C++: λ Demystified

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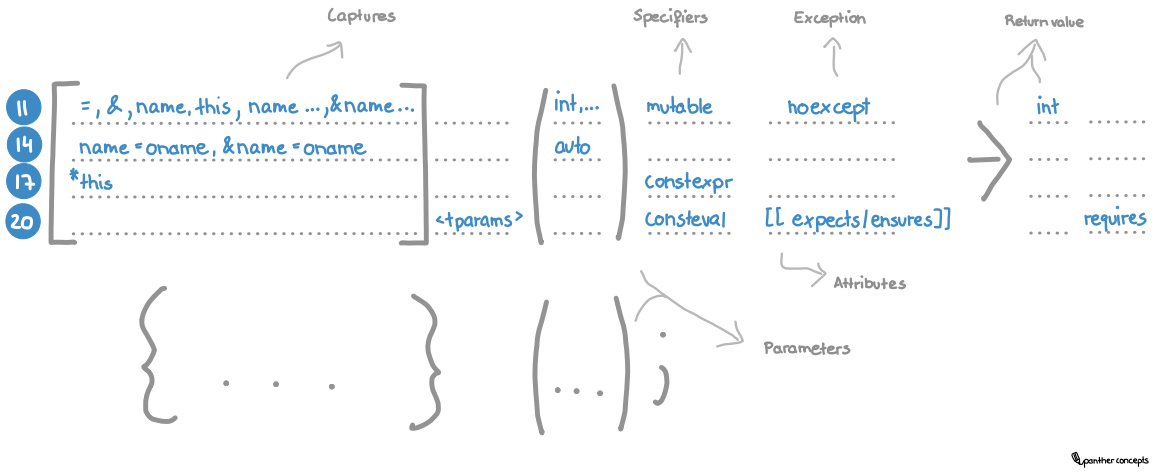
fertig

adjective /ˈfɛrtɪç/

finished
ready
complete
completed

Lambda Evolution



Valid or Not?

```
1 int main()
2 {
3   [] {} = {};
4 }
```

Lambda Internals

```
1 int main()
2 {
3   const char hello[]{"Hello CoreC++"};
4
5   [&] { printf("%s\n", hello); }();
6 }
```

Lambdas can appear everywhere...

```
1 int main()
2 {
3   int x = 5;
4   for(;
5       --x;
6       ) {
7     printf("x: %d\n", x);
8   }
9 }
```

Lambdas can appear everywhere...

```
1 int main()
2 {
3   int x = [] { return 5; }();
4   for([] { printf("started\n"); }();
5       [&] { return --x; }();
6       [] { printf("after\n"); }()) {
7     [&] { printf("x: %d\n", x); }();
8   }
9 }
```


Capturing Global Variables

```
1 int x{1};
2
3 int main()
4 {
5   [] { ++x; }();
6 }
```

Captureless Lambda and Function Pointer

```
1 int (*fp)(int, char) = [](int a, char b) { return a + b; };
```

Lambda as Default Arguments

```
1  int y = 3;
2
3  void Func(int x = [] { return 2 * y; }())
4  {
5    printf("x: %d\n", x);
6  }
7
8  int main()
9  {
10   Func();
11 }
```

Lambda as Default Arguments

```
1  int y = 3;
2
3  void FuncFP(int (*fp)() = [] { return 2 * y; })
4  {
5    printf("fp: %d\n", fp());
6  }
7
8  int main()
9  {
10   FuncFP();
11
12   FuncFP([] { return 22; });
13 }
```


Size of a Lambda

```
1  int main()
2  {
3    char a{2};
4    int  b{1};
5    char c{2};
6
7    auto f = [=] {
8      a;
9      b;
10     c;
11   };
12 }
```

Assume a x64 Platform.

Size of a Lambda

```
 1 int main()
 2 {
 3   char a{2};
 4   int  b{1};
 5   char c{2};
 6
 7   auto s = [=] {
 8     a;
 9     c;
10     b;
11   };
12 }
```

Assume a x64 Platform.

Size of a Lambda

> [...] An implementation may define the closure type differently from what is described below provided this does not alter the observable behavior of the program other than by changing:
>
> (2.1) the size and/or alignment of the closure type,
> (2.2) whether the closure type is trivially copyable (10.1), or
> (2.3) whether the closure type is a standard-layout class (10.1).
> [...]"
>
> — N4800 § 7.5.5.1 p2 [1]

Generic Lambda

C++14

- Have a call operator which is a operator template with return type `auto`.
- The `auto` parameters are template parameters.

```
1 auto l = []( auto  v) { return v * 2; };
2
3 auto d = l(2.0);
4 auto i = l(2);
```

Generic Lambda

C++14

- Have a call operator which is a operator template with return type `auto`.
- The `auto` parameters are template parameters.
- In combination with C++17's constexpr if we can have Lambdas with multiple return types.

```
1  auto l = [](auto v) {
2    if constexpr(std::is_same_v<decltype(v), double>) {
3      return v * 2.0;
4    } else {
5      return v * 2;
6    }
7  };
8
9  auto d = l(2.0);
10 auto i = l(2);
```

The Dangling Reference Trap

- Is that innocent looking lambda okay?

```
1  auto Func()
2  {
3    int x{22};
4
5    auto l = [&] { return x * x; };
6
7    // a bunch of code follows.
8
9    return l;
10 }
```


The Dangling Reference Trap

- Is that innocent looking lambda okay?

> [...] If a non-reference entity is implicitly or explicitly captured by reference, invoking the function call operator of the corresponding lambda-expression after the lifetime of the entity has ended is likely to result in undefined behavior. [...]"
>
> — N4800 § 7.5.5.2 p16 [1]

- As a rule: Only capture by reference, if you pass the lambda into a function or use it locally.

```
1  auto Func()
2  {
3    int x{22};
4
5    auto l = [ = ] { return x * x; };
6
7    // a bunch of code follows.
8
9    return l;
10 }
```

The Dangling Reference Trap

- Is that innocent looking lambda okay?
- As a rule: Only capture by reference, if you pass the lambda into a function or use it locally.
- A slight change, but still capturing by copy.

```
1  auto Func()
2  {
3    int* x = new int{22};
4
5    auto l = [=] { return (*x) * (*x); };
6
7    // a bunch of code follows.
8
9    return l;
10 }
```


The Dangling Reference Trap

- Is that innocent looking lambda okay?
- As a rule: Only capture by reference, if you pass the lambda into a function or use it locally.
- A slight change, but still capturing by copy.
- Ouch...

```
1  auto Func()
2  {
3    int* x = new int{22};
4
5    auto l = [=] { return (*x) * (*x); };
6
7    // a bunch of code follows.
8    // and in the middle of that code:
9    delete x;
10
11   return l;
12 }
```

The Dangling Reference Trap

- Is that innocent looking lambda okay?
- As a rule: Only capture by reference, if you pass the lambda into a function or use it locally.
- A slight change, but still capturing by copy.
- Ouch...
- Not an issue with smart pointers.

```
1  auto Func()
2  {
3    shared_ptr<int> x = make_shared<int>(22);
4
5    auto l = [=] { return (*x) * (*x); };
6
7    // a bunch of code follows.
8
9    return l;
10 }
```

Captures

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      auto l1 = [=] { return a + 2; };
8
9      printf("l1: %d\n", l1());
10
11     ++a;
12
13     printf("l1: %d\n", l1());
14   }
15
16   int a;
17 };
18
19 int main()
20 {
21   Test t{2};
22 }
```

Captures

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      auto l1 = [=] { return a + 2; };
8
9      printf("l1: %d\n", l1());
10
11     ++a;
12
13     printf("l1: %d\n", l1());
14   }
15
16   int a;
17 };
18
19 int main()
20 {
21   Test t{2};
22 }
```

```
$ ./a.out
l1: 4
l1: 5
```


Captures

C++17

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      auto l1 = [ * this ] { return a + 2; };
8
9      printf("l1: %d\n", l1());
10
11     ++a;
12
13     printf("l1: %d\n", l1());
14   }
15
16   int a;
17 };
18
19 int main()
20 {
21   Test t{2};
22 }
```

```
$ ./a.out
l1: 4
l1: 4
```

Captures

C++17

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      auto l2 = [*this] { return a + 2; };
8    }
9
10   int a;
11   int b;
12 };
```

Captures

C++14

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      auto l2 = [al = a] { return al + 2; };
8    }
9
10   int a;
11   int b;
12 };
```

Size of a Lambda - Part II

```
1  class Test
2  {
3  public:
4    Test(int x)
5    : a{x}
6    {
7      const int size = 2;
8
9      auto l2 = [=] {
10       int x[size]{};
11
12       return a + 2;
13     };
14   }
15
16   int a;
17 };
```

Sleeping Lambda

```
1  int main()
2  {
3    std::string foo;
4
5    auto a = [=]    () { printf( "%s\n", foo.c_str()); };
6
7    auto b = [=]    () { };
8
9    auto c = [foo]  () { printf( "%s\n", foo.c_str()); };
10
11   auto d = [foo]  () { };
12
13   auto e = [&foo] () { printf( "%s\n", foo.c_str()); };
14
15   auto f = [&foo] () { };
16 }
```

Assume a x64 Platform.

constexpr Lambdas

C++17

- With C++17 usable in `constexpr` contexts. Algorithm functions from [2].

```
1  template<class InputIt, class UnaryPredicate>
2  constexpr InputIt find_if_not(InputIt first, InputIt last, UnaryPredicate q)
3  {
4    for(; first != last; ++first) {
5      if(!q(*first)) {
6        return first;
7      }
8    }
9    return last;
10 }
11
12 template<class InputIt, class UnaryPredicate>
13 constexpr bool all_of(InputIt first, InputIt last, UnaryPredicate p)
14 {
15   return find_if_not(first, last, p) == last;
16 }
17
18 int main()
19 {
20   constexpr int  ar[5]{1, 3, 5, 7, 9};
21   constexpr bool allEven =
22     all_of(&ar[0], &ar[5], [](int i) { return (i % 2) == 0; });
23
24   return allEven;
25 }
```

constexpr Lambdas

C++20

- With C++17 usable in `constexpr` contexts.
- Thanks to P0202 [3] more algorithms (will) work in C++20.

```
1  #include <algorithm>
2  #include <array>
3
4  int main()
5  {
6    constexpr std::array<int, 5> ar{1, 3, 5, 7, 9};
7    constexpr bool               allEven =
8      std::all_of(ar.begin(), ar.end(), [](int i) { return (i % 2) == 0; });
9
10   return allEven;
11 }
```

Lambdas Applied

- Where / how can lambdas be useful?
  - If additional functionality is required before and / or after a code fragment.

```
1  template<typename T>
2  void CodeGenerator::WrapInParensOrCurlys(const BraceKind        braceKind,
3                                           T&&                    lambda,
4                                           const AddSpaceAtTheEnd addSpaceAtTheEnd)
5  {
6    if(BraceKind::Curlys == braceKind) {
7      mOutputFormatHelper.Append('{');
8    } else {
9      mOutputFormatHelper.Append('(');
10   }
11
12   lambda();
13
14   if(BraceKind::Curlys == braceKind)
15   {
16     mOutputFormatHelper.Append('}');
17   }
18   else { mOutputFormatHelper.Append(')'); }
19
20   if(AddSpaceAtTheEnd::Yes == addSpaceAtTheEnd) {
21     mOutputFormatHelper.Append(' ');
22   }
23 }
```

From C++ Insights.

Lambdas Applied

- Where / how can lambdas be useful?
  - If additional functionality is required before and / or after a code fragment.

```
1  template<typename T, typename Lambda>
2  static inline void ForEachArg(const T&            arguments,
3                                OutputFormatHelper& outputFormatHelper,
4                                Lambda&&            lambda)
5  {
6    OnceFalse needsComma{};
7
8    for(const auto& arg : arguments) {
9      if(needsComma) {
10       outputFormatHelper.Append(", ");
11     }
12
13     lambda(arg);
14   }
15 }
```

From C++ Insights.

Lambdas Applied

- Where / how can lambdas be useful?
  - To achieve more const'ness for variables.
  - Also known as *Immediately-invoked function expression* [4].

```
1  const auto name = [&]() -> std::string {
2    // Handle a special case where we have a lambda
3    // static invoke operator. In that case use the
4    // appropriate using retType as return type
5    if(const auto* m = dyn_cast_or_null<CXXMethodDecl>(meDecl)) {
6      if(const auto* rd = m->getParent(); rd && rd->isLambda()) {
7        skipTemplateArgs = true;
8
9        return StrCat("operator ", GetLambdaName(*rd), "::", BuildRetTypeName(*rd));
10     }
11   }
12
13   return stmt->getMemberNameInfo().getName().getAsString();
14 }();
```

From C++ Insights.

Lambdas Applied

- Where / how can lambdas be useful?
  - Clean up / release resources.

```
1  size_t ReadData(span<char> buffer)
2  {
3    int fd = Open(/* some well known file*/);
4
5    if(-1 == fd) {
6      return 0;
7    }
8
9    const auto len =
10     read(fd, buffer.data(), buffer.size());
11
12   if(-1 == len) {
13     return 0;
14   }
15
16   ftruncate(fd, len);
17
18   close(fd);
19
20   return gsl::narrow_cast<size_t>(len);
21 }
```

Lambdas Applied

- Where / how can lambdas be useful?
  - Clean up / release resources.

```cpp
size_t ReadData(span<char> buffer)
{
  int  fd = Open(/* some well known file*/);
  FinalAction cleanup{[&] {
    if(-1 != fd) {
      close(fd);
    }
  }};

  if(-1 == fd) {
    return 0;
  }

  const auto len =
    read(fd, buffer.data(), buffer.size());

  if(-1 == len) {
    return 0;
  }

  ftruncate(fd, len);

  return gsl::narrow_cast<size_t>(len);
}
```


Lambdas Applied

- Where / how can lambdas be useful?
  - Clean up / release resources.

```cpp
template<typename T>
class FinalAction
{
public:
  explicit FinalAction(T&& action)
  : mAction{std::move(action)}
  {
  }

  ~FinalAction() { mAction(); }

private:
  T mAction;
};
```

```cpp
size_t ReadData(span<char> buffer)
{
  int  fd = Open(/* some well known file*/);
  FinalAction cleanup{[&] {
    if(-1 != fd) {
      close(fd);
    }
  }};

  if(-1 == fd) {
    return 0;
  }

  const auto len =
    read(fd, buffer.data(), buffer.size());

  if(-1 == len) {
    return 0;
  }

  ftruncate(fd, len);

  return gsl::narrow_cast<size_t>(len);
}
```

Lambdas for Retrospection

```
1  void MyState::Transition(State newState)
2  {
3    auto capture = [=] {
4      printf("formerState: %d newState: %d %u/%u",
5             mState,
6             newState,
7             mAckSeqNo,
8             mSeqNo);
9    };
10
11   bool transitionValid;
12   // do the transition
13
14   if(not transitionValid) {
15     capture();  // dump the former state
16   }
17 }
```


Capture Structured Binding Variable

C++20

```
1  struct OddPoint
2  {
3    int  a;
4    char b;
5  };
6
7  int main()
8  {
9    auto [a, b] = OddPoint{};
10
11   auto c = [&] { return b; };
12 }
```

Currently, not supported in Clang and C++ Insights.

Lambda capture pack expansion and use move

C++20

```
1  template<typename... Args>
2  void foo(Args&&... args)
3  {
4    (..., (std::cout << args));
5  }
6
7  template<class... Args>
8  auto InvokeLater(Args&&... args)
9  {
10   return [... margs = std::forward<Args>(args)] { return foo(margs...); };
11 }
12
13 int main()
14 {
15   auto il = InvokeLater("Hello"s, " "s, "World"s);
16   il();
17 }
```

Currently, not supported in Clang and C++ Insights.

Templated Lambdas

C++20

```
1  int main()
2  {
3    auto max = [](auto x, auto y) {
4      return (x > y) ? x : y;
5    };
6
7    max(2, 3);    // ok
8    max(2, 3.0);  // not wanted
9  }
```

Currently, not supported in Clang and C++ Insights.

Templated Lambdas

C++20

```
 1 int main()
 2 {
 3   auto max = []<typename T>(T x, T y)
 4   {
 5     return (x > y) ? x : y;
 6   };
 7
 8   max(2, 3);  // ok
 9   // max(2, 3.0);  // does not compile anymore
10 }
```

Currently, not supported in Clang and C++ Insights.

Templated Lambdas

C++20

```
1 auto lambda = []<typename T>(std::vector<T> t){};
2 std::vector<int> v{};
3
4 lambda(v);
5 // lambda(20);
```

```
 1 #include <array>
 2
 3 int main()
 4 {
 5   auto l = []<size_t N>(std::array<int, N> x) {};
 6
 7   std::array<int, 2> a{};
 8
 9   l(a);
10 }
```

Currently, not supported in Clang and C++ Insights.

Templated Lambdas

C++20

Do it with C++14:

```
1  #include <array>
2
3  int main()
4  {
5    auto l = [](std::array<auto, 2> x) {};
6
7    std::array<int, 2> a{};
8
9    l(a);
10 }
```

Does it compile?

Currently, not supported in Clang and C++ Insights.

Default Constructible Lambdas & `decltype`

C++20

C++14 version:

```
1 auto compare = [](auto x, auto y) { return x > y; };
2 std::map<std::string, int, decltype(compare)> map{{"a", 1}, {"b", 2}};
3
4 for(const auto& [v, k] : map) {
5   printf("%s\n", v.c_str());
6 }
```

Currently, not supported in Clang and C++ Insights.

Default Constructible Lambdas & `decltype`

C++20

```
1 std::map<std::string, int, decltype([](auto x, auto y) { return x > y; })> map{
2   {"a", 1},
3   {"b", 2}};
4
5 for(const auto& [v, k] : map) {
6   printf("%s\n", v.c_str());
7 }
```

Currently, not supported in Clang and C++ Insights.

Lambda Overuse

- Can we have an overuse of lambdas?

```
1 const bool isListInitialization{
2   [&]() { return stmt->getLParenLoc().isInvalid(); }()};
```

Lambda Overuse

- Can we have an overuse of lambdas?

```
1 const bool isListInitialization{stmt->getLParenLoc().isInvalid()};
```


The Work of Others

- Meeting C++ 2018: Higher Order Functions for ordinary developers - Björn Fahller [5]
- compile-time iteration with C++20 lambdas - Vittorio Romeo [6]
- C++ Weekly - Ep 152 - Lambdas: The Key To Understanding C++ - Jason Turner [7]
- Lambdas: From C++11 to C++20, Part 1 - Bartlomiej Filipek [8]
- ...

```
}
```

I am Fertig.

```
https://cppinsights.io
```

Available online:

https://www.AndreasFertig.Info

Images by Franziska Panter:

https://panther-concepts.de

Used Compilers

- Compilers used to compile (most of) the examples.
  - g++ (GCC) 9.0.1 20190421 (experimental)
  - clang version 9.0.0 (https://github.com/llvm-mirror/clang.git 1fa8b1fbd40d147ef9fa0fe73fbd44977250989f) (https://github.com/llvm-mirror/llvm.git a7866b1030537ff197099251d5ee6b46b35c13e2)

References

[1] Smith R., “Working Draft, Standard for Programming Language C++”, *N4800*, May 2019. http://wg21.link/n4800

[2] “cppreference: std::find, std::find_if, std::find_if_not”. https://en.cppreference.com/w/cpp/algorithm/find

[3] Polukhin A., “Add constexpr modifiers to functions in <algorithm> and <utility> headers”. http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2017/p0202r3.html

[4] Filipek B., “life for complex initialization”. https://www.bfilipek.com/2016/11/iife-for-complex-initialization.html

[5] Fahller B., “Higher order functions for ordinary developers”. https://www.youtube.com/watch?v=qL6zUn7iiLg

[6] Romeo V., “compile-time iteration with c++20 lambdas”. https://vittorioromeo.info/index/blog/cpp20_lambdas_compiletime_for.html

[7] Turner J., “C++ weekly - ep 152 - lambdas: The key to understanding c++”. https://www.youtube.com/watch?v=CjExHyCVRYg

[8] Filipek B., “Lambdas: From c++11 to c++20, part 1”. https://www.bfilipek.com/2019/02/lambdas-story-part1.html

Images:

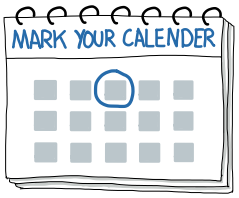
3: Franziska Panter

52: Franziska Panter

Upcoming Events

- *C++: λ Demystified*, Core C++, May 15 2019
- *C++: λ Demystified*, NDC { Oslo }, June 17 2019
- *C++: λ Demystified*, NDC TechTown, September 04 2019
- *C++ Insights: See your source code with the eyes of a compiler*, NDC { TechTown }, September 05 2019
- *C++1x für eingebettete Systeme kompakt*, Seminar QA Systems, November 14 2018
- *C++ Templates - die richtige Dosis kompakt*, Seminar QA Systems, November 15 2018

To keep in the loop, periodically check my *Talks and Training* (`https://andreasfertig.info/talks.html`) page.



About Andreas Fertig

Andreas holds an M.S. in Computer Science from Karlsruhe University of Applied Sciences. Since 2010 he has been a software developer and architect for Philips Medical Systems focusing on embedded systems. He has a profound knowledge of C++ and is a frequent SG14 member.

He works freelance as a lecturer and trainer. Besides this he develops macOS applications and is the creator of cppinsights.io