr<file_handle> _handle;
public:
  file(const string& filename) : _handle(new file_handle(filename)) {}
  file(shared_ptr<file_handle> fh) : _handle(fh) {}
}; //can have multiple file objects over the same file_handle
```

weak_ptr

- Points to a shared object but does not keep it alive (does not affect reference count)
- Breaks cycles between shared_ptrs

```
class employee {
  weak_ptr<employee> _manager;
  vector<shared_ptr<employee>> _direct_reports;
public:
  void beg_for_vacation(int days) {
    if (auto mgr = _manager.lock()) { mgr->beg(days); }
    else { /* your manager has been eliminated :-) */ }
  }
};
```

Guidance for Smart Pointers

- Own memory with smart pointers: don’t delete
- Allocate shared pointers with make_shared
- Most owners of pointers can use unique_ptr, which is more efficient than shared_ptr
- Don’t use smart pointers for passing parameters if the usage lifetime is a subset of the function call’s lifetime
- Pass unique_ptr<T> by value to a sink that retains the object pointer and will destroy it
- Pass shared_ptr<T> by value to express taking shared ownership of the object

Guidance for Smart Pointers: Examples

```
struct window {
  // Okay – takes ownership of the window, will destroy it.
  void set_owned_child(unique_ptr<window> window) {
    child = std::move(window);
  }
  unique_ptr<window> child;
};

// Weird – use plain & or * instead.
currency calculate_tax(const unique_ptr<employee>& emp);

// Okay – takes shared ownership of the callback,
// lifetime has to be extended past the call site
void set_callback(shared_ptr<callback> cb);
```

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In C++ 14…

In C++ 14, you write

```
auto auto(auto auto) { auto; }
```

and the compiler infers the rest from context.

Generic Lambdas

- Lambda parameters can be declared with the auto specifier
- This is not type deduction – this is a template!

```
auto lambda = [](auto f) { f.foo(); };

// equivalent to:
struct __unnamed___{
  template <typename S>
  void operator()(S f) const { f.foo(); }
};
auto lambda =_unnamed__();
```

Lambda Capture Extensions

- Lambdas can now capture arbitrary expressions, which enables renaming and capture-by-move semantics

```
std::async([tid = std::this_thread::get_id()]() {
  cout << "called from thread " << tid << endl;
});

unique_ptr<window> top_level = ...;
auto f = [top = std::move(top_level)]() {
  // access "top"
};
```

Function Return Type Deduction

- Functions can be declared as returning auto, and the compiler deduces the return type (if consistent)

```
// Not okay, return type unknown at recursive call:
auto fibonacci(int n) {
  if (n != 1 && n != 2) return fibonacci(n-1) + fibonacci(n-2);
  return 1;
}
auto fibonacci(int n) { // Okay, return type deduced to be int
  if (n == 1 || n == 2) return 1;
  return fibonacci(n-1) + fibonacci(n-2);
}
```

Miscellaneous Language Features

- Variable templates

```
template <typename T> T MATH_PI;
```

- Runtime-sized arrays
- Binary literals 0b10011101

Library Features

- Shared mutex (reader-writer lock)
- User-defined literals for `std::string` (e.g. `s"hello"`) and duration (`3h`, `50min`, `10ms`, and others)
- Optional type: `optional<T>`