Bloomberg
Engineering

undo

mosaic
CONSULTANTS TO FINANCIAL SERVICES

Let's Look at Lambdas

Roger Orr

Let's Look at Lambdas

Roger Orr

OR/2 Limited

auto λ = [](){};

What is this weird syntax?
Where might we use it?
Why?

– March 2021 –

What's the problem?

- There are times when it is useful to create a C++ function with minimal syntax, and lambdas in C++ provide a relatively terse way to do this
- A typical use case is a short bespoke function being supplied as an argument to a standard library method
- The concept is present in some other languages too, but there are some details that are primarily C++ specific
- Lambdas were added in C++11, so let's start by seeing what we used to do *before* we had lambdas...

Example: C++98 use of algorithms

- One of the exciting things when C++98 first came out was the STL, which provided (and still provides) a very rich paradigm using iterators and algorithms
- The STL at its best enabled terse, powerful, and efficient code

```
void basic_sort(std::vector<int> &v)
{
  ...
  std::sort(v.begin(), v.end());
  ...
}
```

Example: C++98 use of algorithms

- This code instantiates a specialization of the sort algorithm for iterators for a vector of int (based on the types of the arguments supplied)

```
void basic_sort(std::vector<int> &v)
{
  ...
  std::sort<std::vector<int>::iterator>(v.begin(), v.end());
  ...
}
```

  - It was typesafe (the *right* comparison is automatically used)
  - Compile time template instantiation meant this was *faster* than using C's qsort

Example: C++98 use of algorithms

- Some customisation was easy

```
void reverse_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), std::greater<int>());
}
```

- Adding a function object as the *comparator* in this example reverses the direction of the sort
- It's pretty clear what the code is doing and it's hard to get wrong

Example: C++98 use of algorithms

- Some customisation was easy

```
void reverse_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), std::greater<int>());
}
```

- Adding a function object as the *comparator* in this example *reverses* the direction of the sort
- It's pretty clear what the code is doing and it's hard to get wrong – or is it?

```
std::sort(v.begin(), v.end(), std::greater); // error
std::sort(v.begin(), v.end(), std::greater<int>); // error
std::sort(v.begin(), v.end(), std::greater(); // error (up to C++17)
std::sort(v.begin(), v.end(), std::greater<bool>()); // whoops
```

- Ok, maybe I lied...

Example: C++98 use of algorithms

- **C++14** did make this *specific* example a little simpler:

```
void reverse_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), std::greater<>());
}
```

- C++17 made it simpler still, because of Class Template Argument Deduction (CTAD):

```
void reverse_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), std::greater());
}
```

Example: C++98 use of algorithms

- Some customisation was harder – suppose we want to sort **absolute** values?

```
void absolute_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), /* What goes here? */ );
}
```

- We need to supply a *function* or a *function object* that compares the absolute value of two `int` values

Example: C++98 use of algorithms

- Using a function may be simplest:

```
bool abs_less_fn(int a, int b)
{
  return std::abs(a) < std::abs(b);
}

void absolute_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), abs_less_fn);
}
```

Example: C++98 use of algorithms

- We now have a **function** at module scope and have leaked implementation details out of the original function's scope.
- Incidentally, we have also lost some of the benefits of the STL/C++ as
  - the **type** of the instantiation has a comparator that's simply *pointer-to-function* so the comparison will **not** be inlined*
  - functions are stateless

(* I tried different compilers and various optimization settings without success)

Example: C++98 use of algorithms

- Using a function object is more flexible:

```
struct abs_less
{
  bool operator()(int a, int b)
  {
    return std::abs(a) < std::abs(b);
  }
};

void absolute_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), abs_less());
}
```

Example: C++98 use of algorithms

- We now have created a **class** at module scope and have still leaked implementation details out of the original function's scope.
- However, C++98 did not allow you to instantiate templates using a **local** class
  - Proposal N1353 (Anthony Williams) attempted to resolve this
  - It is dated **2001**-10-15 – this morphed along the way but since C++11 local classes **are** valid arguments for template instantiations
  - (Amusingly, perhaps, Visual C++ used to allow this prior to their support for C++98, whereas at least one other vendor had to significantly change their name-mangling implementation to support this for C++11)
- It is much more likely to be optimised (as there is no type erasure)

Example: C++98 use of algorithms

- In C++98/03 you could resolve the scope issue with a **static** function member in a local class

```
void absolute_sort2(std::vector<int> &v)
{
  struct abs_
  {
    static bool less(int a, int b)
    {
      return std::abs(a) < std::abs(b);
    }
  };

  std::sort(v.begin(), v.end(), abs_::less);
}
```

- But that's a lot of 'scaffolding' to support a basically simple piece of code

Boost to the rescue?

- Some library solutions were provided to try and make the process less painful, with varying degrees of success
- Here is an example using boost bind:

```
void boost_absolute_sort(std::vector<int> &v)
{
  int (*abs)(int) = std::abs; // (Needed as std::abs is an overload set)

  std::sort(v.begin(), v.end(),
    boost::bind(std::less<int>(),
      boost::bind(abs, _1), boost::bind(abs, _2)));
}
```

- You may feel this cure is worse than the disease

Recap ….

- In C++98 we had some ways to provide code to algorithms, but with explicit scaffolding:
  - Free functions
  - Member functions
  - Static member functions of local classes
  - Template solutions, such as boost::bind
- Of course, all these *are* still available in C++20

A C++11 Lambda solution

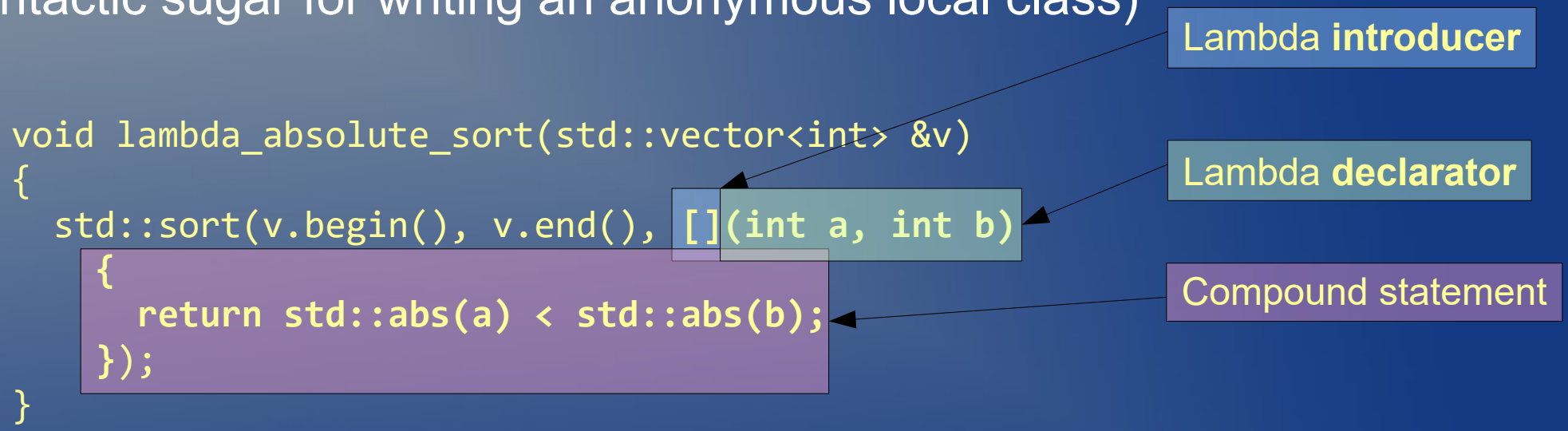
- With C++11 we gained support for lambda expressions (which are syntactic sugar for writing an anonymous local class*)

```
void lambda_absolute_sort(std::vector<int> &v)
{
  std::sort(v.begin(), v.end(), [](int a, int b)
    {
      return std::abs(a) < std::abs(b);
    });
}
```

(*Incidentally, the desire for lambda expressions gave support for Anthony's local classes proposal, mentioned earlier)

A C++11 Lambda solution

- With C++11 we now have support for lambda expressions (which are syntactic sugar for writing an anonymous local class)

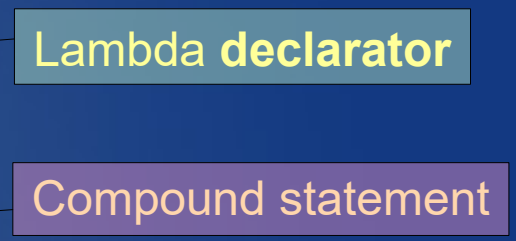


A C++11 Lambda solution

Pseudo-code roughly equivalent to the previous slide

```
void lambda_absolute_sort(std::vector<int> &v)
{
  struct unnamable
  {
    auto operator()(int a, int b)
    {
      return std::abs(a) < std::abs(b);
    }
  };

  std::sort(v.begin(), v.end(), unnamable());
}
```



- The lambda *declarator* defines the **arguments** to `operator()`, and the lambda *compound expression* provides the **body** of `operator()`

A C++11 Lambda solution

Pseudo-code more equivalent to the previous slide

```
void lambda_absolute_sort(std::vector<int> &v)
{
  struct unnamable
  {
    auto operator()(int a, int b) const
    {
      return std::abs(a) < std::abs(b);
    }
  };

  std::sort(v.begin(), v.end(), unnamable());
}
```

- The function call operator in the lambda is implicitly **`const`**. (This doesn't really matter in this example, but stay tuned ...)

A C++11 Lambda solution

- The type of the lambda is unnamable*, but you can give the expression a name for clarity, or to allow it to be re-used, by using a variable

```
void lambda_absolute_sort(std::vector<int> &v)
{
  auto abs_less = [](int a, int b)
    {
      return std::abs(a) < std::abs(b);
    };
  std::sort(v.begin(), v.end(), abs_less);
}
```

*Hence the variable must be declared `auto` as the type cannot be named. This was a strong motivation for adding `auto` to C++11

A C++11 Lambda solution

- As far as I can tell there is no single winner for how to *format* a lambda

```
auto alternative1 = [](int a, int b)
{
  return std::abs(a) < std::abs(b);
};

auto alternative2 = [](int a, int b) {
    return std::abs(a) < std::abs(b);
  };

auto alternative3 = []
  (int a, int b)
  {
    return std::abs(a) < std::abs(b);
  };

...
```

Lambda decay

- For a simple lambda like the one in the previous example C++ provides a conversion to a function pointer. Hence you can pass a lambda to an existing function that takes a function pointer

```
// in some header
using callback = void(int);
void set_callback(callback *cb);

// code that uses this header
void setup()
{
  set_callback([](int val)
    {
      std::cout << "callback with " << val << '\n';
    });
}
```

- This is known as *lambda decay*

Lambda decay

- Lambda decay calls a conversion function that returns a pointer to a function that invokes the lambda (typically optimised away)
- **Use** of the pointer *in a template* is likely to prevent optimization

```
void lambda_absolute_sort(std::vector<int> &v)
{
  using bin_func = bool(int,int);
  bin_func *abs_less = [](int a, int b)
    {
      return std::abs(a) < std::abs(b);
    };
  std::sort(v.begin(), v.end(), abs_less); // << Don't do this
}
```

Lambda capture

- A lambda can refer to **local variables** in scope at the point of definition
  - The local variables can be *named* in the lambda introducer

```
struct type
{
  bool method(int value)
  {
    auto lambda = [value](int test)
      {
        return test < value;
      };
    return lambda(42);
  }
};
```

Lambda capture

- A lambda can refer to local variables in scope at the point of definition and can *also* refer to **members** of the enclosing class (if any)
  - The local variables can be *named* in the lambda introducer
  - Members of the enclosing class can be referred to if **`this`** is captured

```
struct type
{
  int field;
  bool method(int value)
  {
    auto lambda = [value, this]()
      {
        return field < value;
      };
    return lambda();
  }
};
```

Lambda capture – by value or by reference?

- Of course, it's never quite that simple.
- There is a choice with capturing variables between copying the object and forming a reference to the object
- Use an '&' to form a reference

```
void test(int value, int reference)
{
  auto lambda = [value, &reference]()
    {
      std::cout << value << ", " << reference << '\n';
    };
  ++value; ++reference;
  lambda();
}

test(10, 10) → 10, 11
```

Lambda capture – by value or by reference?

- Some pseudo-code may help here

```
void test(int value, int reference)
{
  class __anon
  {
    int __value;
    int& __reference;
  public:
    __anon(int value, int& reference)
    : __value(value), __reference(reference) {}
    void operator()() const
    {
      std::cout << __value << ", " << __reference << '\n';
    }
  };
  auto lambda = __anon(value, reference);
  ...
```

Lambda capture by reference

- When you use reference capture you need to think about the *lifetime* of the captured object to avoid dangling references

```
auto make_adder(int value)
{
  return [&value](int n){ return n + value; };
}

int main()
{
  auto add_ten = make_adder(10);
  int result = add_ten(9);

  std::cout << "9 + 10 = " << result << '\n';
}
→ 9 + 10 = 18*

(*possibly; or 9, or -13319, or ...)
```

What *isn't* a capture

- A lambda can refer *directly* to global and block scope static variables and static members of the containing class – note these are **not** captures:

```
int global = 1;

struct X {
  static int class_static;
  int method()
  {
    static int block_static = 2;

    auto l = []() {
        return global + block_static + class_static;
      };
    return l();
  }
};
```

Default lambda capture

- You can also define a *default* capture mode for a lambda, and this allows you to *implicitly* capture variables.
- The options are “=” (for copy) and “&” (for reference)
- Any captures *not* using the default can be specified explicitly

```
void test(int value, int reference)
{
  auto lambda = [=, &reference]()
    {
      std::cout << value << ", " << reference << '\n';
    };
}
```

- `value` is captured *implicitly* by value, and `reference` *explicitly* by ref

Default lambda capture

- Use with care! It's can be quite easy to *accidentally* capture something and end up with either two separate objects with the same name, or a 'dangling' reference to something that has gone out of scope
- There is also a confusion about member variables if you capture `this` implicitly: members of the class are still accessed by *reference*

```
bool type::method(int value)
{
  auto lambda = [=]()
    {
      return field < value; // field (by ref), value (copy)
    };
  return lambda();
}
```

- *(Capturing `this` implicitly, as shown here, is deprecated in C++20)*

Default lambda capture

- Pseudo-code to help to show why **members** of the captured class are accessed by *reference*

```
bool type::method(int value)
{
  class __anon {
    type *__this; // copy of the 'this' pointer
    int __value;
  public:
    auto operator()() const
    {
      return __this->field < __value;
    } lambda{this, value};
  ...
}
```

Modifying capture variables

- Lambda functions are `const` by default; you can change this by adding the `mutable` keyword

```
int main()
{
  int counter = 0;
  auto lambda = [counter]() mutable
    {
      std::cout << ++counter << '\n';
    };

  Lambda(); // output: 1
  Lambda(); // output: 2
  std::cout << counter << '\n'; // local variable counter is still 0
}
```

Modifying capture variables

- Warning: `const` is shallow (just like in regular classes) so variables captured by **reference** can be modified even *without* the `mutable` keyword

```
int main()
{
  int counter = 0;
  auto lambda = [&counter]()
    {
      std::cout << ++counter << '\n';
    };

  Lambda(); // output: 1
  Lambda(); // output: 2
  std::cout << counter << '\n'; // counter is now 2
}
```

Can you cheat the anonymity?

- The type of the lambda is *unnamable* - but not *unusable*

```
int main()
{
  int counter = 0;
  auto lambda = [&counter]() {
      std::cout << ++counter << '\n';
    };

  int size = sizeof(lambda);
  std::cout << typeid(lambda).name() << '\n';
  decltype(lambda) l2 = lambda;
}
```

- You can't however create a **different** lambda object as the constructors you would need are deleted

Recap ….

- Lambda syntax, which removes some of the scaffolding
- The lambda behaves very like an anonymous local class
- Capturing variables: by value or by reference
- Mutable lambdas

Generic lambdas (since C++14)

- C++14 added the ability to make the lambda function generic on the type of the arguments, using `auto`
- This means we can make code using lambdas more generic (!)

```
template <typename T>
void lambda_absolute_sort(std::vector<T> &v)
{
  std::sort(v.begin(), v.end(), [](auto a, auto b)
    {
      return std::abs(a) < std::abs(b);
    });
}
```

Generic lambdas (C++14)

- We can also, of course, use this to invoke the *same* lambda with different argument types (hence the alternative name of *polymorphic* lambdas)

```
void fred(int idx, double* ptr)
{
  auto increment = [](auto& v) { ++v; };
  increment(idx);
  increment(ptr);
}
```

Generic lambdas (C++14) - aside

- Note that, with both C++14 and C++17, this means you could create a lambda with deduced argument types but you could not do the same for a regular function

```
void increment(auto& v) { ++v; } // error in C++14/17
```

- However, support for using `auto` like this was added to C++20 as part of adding **concepts** to the language

Generic lambdas (C++14)

- The previous example is syntactic sugar for:

```
void fred(int idx, double* ptr)
{
  class __anon
  {
    template <typename T>
    void operator()(T& v) const { ++v; };
  };
  auto increment = __anon();
  ...
```

- except … you are not allowed template members of inner classes!
- This is one of the few places where a lambda is not *just* syntactic sugar

Generic lambdas (C++14)

- The previous example is syntactic sugar for:

```
void fred(int idx, double value)
{
  class __anon
  {
    template <typename T>
    void operator()(T& v) const { ++v; };
  };
  auto increment = __anon();
  ...
```

- except … you are not allowed template members of inner classes!
- There are **two** papers, P1988 (“Allow templates in local classes”) and P2044 (“Member Templates for Local Classes”) trying to fix this. A single merged proposal (P2044) is going forward

Init capture (C++14)

- Sometimes it is useful to be able to initialise the capture variable from an expression.

```
int main()
{
  auto lambda = [counter = 0]() mutable
    {
      std::cout << ++counter << '\n';
    };

  lambda();
  lambda();
}
```

- The type of the variable is deduced from the type of the expression

Init capture (C++14)

- Sometimes it is useful to be able to *rename* the capture variable.

```
int main()
{
  int value = ...;

  auto lambda = [counter = value]() mutable
    {
      std::cout << ++counter << '\n';
    };

  lambda();
  lambda();
}
```

Init capture (C++14)

- Init capture also allows you to explicitly capture a **single** field from the containing class, rather than via `this`, and/or to `move` construct

```
bool type::method(std::string value)
{
  auto lambda = [field{field}, value{std::move(value)}]()
    {
      return field < value;
    };
  return lambda();
}
```

- Here I've kept the same name for the captured variables – this is fine, at least syntactically, just as it is in a constructor initializer list

`*this` copy capture (C++17)

- In C++17 capture of `*this` was added; this captures a *copy* of the current object (or a *slice* if a class hierarchy)
- This is useful when you wish to pass the lambda on and it will outlive the current object. From the proposal paper, P0018:

```
// C++14, using init-capture
std::future spawn() {
  return std::async( [=, tmp=*this]()->int { return tmp.value; });
}

// Can now be written as

std::future spawn() {
  return std::async( [=, *this]()->int { return value; });
}
```

Use case: delayed initialising

- Lambdas can be useful for complex variable initialisation to enable, for instance, a variable to be declared const

```
double delta;
if (high_precision) {
  double h1 = 1e-10;
  h1 = some_complex_calculation(h1, other_args);
  delta = h1;
} else if (something_else) {
  delta = 1e-8;
} else {
  delta = 1e-6;
}
```

- Can `delta` change later in the function?
- Do I *always* initialise `delta`?

Use case: delayed initialising

- Lambdas can be useful for complex variable initialisation to enable, for instance, a variable to be declared const

```
const double delta = [&]() {
  if (high_precision) {
    double h1 = 1e-10;
    return some_complex_calculation(h1, other_args);
  } else if (something_else) {
    return 1e-8;
  }
  return 1e-6;
} ();
```

- `delta` is `const` so cannot change later in the function
- `delta` is always initialised (you get a warning about not returning a value)

Use case: as a refactoring tool

- Lambdas can be useful during refactoring
- You've a large method in which you identify a block of code that performs a single function
  - This is traditionally a candidate for 'extract method'
  - A lambda could be used as a more local alternative
  - The **name** and the **scope** help partition the method
- A very similar sequence of operations may be repeated within a method, you may be able to turn this into a lambda which is used repeatedly and reduce the code duplication
  - The **body** of the lambda is the commonality
  - The **arguments** supplied to the lambda differentiate the uses

C++20: lambda and template arguments

- In previous versions of C++ there was an asymmetry between lambdas and the regular operator() syntax:

```
auto lambda = [](auto x) { return x; }; // Ok

struct {
  template<typename T>
  auto operator()(T x) { return x; }
} functor;
```

- The *usage* is the same:

```
double d = lambda(1.0);

int i = functor(1);
```

C++20: lambda and template arguments

- In the current version of C++ you can now use auto in the regular operator() syntax, so you can now write:

```
struct {
  auto operator()(auto x) { return x; }
} functor;
```

- Conversely, you can now use typename in the lambda syntax:

```
auto lambda = []<typename T>(T x) { return x; };
```

- There can be advantages in having the name T available

C++20: lambda and template arguments

- The changes also include being able to constrain arguments using concepts, in the same way that regular functions can be
- As an example, a lambda with a "`numeric`" constraint:

```
auto square1 = [](numeric auto x) { return x * x; };

auto square2 = []<numeric T>(T x) { return x * x; };

auto square3 = []<typename T>(T x) requires numeric<T> {
  return x * x;
}
```

- The last syntax allows more complex constraints to be expressed, such as a constraint between *two* argument types

Recap ….

- Generic lambdas
- Init capture
- *this copy capture
- A couple of use cases
- Harmonisation of lambda and template arguments, and concepts

Performance

- Lambdas are very useful – but what's the cost?
- As the title of Chandler Carruth's 2019 CppCon presentation provocatively puts it: “There are no Zero-cost Abstractions”
- While lambdas look simple there is a reasonable amount of 'supporting machinery' being written by the compiler
- Fortunately there is little evidence that this impacts **compilation time**
- However, might we get “code bloat”?

Performance – code bloat

- Lambdas are classes and so can potentially introduce code bloat when polymorphic and also when used *inside* templates

```
template<class T, class U, class V>
void f() {
 ...;
 [](T t) { ... }(t);
 ...;
}
```

- Each instantation of f() will include a separate instantiation of the lambda, as it is scoped within f(), even if all the 'T' arguments are the same
- This can be resolved, where it becomes a problem, using the technique popularised by SCARY iterators (where the type of the iterator only depends on *some* of the template arguments types and not all of them - N2911)

Performance – code bloat

- The lambda in the previous example could be hoisted outside the function, perhaps like this:

```
constexpr auto the_lambda = [](auto t) {
  ...
};

template<class T, class U, class V>
void f() {
  ...;
  the_lambda(t);
  ...;
}
```

Performance

- Lambdas are very useful – but what's the cost?
- As the title of Chandler Carruth's 2019 CppCon presentation provocatively puts it: “There are no Zero-cost Abstractions”
- The additional cost at *compile* time appears to be relatively low
- But I'm sure most people are more concerned about runtime cost...

Performance

- Lambdas are very useful – but what's the cost?
- One hint is that you can add `constexpr` to a lambda*. So the compiler must be able to deconstruct it at compile time.
- In C++20 you can also mark a lambda as `consteval` meaning it can *only* be evaluated in an immediate context (and back-end likely never *sees* it)

- *If you *don't* mark the lambda `constexpr` the function call operator will be *implicitly* constexpr anyway, if it happens to satisfy all the constexpr function requirements.

constexpr lambda

- Here is a simple example of a constexpr lambda.

```
template <int dims>
void function() {
    ...
    auto square = [](auto v) constexpr {
        return v * v;
    };

    double ret[square(dims)];
    ...
```

Performance

- In an unoptimised build you would expect to see the call to the lambda `operator()` and so you will see a runtime cost. This is not a great concern to most people.
- Optimisers in many cases will inline the whole lambda class and the calls to its `operator()`.

```
int raw_func(int val)
{
    return val * val;
}
```

```
int lambda_func(int val)
{
    auto sq = [val]() {
        return val * val;
    };

    int ret = sq();

    return ret;
}
```

Performance

- In an unoptimised build on x86_64
- raw_func:
  - 4 instructions (msvc) or 7 (gcc and clang)
- lambda_func:
  - 11 instructions (msvc) or 13 (gcc and clang)
  - includes 2 (msvc) or 1 (gcc and clang) methods calls
  - the methods total 14 (msvc) or 10 (gcc amd clang) instructions
- In a minimally optimised build (-O1) on x86_64
- raw_func and lambda_func are **identical**
- Both are 3 instructions in all three compilers

Performance

- In less trivial source code you would need to confirm whether the compiler does indeed optimise away the lambda
- As you build up more complex code, for example passing lambdas as arguments to another function templates, you will eventually hit the limit of the optimiser. However, you may be surprised how far you can get.

Performance

- Where a lambda is not totally erased, one thing to bear in mind is that the implicit class layout of the lambda class is decided early in compilation, and can't be reduced later on during optimisation even if the compiler is able to eliminate some of the captured variables
- It's not clear (to me anyway) how often this is a significant problem
- As always, I suggest getting the code working solidly first and worrying about this issue later if it is identified by things such as profiling

Down with ()!

- When there are no arguments to the lambda the () can be omitted:

```
auto sq = [val] () { return val * val; };
```

- can also be written as:

```
auto sq = [val] { return val * val; };
```

- Of course, some coding styles prefer retaining the ().
- Unfortunately the () is currently *required* if you wish to use `mutable`

```
auto seq = [val = 0] () mutable { return ++val; };
```

- This will be fixed in C++23 (See P1102R2, approved 2021-02-22)

```
auto seq = [val = 0] mutable { return ++val; };
```

- This may not change your world greatly

Possible future shortening?

- Lambdas in C++ require more syntax than in some other languages
- There is disagreement about how much of this is *necessary*
  - C++ has value and reference semantics, and const
  - Substitution failure is not an error (SFINAE) imposes some constraints
  - C++ syntax makes parsing complicated
- There have been attempts to allow abbreviated syntax. In particular, some would like to remove the necessity of providing the 'scaffolding' of a function call (braces and a return statement). For example, P0583R2 (2017) proposed the syntax => *expression*. While this paper was rejected by EWG they did not reject the principle of exploring shorter syntax in the future.

Conclusion

- Lambdas are a very useful feature of C++
- They are primarily “syntactic sugar” to remove supporting code
- Capture by value or by reference as appropriate, and consider lifetime
- Prefer to avoid implicit capture
- Using a named variable for the lambda expression can aid readability