

Lambda expressions

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1. Why lambda expressions?

Lambda expressions (sometimes incorrectly called 'closures') are 'anonymous functions'. Why are they needed?

- Small functions may be needed; defining them is tedious, would be nice to just write the function recipe in-place.
- C++ can not define a function dynamically, depending on context.

Example:

1. we read `float c`
2. now we want function `float f(float)` that multiplies by `c`:

```
float c; cin >> c;  
float mult( float x ) { // DOES NOT WORK  
    // multiply x by c  
};
```

2. Introducing: lambda expressions

Traditional function usage:

explicitly define a function and apply it:

```
float sum(float x,float y) { return x+y; }  
cout << sum( 1.2f, 3.4f );
```

New:

apply the function recipe directly:

Code:

```
// lambda/lambdaex.cpp  
[] (float x,float y) -> float {  
    return x+y; } ( 1.5, 2.3 )
```

Output:

3.8

3. Lambda syntax

```
[capture] ( inputs ) -> outtype { definition };  
[capture] ( inputs ) { definition };
```

- The square brackets are how you recognize a lambda; we will get to the 'capture' later. For now it will often be empty.
- Inputs: like function parameters
- Result type specification `-> outtype`: can be omitted if compiler can deduce it;
- Definition: function body.

4. Assign lambda expression to variable

Code:

```
// lambda/lambdaex.cpp
auto summing =
    [] (float x,float y) -> float {
        return x+y; };
cout << summing ( 1.5, 2.3 ) << '\n';
cout << summing ( 3.7, 5.2 ) << '\n';
```

Output:

3.8
8.9

- This is a variable declaration.
- Uses `auto` for technical reasons; see later.

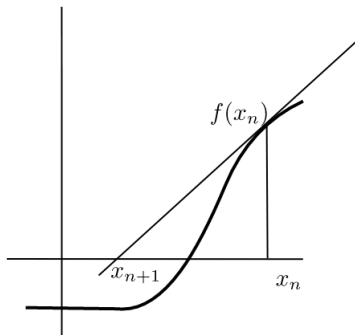
Return type could have been omitted:

```
auto summing =
    [] (float x,float y) { return x+y; };
```

Example of lambda usage: Newton's method

5. Newton's method

$$x_{n+1} = x_n - f(x_n)/f'(x_n)$$



6. Newton for root finding

With

$$f(x) = x^2 - 2$$

zero finding is equivalent to

$$f(x) = 0 \quad \text{for } x = \sqrt{2}$$

so we can compute a square root if we have a zero-finding function.

Newton's method for this f :

$$x_{n+1} = x_n - f(x_n)/f'(x_n) = x_n - \frac{(x_n^2 - 2)}{2x_n} = x_n/2 + 2/x_n$$

Square root computation only takes division!

Exercise 1

Rewrite your code to use lambda functions for f and f_{prime} .

If you use variables for the lambda expressions, put them in the main program.

You can base this off the file `newton.cpp` in the repository

7. Function pointers

You can pass a function to another function.

In C syntax:

```
1 void f(int i) { /* something with i */ };
2 void apply_to_5( (void)(*func)(int) ) {
3     func(5);
4 }
5 int main() {
6     apply_to_5(f);
7 }
```

(You don't have to understand this syntax. The point is that you can pass a function as argument.)

8. Lambdas as parameter

We want to write lambda expressions in-line in a function call:

```
1  int main() {  
2      apply_to_5  
3      ( [] (double x) { cout << x; } );  
4  }
```

9. Lambdas as parameter: the problem

Lambdas have a type that is dynamically generated, so you can not write a function that takes a lambda as argument, because you can't write the type.

```
1 void apply_to_5( /* what? */ func ) {  
2     func(5);  
3 }  
4 int main() {  
5     apply_to_5  
6     ( [] (double x) { cout << x; } );  
7 }
```

10. Lambdas as parameter: the solution

Header:

```
#include <functional>
using std::function;
```

declare function parameters by their signature
(that is, types of parameters and output):

Code:

```
// lambda/lambdaex.cpp
void apply_to_5
( function< void(int) > f
) {
    f(5);
}

/* ... */
apply_to_5
( [] (int i) {
    cout << "Int: " << i
        << '\n'; } );
```

Output:

Int: 5

11. Lambdas expressions for Newton

We are going to write a Newton function which takes two parameters: an objective function, and its derivative; it has a `double` as result.

```
// newton/newton-lambda.cpp
double newton_root
( function< double(double) > f,
  function< double(double) > fprime ) {
```

This states that $f, fprime$ are in the class of `double(double)` functions: `double` parameter in, `double` result out.

Exercise 2

Rewrite the Newton exercise by implementing a *newton_root* function:

```
double root = newton_root( f, fprime );
```

Call the function

1. first with the lambda variables you already created;
2. then directly with the lambda expressions as arguments, that is, without assigning them to variables.

Captures

12. Capture variable

Increment function:

- scalar in, scalar out;
- the increment amount has been fixed through the capture.

Code:

```
// lambda/lambdacapture.cpp
int n;
cin >> n;
auto increment_by_n =
    [n] ( int input ) -> int {
    return input+n;
};
cout << increment_by_n (5) << '\n';
cout << increment_by_n (12) << '\n';
cout << increment_by_n (25) << '\n';
```

Output:

(input value:
↪1)

6
13
26

13. Capture more than one variable

Example: multiply by a fraction.

```
int d=2,n=3;  
times_fraction = [d,n] (int i) ->int {  
    return (i*d)/n;  
}
```

Exercise 3

- Set two variables

```
float low = .5, high = 1.5;
```

- Define a function `is_in_range` of one variable that tests whether that variable is between `low, high`.
(Hint: what is the signature of that function? What is/are input parameter(s) and what is the return result?)

14. Capture value is copied

Illustrating that the capture variable is copied once and for all:

Code:

```
// lambda/lambdacapture.cpp
int inc;
cin >> inc;
auto increment =
    [inc] ( int input ) -> int {
        return input+inc;
    };
cout << "increment by: "
      << inc << '\n';
cout << "1 -> "
      << increment(1) << '\n';
inc = 2*inc;
cout << "1 -> "
      << increment(1) << '\n';
```

Output:

```
increment by: 2
1 -> 3
1 -> 3
```

Exercise 4

Extend the newton exercise to compute roots in a loop:

```
// newton/newton-lambda.cpp
for (int n=2; n<=8; ++n) {
    cout << "sqrt(" << n << ") = "
         << newton_root(
/* ... */
         )
    << '\n';
}
```

Without lambdas, you would define a function

```
double squared_minus_n( double x,int n ) {
    return x*x-n; }
```

However, the `newton_root` function takes a function of only a real argument. Use a capture to make f dependent on the integer parameter.

(Do not define variables for the lambda expression: they should be used directly.)

15. Derivative by finite difference

You can approximate the derivative of a function f as

$$f'(x) = (f(x+h) - f(x))/h$$

where h is small.

This is called a 'finite difference' approximation.

Exercise 5

Write a version of the root finding function that only takes the objective function:

```
double newton_root( function< double(double)> f )
```

and approximates the derivative by a finite difference. You can use a fixed value $h=1e-6$.

Do not reimplement the whole newton method: instead create a lambda for the gradient and pass it to the function `newton_root` you coded earlier.

This is polymorphism: you now have two definition for the same function. They differ in the number of arguments.

16. Turn it in!

Write a program that

1. reads an floating point value from the commandline
2. prints a line:
The root of this number is 1.4142
which contains the word `root` and the value of the square root of the input in default output format.

Your program should

- have a subroutine `newton_root` as described above.
- (8/10 credit): call it with two lambda expressions: one for the function and one for the derivative, *or*
- (10/10 credit) call it with a single lambda expression for the function and approximate the derivative as described above.

17. Lambda in object

A set of integers, with a test on which ones can be admitted:

```
// lambda/lambdafun.cpp
#include <functional>
using std::function;
    /* ... */
class SelectedInts {
private:
    vector<int> bag;
    function< bool(int) >
        selector;
public:
    SelectedInts
        ( function< bool(int)
          > f ) {
        selector = f; };
};
```

```
void add(int i) {
    if (selector(i))
        bag.push_back(i);
};

int size() {
    return bag.size(); };

std::string string() {
    std::string s;
    for ( int i : bag )
        s += to_string(i)+" ";
    return s;
};

};
```

18. Illustration

The above code in use:

Code:

```
// lambda/lambdafun.cpp
cout << "Give a divisor: ";
cin >> divisor; cout << '\n';
cout << ".. divisor " <<
    divisor
    << '\n';
auto is_divisible =
    [divisor] (int i) -> bool {
    return i%divisor==0; };
SelectedInts multiples(
    is_divisible );
for (int i=1; i<50; ++i)
    multiples.add(i);
```

Output:

```
Give a divisor:
.. using 7
Multiples of 7:
7 14 21 28 35 42 49
```

Advanced topics

19. Capture by value

Normal capture is by value:

Code:

```
// lambda/lambdacapture.cpp
int n;
cin >> n;
auto increment_by_n =
    [n] ( int input ) -> int {
    return input+n;
};
cout << increment_by_n (5)
    << '\n';
cout << increment_by_n (12)
    << '\n';
cout << increment_by_n (25)
    << '\n';
```

Output:

(input value: 1)

6

13

26

20. Capture by reference

Capture a variable by reference so that you can update it:

```
int count=0;
auto count_if_f =
    [&count] (int i) {
        if (f(i)) count++; }
for ( int i : int_data )
    count_if_f(i);
cout << "We counted: " << count;
```

21. Lambdas vs function pointers

Lambda expression with empty capture are compatible with C-style function pointers:

Code:

```
// lambda/lambdactr.cpp
int cfun_add1( int i ) {
    return i+1; };
int apply_to_5( int(*f)(int) ) {
    return f(5); };
/* ... */
auto lambda_add1 =
    [] (int i) { return i+1; };
cout << "C ptr: "
      << apply_to_5(&cfun_add1)
      << '\n';
cout << "Lambda: "
      << apply_to_5(lambda_add1)
      << '\n';
```

Output:

C ptr: 6
Lambda: 6

22. Use in algorithms

```
for_each( myarray, [] (int i) { cout << i; } );  
  
transform( myarray, [] (int i) { return i+1; } );
```

See later.