

Everything you (n)ever wanted to know about C++'s Lambdas

Sharing Good Practice

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Before we start ...

- If I manage to get to my last slide **you** made a terrible job asking questions!
- Please, **ask questions** at **any time**!

(slides & exercises: github.com/avitase/cpp_lambda_talk)

What is a Lambda Expression in C++?

cube is a lambda ...

```
1 int main() {  
2     auto cube = [](int x) { return x * x * x; };  
3     return cube(3);  
4 }
```

godbolt.org/z/xWqMss

is_even is a lambda ...

```
1 #include <algorithm>  
2 #include <vector>  
3  
4 int main() {  
5     std::vector<int> xs{1, 2, 3, 4, 5, 6, 7};  
6     auto is_even = [](int x) { return x % 2 == 0; };  
7     return std::count_if(xs.begin(), xs.end(), is_even);  
8 }
```

godbolt.org/z/bn5jYT

C++'s Lambda Expression

The simplest (and most boring) lambda

```
1 auto x = []{};
```

...no capturing, takes no parameters and returns nothing

A slightly more “useful” lambda

```
1 int main() {  
2     auto x = [] { return 5; };  
3     return x();  
4 }
```

godbolt.org/z/1T8zYE

...is equivalent to^{*}

```
1 int main() {  
2     struct {  
3         auto operator()() const {  
4             return 5;  
5         }  
6     } x;  
7     return x();  
8 }
```

godbolt.org/z/foj6Kq

^{*} check Compiler Explorer links (note -00 !)

C++'s Lambda Expression

An even more “useful” lambda

```
1 int main() {  
2     auto x = [](int y) { return y; };  
3     return x(42);  
4 }
```

godbolt.org/z/963TMh

...is equivalent to^{*}

```
1 int main() {  
2     struct {  
3         auto operator()(int y) const {  
4             return y;  
5         }  
6     } x;  
7     return x(42);  
8 }
```

godbolt.org/z/xfcYM7

Lambda expressions are **pure syntactic sugar** and are equivalent to structs with an appropriate `operator()()` overload!

^{*} check Compiler Explorer links (note -00 !)

Q: What is the output of the program?

```
1 #!/usr/bin/env python3
2
3 if __name__ == '__main__':
4     f = {k: lambda x: x + k for k in range(3)}
5
6     for k in range(3):
7         print(f[k](2), end='')
```

```
1 #!/usr/bin/env python3
2
3 if __name__ == '__main__':
4     f = {k: lambda x: x + k for k in range(3)}
5
6     for k in range(3):
7         print(f[k](2), end='')
```

Why? implicit capture by reference

```
1  #!/usr/bin/env python3
2
3  from functools import partial
4
5  if __name__ == '__main__':
6      f = {k: partial(lambda x, k: x + k, k=k) for k in range(3)}
7      # f = {k: lambda x, k=k: x + k for k in range(3)}
8      # ... would change API
9
10     for k in range(3):
11         print(f[k](2), end='')
```

Now prints: 234

Q: What is the output of the program?

```
1 #include <functional>
2 #include <iostream>
3 #include <map>
4
5 int main() {
6     std::unordered_map<int, std::function<int(int)>> f;
7
8     for (int k = 0; k < 3; k++) {
9         f.emplace(k, [](int x) { return x + k; });
10    }
11
12    for (int i = 0; i < 3; i++) {
13        std::cout << f[i](2);
14    }
15 }
```

godbolt.org/z/Ga1rTj

Q: What is the output of the program?

```
1 #include <functional>
2 #include <iostream>
3 #include <map>
4
5 int main() {
6     std::unordered_map<int, std::function<int(int)>> f;
7
8     for (int k = 0; k < 3; k++) {
9         f.emplace(k, [](int x) { return x + k; });
10    }
11
12    for (int i = 0; i < 3; i++) {
13        std::cout << f[i](2);
14    }
15 }
```

godbolt.org/z/Ga1rTj

error: “k” is not captured

Q: What is the output of the program?

```
1 #include <functional>
2 #include <iostream>
3 #include <map>
4
5 int main() {
6     std::unordered_map<int, std::function<int(int)>> f;
7
8     for (int k = 0; k < 3; k++) {
9         f.emplace(k, [k](int x) { return x + k; });
10    }
11
12    for (int i = 0; i < 3; i++) {
13        std::cout << f[i](2);
14    }
15 }
```

godbolt.org/z/59KGYs

```
1 #include <functional>
2 #include <iostream>
3 #include <map>
4
5 int main() {
6     std::unordered_map<int, std::function<int(int)>> f;
7
8     for (int k = 0; k < 3; k++) {
9         f.emplace(k, [k](int x) { return x + k; });
10    }
11
12    for (int i = 0; i < 3; i++) {
13        std::cout << f[i](2);
14    }
15 }
```

godbolt.org/z/59KGYs

Q: What is the output of the program?

```
1  #include <functional>
2  #include <iostream>
3  #include <map>
4
5  int main() {
6      std::unordered_map<int, std::function<int(int)>> f;
7
8      int k = 0;
9      for (; k < 3; k++) {
10         f.emplace(k, [&k](int x) { return x + k; });
11     }
12
13     for (int i = 0; i < 3; i++) {
14         std::cout << f[i](2);
15     }
16 }
```

godbolt.org/z/hzTPK3

A: 555 (not 444)

```
1  #include <functional>
2  #include <iostream>
3  #include <map>
4
5  int main() {
6      std::unordered_map<int, std::function<int(int)>> f;
7
8      int k = 0;
9      for (; k < 3; k++) {
10         f.emplace(k, [&k](int x) { return x + k; });
11     }
12
13     for (int i = 0; i < 3; i++) {
14         std::cout << f[i](2);
15     }
16 }
```

godbolt.org/z/hzTPK3

Capturing rules

- `[x]`: captures `x` by value
- `[&x]`: captures `x` by reference
- `[=]`: captures all variables (used in the lambda) by value
- `[&]`: captures all variables (used in the lambda) by reference
- `[=, &x]`: captures variables like with `[=]`, but `x` by reference
- `[&, x]`: captures variables like with `[&]`, but `x` by value

Capturing by value

```
1 int main() {  
2     int i = 1;  
3     auto z = [i](int y) {  
4         return i + y;  
5     }(3);  
6     return z;  
7 }
```

godbolt.org/z/3M3cne

...or equivalently

```
1 class X {  
2     private:  
3         int i;  
4  
5     public:  
6         X(int i): i(i) {}  
7  
8         int operator()(int y) const {  
9             return i + y;  
10        }  
11    };  
12  
13    // potentially lots of lines of code  
14  
15    int main() {  
16        int i = 1;  
17        auto z = X{i}(3);  
18        return z;  
19    }
```

godbolt.org/z/oPq3xd

Capturing by reference

```
1 int main() {  
2     int i = 1;  
3     auto z = [&i](int y) {  
4         return i + y;  
5     }(3);  
6     return z;  
7 }
```

godbolt.org/z/8qrx6b

...or equivalently

```
1 class X {  
2     private:  
3         int& i;  
4  
5     public:  
6         X(int& i): i(i) {}  
7  
8         int operator()(int y) /*const*/ {  
9             return i + y;  
10        }  
11    };  
12  
13    // potentially lots of lines of code  
14  
15    int main() {  
16        int i = 1;  
17        auto z = X{i}(3);  
18        return z;  
19    }
```

godbolt.org/z/EP1o1z

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [i]() { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/z16fG9

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [i]() { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/z16fG9

error: cannot assign to a variable captured by copy in a non-mutable lambda

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [i]() mutable { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/M8Pjjb

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [i]() mutable { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/M8Pjjb

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [&i]() mutable { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/shheYa

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     auto x = [&i]() mutable { return ++i; };
6     std::cout << i << x() << i;
7 }
```

godbolt.org/z/shheYa

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     auto x = [i=0]() mutable { return ++i; };
5     std::cout << x() << x();
6 }
```

godbolt.org/z/MYaq3s


```
1 #include <iostream>
2
3 int main() {
4     auto x = [i=0]() mutable { return ++i; };
5     std::cout << x() << x();
6 }
```

godbolt.org/z/MYaq3s

Q: What is the output of the program?

```
1 #include <iostream>
2 #include <utility>
3
4 int main() {
5     auto x = [i=0, j=1]() mutable {
6         i = std::exchange(j, j + i);
7         return i;
8     };
9
10    for (int i = 0; i < 5; ++i) {
11        std::cout << x();
12    }
13 }
```

godbolt.org/z/e95d1x

cppreference.com/w/cpp/utility/exchange

or

Ben Deane, *std::exchange Patterns: Fast, Safe, Expressive, and Probably Underused* on fluentcpp.com

A: 11235

```
1 #include <iostream>
2 #include <utility>
3
4 int main() {
5     auto x = [i=0, j=1]() mutable {
6         i = std::exchange(j, j + i);
7         return i;
8     };
9
10    for (int i = 0; i < 5; ++i) {
11        std::cout << x();
12    }
13 }
```

godbolt.org/z/e95d1x

cppreference.com/w/cpp/utility/exchange
or

Ben Deane, *std::exchange Patterns: Fast, Safe, Expressive, and Probably Underused* on fluentcpp.com

C++'s Lambda Expression

Remember, lambda expressions are pure syntactic sugar and are equivalent to structs with an appropriate `operator()()` overload ...

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     auto x = [] { return 1; };
5     auto y = x;
6     std::cout << x() << y();
7 }
```

godbolt.org/z/jsTKEc

```
1 #include <iostream>
2
3 int main() {
4     auto x = [] { return 1; };
5     auto y = x;
6     std::cout << x() << y();
7 }
```

godbolt.org/z/jsTKEc

Q: What is the output of the program?

```
1  #include <iostream>
2
3  int main() {
4      int i = 1;
5      int j = 2;
6      auto x = [&i, j] { return i + j; };
7      i = 4;
8      j = 6;
9      auto y = x;
10     std::cout << x() << y();
11 }
```

godbolt.org/z/dhTv5o

```
1 #include <iostream>
2
3 int main() {
4     int i = 1;
5     int j = 2;
6     auto x = [&i, j] { return i + j; };
7     i = 4;
8     j = 6;
9     auto y = x;
10    std::cout << x() << y();
11 }
```

godbolt.org/z/dhTv5o

Q: What is the output of the program?

```
1 #include <iostream>
2 #include <memory>
3
4 int main() {
5     auto x = [i=std::make_unique<int>(1)] { return *i; };
6     auto y = x;
7     std::cout << x () << y();
8 }
```

godbolt.org/z/5ja7ze

Q: What is the output of the program?

```
1 #include <iostream>
2 #include <memory>
3
4 int main() {
5     auto x = [i=std::make_unique<int>(1)] { return *i; };
6     auto y = x;
7     std::cout << x () << y();
8 }
```

godbolt.org/z/5ja7ze

error: call to implicitly-deleted copy ctor

Stateful Lambdas

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     auto x = [i=0]() mutable { return ++i; };
5     auto y = x;
6     x();
7     x();
8     y();
9     y();
10    std::cout << x();
11 }
```

godbolt.org/z/8xfGfz

```
1 #include <iostream>
2
3 int main() {
4     auto x = [i=0]() mutable { return ++i; };
5     auto y = x;
6     x();
7     x();
8     y();
9     y();
10    std::cout << x();
11 }
```

godbolt.org/z/8xfGfz

Q: What is the output of the program?

```
1 #include <iostream>
2
3 int main() {
4     auto x = [] { static int i = 0; return ++i; };
5     auto y = x;
6     x();
7     x();
8     y();
9     y();
10    std::cout << x();
11 }
```

godbolt.org/z/YGEfqq

```
1 #include <iostream>
2
3 int main() {
4     auto x = [] { static int i = 0; return ++i; };
5     auto y = x;
6     x();
7     x();
8     y();
9     y();
10    std::cout << x();
11 }
```

godbolt.org/z/YGEfqq

(* undefined in a threaded context, since `static` is not thread-safe!)

Fibonacci (again):

```
1 #include <utility>
2
3 int main() {
4     auto fib = [i=0, j=1]() mutable {
5         struct Result {
6             int &i, &j;
7
8             auto next() {
9                 i = std::exchange(j, j + i);
10                return *this;
11            }
12        };
13        return Result{.i=i, .j=j}.next();
14    };
15
16    fib().next().next().next(); // mutate state
17    return fib().i;
18 }
```

godbolt.org/z/nx8vzq

Stateful Lambdas

Let us now try to interact with the state of the Lambda ...

```
1 #include <utility>
2
3 int main() {
4     auto fib = [i=0, j=1]() mutable {
5         struct Result {
6             int &i, &j;
7
8             auto next() {
9                 i = std::exchange(j, j + i);
10                return *this;
11            }
12        };
13        return Result{.i=i, .j=j}.next();
14    };
15
16    auto r = fib();
17    r.i = 2; // mutate state
18    r.j = 3; // mutate state
19    return fib().j; // 5
20 }
```

godbolt.org/z/44nM7Y

Stateful Lambdas

...or slightly more conveniently:

```
1 #include <utility>
2
3 int main() {
4     auto fib = [i=0, j=1]() mutable {
5         struct Result {
6             int &i, &j;
7
8             auto next(int n = 1) {
9                 while (n-- > 0) {
10                     i = std::exchange(j, j + i);
11                 }
12                 return *this;
13             }
14         };
15         return Result{.i=i, .j=j}.next();
16     };
17
18     return fib().next(3).j; // 5
19 }
```

godbolt.org/z/K93vT4

Stateful Lambdas

```
1 #include <utility>
2
3 int main() {
4     auto fib = [i=0, j=1]() mutable {
5         struct Result {
6             int &i, &j;
7
8             auto next(int n = 1) {
9                 while (n-- > 0) {
10                     i = std::exchange(j, j + i);
11                 }
12                 return *this;
13             }
14         };
15         return Result{.i=i, .j=j}.next();
16     };
17
18     return fib().next(10).j; // 144
19 }
```

godbolt.org/z/ePEMEe

```
# g92 -O3
| main:
19|     mov eax, 144
19|     ret
```

godbolt.org/z/ePEMEe

Best Practices

(partially taken from “Effective Modern C++” by Scott Meyers)

Use Lambdas in STL algorithm

```
1 #include <algorithm>
2 #include <vector>
3
4 std::vector<int> get_ints();
5
6 int main() {
7     auto ints = get_ints();
8     auto in_range = [](int x) { return x > 0 && x < 10; };
9     return *std::find_if(ints.begin(), ints.end(), in_range);
10 }
```

godbolt.org/z/98ff4e

Use Lambdas in STL algorithm

```
1 #include <algorithm>
2 #include <vector>
3
4 std::vector<int> get_ints();
5
6 int main() {
7     auto ints = get_ints();
8     return *std::find_if(ints.begin(), ints.end(),
9                          [](int x) { return x > 0 && x < 10; });
10 }
```

godbolt.org/z/z6384d

Stop pollution of namespace with helper variables

```
1 #include <cmath>
2 #include <iostream>
3
4 int main() {
5     auto y = [<typename T>(T x) {
6         T mean = 1.;
7         T width = 3.;
8         auto norm = 1. / std::sqrt(2. * M_PI);
9         auto arg = (x - mean) / width;
10        return norm * std::exp(-.5 * arg * arg);
11    }(.5);
12
13    std::cout << y;
14 }
```

godbolt.org/z/3jKdM7

Allow variables to be const

```
1 #include <vector>
2
3 std::vector<int> get_ints();
4
5 int main() {
6     auto ints = get_ints();
7     const auto sum = [&ints] {
8         int acc = 0;
9         for (auto& x: ints) acc += x;
10        return acc;
11    }();
12
13    return sum;
14 }
```

godbolt.org/z/oTW3r6

(cf. *IIFE*: bfilipek.com/2016/11/iife-for-complex-initialization.html
or
foonathan.net/2020/10/iife-metaprogramming/)

Avoid default capture modes

Below, there is a dangling pointer lurking in the wings ...

```
1 void add_filter() {  
2     auto divisor = get_magic_number();  
3     filters.emplace_back([&](int x) { return x % divisor == 0; });  
4 }
```

This error becomes more obvious, when explicit capturing is used:

```
1 void add_filter() {  
2     auto divisor = get_magic_number();  
3     filters.emplace_back([&divisor](int x) { return x % divisor == 0; });  
4 }
```

Avoid default capture modes

Mitigation of copy & paste bugs:

```
1 auto divisor = get_magic_number();  
2 std::find_if(container.begin(),  
3             container.end(),  
4             [&divisor](int x) { return x % divisor == 0; });
```

`[&divisor]` indicates that there is an *external* dependency and it is not enough to “just copy” the lambda function if needed elsewhere.

(off-topic: check out this interesting article about copy & paste bugs in real world applications: “The Last Line Effect” by the PVS-Studio team, www.viva64.com/en/b/0260/)

Avoid default capture modes

Does the following implementation looks fine?

```
1 struct Widget {  
2     int divisor = 2;  
3  
4     void add_filter() const {  
5         filters.emplace_back(=](int x) { return x % divisor == 0; });  
6     }  
7 };
```

...given a sufficient implementation of `filters`

Avoid default capture modes

Does the following implementation looks fine?

```
1 struct Widget {  
2     int divisor = 2;  
3  
4     void add_filter() const {  
5         filters.emplace_back(=](int x) { return x % divisor == 0; });  
6     }  
7 };
```

...given a sufficient implementation of `filters`

No! Horrible code! Capturing only applies to non-static local variables. Why does this work?

Avoid default capture modes

Capturing only applies to non-`static` local variables. Why does this work?

```
1 Widget::add_filter() const {  
2     filters.emplace_back(=[](int x) { return x % divisor == 0; });  
3 }
```

...but this fails

```
1 Widget::add_filter() const {  
2     filters.emplace_back([](int x) { return x % divisor == 0; });  
3 }
```

...and this also

```
1 Widget::add_filter() const {  
2     filters.emplace_back([divisor](int x) { return x % divisor == 0; });  
3 }
```

Avoid default capture modes

There is no local variable `divisor`! But what happens is the following

```
1 Widget::add_filter() const {  
2     filters.emplace_back(=[](int x) {  
3         return x % divisor == 0;  
4     });  
5 }
```

copies (implicitly) this pointer (until C++17), i.e.

```
1 Widget::add_filter() const {  
2     auto copy_of_this = this;  
3     filters.emplace_back([copy_of_this](int x) {  
4         return x % copy_of_this->divisor == 0;  
5     });  
6 }
```

...welcome to the world of undefined behavior, when `Widget` goes out of scope!

Avoid default capture modes

Default capturing by value can be misleading and gives the impression that a lambda is self-contained:

```
1 static auto divisor = 1;  
2 filters.emplace_back([=](int x) { return x % divisor == 0; });  
3 ++divisor;
```

Above, `divisor` is not copied! (as one may have guessed seeing `[=]`)

Stop using `std::bind`

Stop using `std::bind`

...and prefer lambda expression, since

- this increases readability,
- lambdas are much more flexible,
- `std::bind` can potentially introduce additional overhead at run-time, whereas lambdas are default `constexpr`

Stop using `std::function`

Stop using `std::function`

- `std::function` adds multiple copies of passed object (consider using drop-in replacements such as *delegates*^{*})
- may cause heap allocation
- is just a wrapper ...

...deduce type of lambda via `auto` or template deduction, **if possible** (cf. exercise)

^{*}codereview.stackexchange.com/questions/14730/impossibly-fast-delegate-in-c11

std::function: Const-correctness / thread-safety bug

```
1 #include <functional>
2 #include <iostream>
3
4 struct Callable {
5     auto operator()() {
6         return 1;
7     }
8
9     auto operator()() const {
10         return 2;
11     }
12 } c;
13
14 int main() {
15     std::function<int(void)> f = c;
16     const auto cf = f;
17     std::cout << f() << cf(); // 11
18 }
```

godbolt.org/z/f1fE7G

```
1 #include <iostream>
2 #include <optional>
3
4 int main() {
5     using opt_t = std::optional<int>;
6     auto o = []() -> opt_t {
7         return 42;
8     }();
9     const auto co = o;
10    std::cout << (*o)++; // 0.K.
11    std::cout << (*co)++; // error!
12 }
```

godbolt.org/z/cT7E9j

Compile-time Error: increment of read-only location

(shamelessly stolen from Titus Winters, Pacific++ 2018: *C++ Past vs. Future*)

Inheriting from Lambdas

Inheriting from Lambdas

Consider two lambdas

```
1 auto f1 = [] { return 1; };  
2 auto f2 = [](int x) { return x; };
```

Is it possible to combine both lambdas (by inheritance) in one common type X?

```
1 X combined{f1, f2};  
2 auto a = combined(); // should return 1  
3 auto b = combined(42); // should return 42
```

Inheriting from Lambdas

```
1 struct X: F1, F2 {  
2     X(F1 f1, F2 f2): F1(std::move(f1)), F2(std::move(f2)) {}  
3  
4     using F1::operator( );  
5     using F2::operator( );  
6 };
```

...but what is the type of a lambda / what are F1 and F2?

According to the C++17 standard, will this compile?

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     X(F1 f1, F2 f2): F1(std::move(f1)), F2(std::move(f2)) {}
5     using F1::operator();
6     using F2::operator();
7 };
8
9 int main() {
10     auto f1 = [] { return 1; };
11     auto f2 = [](int x) { return x; };
12     X combined{f1, f2};
13     std::cout << combined() << combined(2); // should print "12"
14 }
```

godbolt.org/z/qrex3v

According to the C++14 standard, will this compile?

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     X(F1 f1, F2 f2): F1(std::move(f1)), F2(std::move(f2)) {}
5     using F1::operator();
6     using F2::operator();
7 };
8
9 int main() {
10     auto f1 = [] { return 1; };
11     auto f2 = [](int x) { return x; };
12     X combined{f1, f2};
13     std::cout << combined() << combined(2); // should print "12"
14 }
```

godbolt.org/z/qrex3v

According to the C++14 standard, will this compile?

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     X(F1 f1, F2 f2): F1(std::move(f1)), F2(std::move(f2)) {}
5     using F1::operator();
6     using F2::operator();
7 };
8
9 int main() {
10     auto f1 = [] { return 1; };
11     auto f2 = [](int x) { return x; };
12     X combined{f1, f2};
13     std::cout << combined() << combined(2); // should print "12"
14 }
```

godbolt.org/z/qrex3v

error: use of class template “X” requires template arguments

Inheriting from Lambdas

What are the deduced types of `auto` / what are the types of `f1` and `f2`?

```
1 auto f1 = [] { return 1; };  
2 auto f2 = [](int x) { return x; };
```

Use `decltype` to find out!

```
1 X<decltype(f1), decltype(f2)> combined{f1, f2};
```

Inheriting from Lambdas

...or extract this to a factory function `make_combined`

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     X(F1 f1, F2 f2): F1(std::move(f1)), F2(std::move(f2)) {}
5     using F1::operator();
6     using F2::operator();
7 };
8
9 template <typename F1, typename F2> auto make_combined(F1&& f1, F2&& f2) {
10     return X<std::decay_t<F1>, std::decay_t<F2>>{std::forward<F1>(f1),
11                                                    std::forward<F2>(f2)};
12 }
13
14 int main() {
15     auto f1 = [] { return 1; };
16     auto f2 = [](int x) { return x; };
17     auto combined = make_combined(f1, f2);
18     std::cout << combined() << combined(2); // should print "12"
19 }
```

godbolt.org/z/b7vznr

According to the C++17 standard, will this compile?

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     using F1::operator();
5     using F2::operator();
6 };
7
8 int main() {
9     auto f1 = [] { return 1; };
10    auto f2 = [](int x) { return x; };
11    X combined{f1, f2};
12    std::cout << combined() << combined(2); // should print "12"
13 }
```

godbolt.org/z/sM1jhw

According to the C++17 standard, will this compile?

```
1 #include <iostream>
2
3 template <typename F1, typename F2> struct X: F1, F2 {
4     using F1::operator();
5     using F2::operator();
6 };
7
8 int main() {
9     auto f1 = [] { return 1; };
10    auto f2 = [](int x) { return x; };
11    X combined{f1, f2};
12    std::cout << combined() << combined(2); // should print "12"
13 }
```

godbolt.org/z/sM1jhW

error: cannot deduce template arguments of “X<F1, F2>”, as it has no viable deduction guides

According to the C++17 standard, will this compile?

```
1  #include <iostream>
2
3  template <typename F1, typename F2> struct X: F1, F2 {
4      using F1::operator();
5      using F2::operator();
6  };
7
8  template <typename F1, typename F2>
9  X(F1, F2) -> X<std::decay_t<F1>, std::decay_t<F2>>;
10
11 int main() {
12     auto f1 = [] { return 1; };
13     auto f2 = [](int x) { return x; };
14     X combined{f1, f2};
15     std::cout << combined() << combined(2); // should print "12"
16 }
```

godbolt.org/z/6fEGPT

Variadic Templates

```
1  #include <iostream>
2
3  template <typename... Fs> struct X: Fs... {
4      using Fs::operator()...;
5  };
6
7  template <typename... Fs>
8  X(Fs...) -> X<std::decay_t<Fs>...>;
9
10 int main() {
11     auto f1 = [] { return 1; };
12     auto f2 = [](int x) { return x; };
13     auto f3 = [](double x) { return -x; };
14     X combined{f1, f2, f3};
15     std::cout << combined() << '\n'      // should print "1"
16               << combined(2) << '\n'    // should print "2"
17               << combined(3.4) << '\n'; // should print "-3.4"
18 }
```

godbolt.org/z/jdqWYa

Why?

}

std::variant

An enum class models a **choice between values**:

```
1 enum class Oven { on, off };
```

std::variant models a **choice between types**:

```
1 struct on { double temperature; };  
2 struct off {};  
3 using Oven = std::variant<on, off>;
```

An aggregate type of some simple shapes ...

```
1 struct Shape {  
2     enum class Type { Circle, Box } type;  
3  
4     union {  
5         struct { double radius; } circle;  
6         struct { double width, height; } box;  
7     } geometry;  
8 };
```

std::variant

...and an outer function that calculates the respective area

```
1  auto area(const Shape& shape) {  
2      switch(shape.type) {  
3          case Shape::Type::Circle: {  
4              const auto& g = shape.geometry.circle;  
5              return M_PI * g.radius * g.radius;  
6          }  
7          case Shape::Type::Box: {  
8              const auto& g = shape.geometry.box;  
9              return g.width * g.height;  
10         }  
11     }  
12  
13     assert(false);  
14     __builtin_unreachable();  
15 }
```

```
1 #include <cassert>
2 #include <cmath>
3
4 struct Shape {
5     enum class Type { Circle, Box } type;
6
7     union {
8         struct { double radius; } circle;
9         struct { double width, height; } box;
10    } geometry;
11 };
12
13 auto area(const Shape& shape) {
14     switch(shape.type) {
15         case Shape::Type::Circle: {
16             const auto& g = shape.geometry.circle;
17             return M_PI * g.radius * g.radius;
18         }
19         case Shape::Type::Box: {
20             [...]
```

godbolt.org/z/zYqTKn

Using `std::variant` instead

```
1 #include <cmath>
2 #include <variant>
3
4 struct Circle { double radius; };
5 struct Box { double width, height; };
6 using Shape = std::variant<Circle, Box>;
7
8 auto area(const Shape& shape) {
9     struct {
10         auto operator()(const Circle& c) const {
11             return M_PI * c.radius * c.radius;
12         }
13         auto operator()(const Box& b) const {
14             return b.width * b.height;
15         }
16     } visitor;
17
18     return std::visit(visitor, shape);
19 }
```

godbolt.org/z/6eT7qf

}

Q: What is the output of the program?

```
1 #include <algorithm>
2 #include <iostream>
3 #include <variant>
4 #include <vector>
5
6 template <typename... Fs> struct X: Fs... {
7     using Fs::operator( )...;
8 };
9 template <typename... Fs> X(Fs...) -> X<std::decay_t<Fs>...>;
10
11 int main() {
12     int a = 0; double b = 0.;
13     X visitor{[&a](int x) { a += x; },
14              [&b](double x) { b += x; }};
15     std::vector<std::variant<int, double>> v{1, 1.9, 2, 2.1};
16     std::for_each(v.begin(), v.end(), [&visitor](const auto &x) {
17         std::visit(visitor, x);
18     });
19     std::cout << a << ' ' << b;
20 }
```

godbolt.org/z/rKdTv5

```

1  #include <algorithm>
2  #include <iostream>
3  #include <variant>
4  #include <vector>
5
6  template <typename... Fs> struct X: Fs... {
7      using Fs::operator( )...;
8  };
9  template <typename... Fs> X(Fs...) -> X<std::decay_t<Fs>...>;
10
11 int main() {
12     int a = 0; double b = 0.;
13     X visitor{[&a](int x) { a += x; },
14              [&b](double x) { b += x; }};
15     std::vector<std::variant<int, double>> v{1, 1.9, 2, 2.1};
16     std::for_each(v.begin(), v.end(), [&visitor](const auto &x) {
17         std::visit(visitor, x);
18     });
19     std::cout << a << ' ' << b;
20 }

```

godbolt.org/z/rKdTv5

Q: What is the output of the program?

```
1 #include <algorithm>
2 #include <iostream>
3 #include <variant>
4 #include <vector>
5
6 template <typename... Fs> struct X: Fs... {
7     using Fs::operator( )...;
8 };
9 template <typename... Fs> X(Fs...) -> X<std::decay_t<Fs>...>;
10
11 int main() {
12     int a = 0; double b = 0.;
13     X visitor{[&a](int x) { a += x; },
14              [&b](double x) { b += x; }};
15     std::vector<std::variant<int, double, const char*>> v{1, 1.9, 2, 2.1, "foo"};
16     std::for_each(v.begin(), v.end(), [&visitor](const auto& x) {
17         std::visit(visitor, x);
18     });
19     std::cout << a << b;
20 }
```

godbolt.org/z/9fv85o

A: Compile-time error! (visitor is not exhaustive)

```
1 #include <algorithm>
2 #include <iostream>
3 #include <variant>
4 #include <vector>
5
6 template <typename... Fs> struct X: Fs... {
7     using Fs::operator( )...;
8 };
9 template <typename... Fs> X(Fs...) -> X<std::decay_t<Fs>...>;
10
11 int main() {
12     int a = 0; double b = 0.;
13     X visitor{[&a](int x) { a += x; },
14              [&b](double x) { b += x; }};
15     std::vector<std::variant<int, double, const char*>> v{1, 1.9, 2, 2.1, "foo"};
16     std::for_each(v.begin(), v.end(), [&visitor](const auto& x) {
17         std::visit(visitor, x);
18     });
19     std::cout << a << b;
20 }
```

godbolt.org/z/9fv85o

Using plain old structs

```
1 #include <algorithm>
2 #include <iostream>
3 #include <variant>
4 #include <vector>
5
6 struct X {
7     int &a; double &b;
8     auto operator()(int x) { a += x; };
9     auto operator()(double x) { b += x; };
10 };
11
12 int main() {
13     int a = 0; double b = 0.;
14     X visitor{.a=a, .b=b};
15     std::vector<std::variant<int, double>> v{1, 1.9, 2, 2.1};
16     std::for_each(v.begin(), v.end(), [&visitor](const auto& x) {
17         std::visit(visitor, x);
18     });
19     std::cout << a << b;
20 }
```

godbolt.org/z/r3a1q4

One could also use a generic lambda...

```
1 #include <algorithm>
2 #include <iostream>
3 #include <variant>
4 #include <vector>
5
6 int main() {
7     int a = 0; double b = 0.;
8     std::vector<std::variant<int, double>> v{1, 1.9, 2, 2.1};
9     std::for_each(v.begin(), v.end(), [&a, &b](const auto& x) {
10         std::visit([&a, &b](auto x) {
11             if constexpr (std::is_same_v<int, decltype(x)>) a += x;
12             else b += x;
13         }, x);
14     });
15     std::cout << a << b;
16 }
```

godbolt.org/z/5T7nTx

...however, no check for exhaustiveness at compile-time here!

Q: What is the output of the program?

```
1 #include <iostream>
2 #include <variant>
3
4 struct A { auto f() { return 1; } };
5 struct B { auto g() { return 2; } };
6
7 int main() {
8     std::visit([](auto x) {
9         using X = decltype(x);
10        if constexpr (std::is_same_v<X, A>) {
11            std::cout << x.f();
12        } else if constexpr (std::is_same_v<X, B>) {
13            std::cout << x.g();
14        } else {
15            std::cout << x.palim();
16        }
17    }, std::variant<A, B>{A{}});
18 }
```

godbolt.org/z/63zbqd

A: 1

```
1 #include <iostream>
2 #include <variant>
3
4 struct A { auto f() { return 1; } };
5 struct B { auto g() { return 2; } };
6
7 int main() {
8     std::visit([](auto x) {
9         using X = decltype(x);
10        if constexpr (std::is_same_v<X, A>) {
11            std::cout << x.f();
12        } else if constexpr (std::is_same_v<X, B>) {
13            std::cout << x.g();
14        } else {
15            std::cout << x.palim();
16        }
17    }, std::variant<A, B>{A{}});
18 }
```

godbolt.org/z/63zbqd

std::variant evaluation at compile-time

```
1 #include <variant>
2
3 template<typename... Ts> struct overloaded : Ts... { using Ts::operator()...; };
4 template<typename... Ts> overloaded(Ts...) -> overloaded<Ts...>;
5
6 int main() {
7     using T = std::variant<int, double>;
8     overloaded visitor = overloaded{[] (int x) -> T { return x + 1; },
9                                     [] (double x) -> T { return x + 2.; } };
10    constexpr auto result = std::visit(visitor, T{41});
11    static_assert(result.index() == 0 && std::get<0>(result) == 42);
12 }
```

godbolt.org/z/KM9nej