Demystifying Value Categories in C++

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Disclaimer

Disclaimer

- → This talk is mainly about hounding (unnecessary) copy ctors
- → In case you don't care:

"If you're not at all interested in performance, shouldn't you be in the Python room down the hall?" (Scott Meyers)

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PART I

Understanding References

Q: What is the output of the programs?

```python
#!/usr/bin/env python3

class S:
    def __init__(self, x):
        self.x = x

def swap(a, b):
    b, a = a, b

if __name__ == '__main__':
    a, b = S(1), S(2)
    swap(a, b)
    print(f'{a.x}{b.x}')
```

```cpp
#include <iostream>

struct S {
    int x;
};

void swap(S& a, S& b) {
    S& tmp = a;
    a = b;
    b = tmp;
}

int main() {
    S a{1}; S b{2};
    swap(a, b);
    std::cout << a.x << b.x;
}
```

godbolt.org/z/rE6Ecd

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct S {
4      int x;
5  };
6
7  void swap(S& a, S& b) {
8      S tmp = a;
9      a = b;
10     b = tmp;
11 }
12
13 int main() {
14     S a{1}; S b{2};
15     swap(a, b);
16     std::cout << a.x << b.x;
17 }
```

godbolt.org/z/r6oq55

Q: What is the output of the program?

```
#include <iostream>

struct S {
    int x;
    S(int x): x(x) { std::cout << 'a'; }
    S(const S& other): x(other.x) { std::cout << 'b'; }
    S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
};

void swap(S& a, S& b) {
    S& tmp = a;
    a = b;
    b = tmp;
}

int main() {
    S a{1}; S b{2};
    swap(a, b);
    std::cout << a.x << b.x;
}
```

godbolt.org/z/jfM6h1

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct S {
4      int x;
5      S(int x): x(x) { std::cout << 'a'; }
6      S(const S& other): x(other.x) { std::cout << 'b'; }
7      S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
8  };
9
10 void swap(S& a, S& b) {
11     S tmp = a;
12     a = b;
13     b = tmp;
14 }
15
16 int main() {
17     S a{1}; S b{2};
18     swap(a, b);
19     std::cout << a.x << b.x;
20 }
```

godbolt.org/z/ohe3Wb

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct S {
4      int x;
5      S(int x): x(x) { std::cout << 'a'; }
6      S(const S& other): x(other.x) { std::cout << 'b'; }
7      S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
8  };
9
10 void swap(S* a, S* b) {
11     S* tmp = a;
12     a = b;
13     b = tmp;
14 }
15
16 int main() {
17     S a{1}; S b{2};
18     swap(&a, &b);
19     std::cout << a.x << b.x;
20 }
```

godbolt.org/z/8fovsa

Q: What is the output of the program?

```cpp
#include <iostream>

struct S {
    int x;
    S(int x): x(x) { std::cout << 'a'; }
    S(const S& other): x(other.x) { std::cout << 'b'; }
    S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
};

void swap(S* a, S* b) {
    S* tmp = a;
    a = b;
    b = tmp;
}

int main() {
    S a{1}; S b{2}; S* a_ptr = &a; S* b_ptr = &b;
    swap(a_ptr, b_ptr);
    std::cout << a_ptr->x << b_ptr->x;
}
```

godbolt.org/z/6357rq

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct S {
4      int x;
5      S(int x): x(x) { std::cout << 'a'; }
6      S(const S& other): x(other.x) { std::cout << 'b'; }
7      S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
8  };
9
10 void swap(S*& a, S*& b) {
11     S* tmp = a;
12     a = b;
13     b = tmp;
14 }
15
16 int main() {
17     S a{1}; S b{2}; S* a_ptr = &a; S* b_ptr = &b;
18     swap(a_ptr, b_ptr);
19     std::cout << a_ptr->x << b_ptr->x;
20 }
```

godbolt.org/z/dEsxEY

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct S {
4      int x;
5      S(int x): x(x) { std::cout << 'a'; }
6      S(const S& other): x(other.x) { std::cout << 'b'; }
7      S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
8  };
9
10 void swap(S*& a, S*& b) {
11     S* tmp = a;
12     a = b;
13     b = tmp;
14 }
15
16 int main() {
17     S a{1}; S b{2};
18     swap(&a, &b);
19     std::cout << a.x << b.x;
20 }
```

godbolt.org/z/Eh656x

Q: What is the output of the program?

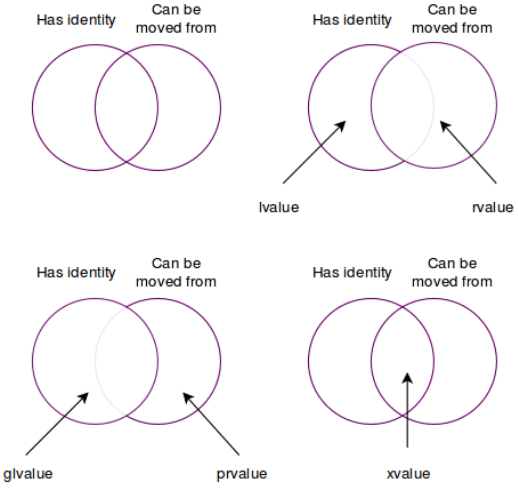
error: cannot bind non-const lvalue reference of type “S*&” to an rvalue of type “S*”

```
1  #include <iostream>
2
3  struct S {
4      int x;
5      S(int x): x(x) { std::cout << 'a'; }
6      S(const S& other): x(other.x) { std::cout << 'b'; }
7      S& operator=(const S& other) { x = other.x; std::cout << 'c'; return *this; }
8  };
9
10 void swap(S*& a, S*& b) {
11     S* tmp = a;
12     a = b;
13     b = tmp;
14 }
15
16 int main() {
17     S a{1}; S b{2};
18     swap(&a, &b);
19     std::cout << a.x << b.x;
20 }
```

godbolt.org/z/Eh656x

Value Categories

Value categories with Venn diagrams



(diagrams shamelessly stolen from `bajamircea.github.io/coding/cpp/2016/04/07/move-forward.html`)

Value categories with Venn diagrams

(diagrams shamelessly stolen from `bajamircea.github.io/coding/cpp/2016/04/07/move-forward.html`)

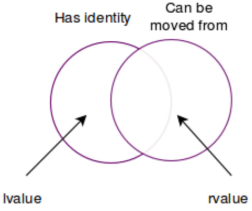
```cpp
struct S{ int x; };

S make_S(int x) {
    S s{.x = x};
    return s; // has no name after returning
}

int main() {
    S a = make_S(42); // `a` is an lvalue
                      // initialized with a prvalue

    S b = std::move(a); // prepare to die, `a`!
                        // now `a` became an xvalue

    auto x = a.x; // ERROR: `a` is in an undefined state
    a = make_S(13);
    x = a.x; // fine!
}
```



Value categories with Venn diagrams

(diagrams shamelessly stolen from `bajamircea.github.io/coding/cpp/2016/04/07/move-forward.html`)

```cpp
struct S{ int x; };

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    S s{.x = x};
    return s; // has no name after returning
}

int main() {
    S a = make_S(42); // `a` is an lvalue
                      // initialized with a prvalue

    S b = std::move(a); // prepare to die, `a`!
                        // now `a` became an xvalue

    auto x = a.x; // ERROR: `a` is in an undefined state
    a = make_S(13);
    x = a.x; // fine!
}
```
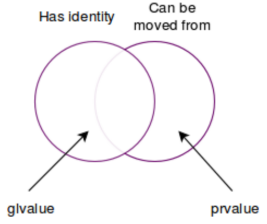
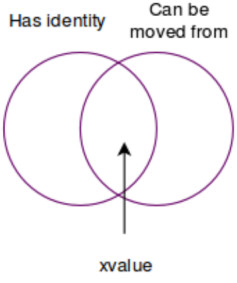



Value categories with Venn diagrams

(diagrams shamelessly stolen from `bajamircea.github.io/coding/cpp/2016/04/07/move-forward.html`)

```cpp
struct S{ int x; };

S make_S(int x) {
    S s{.x = x};
    return s; // has no name after returning
}

int main() {
    S a = make_S(42); // `a` is an lvalue
                      // initialized with a prvalue

    S b = std::move(a); // prepare to die, `a`!
                        // now `a` became an xvalue

    auto x = a.x; // ERROR: `a` is in an undefined state
    a = make_S(13);
    x = a.x; // fine!
}
```



Binding references to temporaries

error: cannot bind non-const lvalue reference of type “S*&” to an rvalue of type “S*”

```
1  template <typename T>
2  void swap(T& a, T& b) { ... }
3
4  int main() {
5      S a{1};
6      S b{2};
7      swap(&a, &b);
8  }
```

- → Memory addresses are always rvalues!
- → One cannot refer to something that doesn’t has a name…
- → …except it is a const reference (lifetime extension)

std::move

std::move

```cpp
#include <iostream>
#include <utility>

struct S{};

void f(const S&) { std::cout << 'a'; }
void f(S&&) { std::cout << 'b'; }

int main() {
    S s;
    f(s);            // prints 'a'
    f(std::move(s)); // prints 'b'
}
```

godbolt.org/z/aKbGEc

- `std::move` creates xvalues
- Syntax:
  - lvalue ref.: S&
  - rvalue ref.: S&&

Q: What is the output of the program?

```cpp
#include <iostream>
#include <utility>

struct S{
    S() { std::cout << 'a'; }
    S(const S&) { std::cout << 'b'; }
    S(S&&) { std::cout << 'c'; }
};

int main() {
    S s1;
    S s2(s1);
    S s3(S{});
    S s4(std::move(s1));
}
```

godbolt.org/z/16hYbz

A: abac

```cpp
#include <iostream>
#include <utility>

struct S{
    S() { std::cout << 'a'; }
    S(const S&) { std::cout << 'b'; }
    S(S&&) { std::cout << 'c'; }
};

int main() {
    S s1;
    S s2(s1);
    S s3(S{});
    S s4(std::move(s1));
}
```

godbolt.org/z/16hYbz

- `S s1`: no surprise
- `S s2(s1)`: no surprise
- `S s3(S{})`: *mandatory* copy elision (initializer is prvalue of the same class type)
- `S s4(std::move(s1))`: forced move construction

Q: What is the output of the program?

```cpp
#include <iostream>
#include <utility>

struct S {
    S() { std::cout << 'a'; }
    S(const S&) { std::cout << 'b'; }
    S(S&&) { std::cout << 'c'; }
};

void f(const S&) { std::cout << '1'; }
void f(S&) { std::cout << '2'; }
void f(S&&) { std::cout << '3'; }

int main() {
    S s1;
    f(s1);
    f(S{});
    f(std::move(s1));
}
```

godbolt.org/z/4MKojT

Q: What is the output of the program?

```
1  #include <iostream>
2  #include <utility>
3
4  struct S {
5      S() { std::cout << 'a'; }
6      S(const S&) { std::cout << 'b'; }
7      S(S&&) { std::cout << 'c'; }
8  };
9
10 void f(const S&) { std::cout << '1'; }
11 void f(S) { std::cout << '2'; }
12 void f(S&&) { std::cout << '3'; }
13
14 int main() {
15     S s1;
16     f(s1);
17     f(S{});
18     f(std::move(s1));
19 }
```

godbolt.org/z/jaYTYP

Q: What is the output of the program?

```
1  #include <iostream>
2  #include <utility>
3
4  struct S {
5      S() { std::cout << 'a'; }
6      S(const S&) { std::cout << 'b'; }
7      S(S&&) { std::cout << 'c'; }
8  };
9
10 void f(const S&) { std::cout << '1'; }
11 void f(S) { std::cout << '2'; }
12 void f(S&&) { std::cout << '3'; }
13
14 int main() {
15     S s1;
16     f(s1);
17     f(S{});
18     f(std::move(s1));
19 }
```

godbolt.org/z/jaYTYP

Compile-time error (in all three cases)

- → `f(s1)`: ambiguity between 2 and 1
- → `f(S{})`: ambiguity between 2 and 3
- → `f(std::move(s1))`: same as `f(S)`

↪ compiler cannot differentiate between copy and reference overloads! (neither lvalue, nor rvalue)

Q: What is the output of the program?

```cpp
#include <iostream>
#include <utility>

struct S {
    ~S() { std::cout << 'a'; }
};

void f(const S&) { std::cout << '1'; }
void f(S&) { std::cout << '2'; }
void f(S&&) { std::cout << '3'; }

int main() {
    S&& r1 = S{};
    f(r1);

    S&& r2 = S{};
    f(std::move(r2));
}
```

godbolt.org/z/5s1zc5

A: 23aa

```
1  #include <iostream>
2  #include <utility>
3
4  struct S {
5      ~S() { std::cout << 'a'; }
6  };
7
8  void f(const S&) { std::cout << '1'; }
9  void f(S&) { std::cout << '2'; }
10 void f(S&&) { std::cout << '3'; }
11
12 int main() {
13     S&& r1 = S{};
14     f(r1);
15
16     S&& r2 = S{};
17     f(std::move(r2));
18 }
```

godbolt.org/z/5s1zc5

- → S&&: object that nobody cares about anymore and which will die soon (cf. lifetime extension!)
- → `std::move` does not actually kill, but makes the object look like a dying object

NB: an rvalue ref behaves like an lvalue ref except that it can bind to a temporary (an rvalue), whereas one cannot bind a (non const) lvalue ref to an rvalue.

std::move

```
1  #include <type_traits>
2
3  template <typename T>
4  decltype(auto) move(T&& t) {
5      using R = std::remove_reference_t<T>&&;
6      return static_cast<R>(t);
7  }
```

godbolt.org/z/W8zb8G

So what does `std::move`?

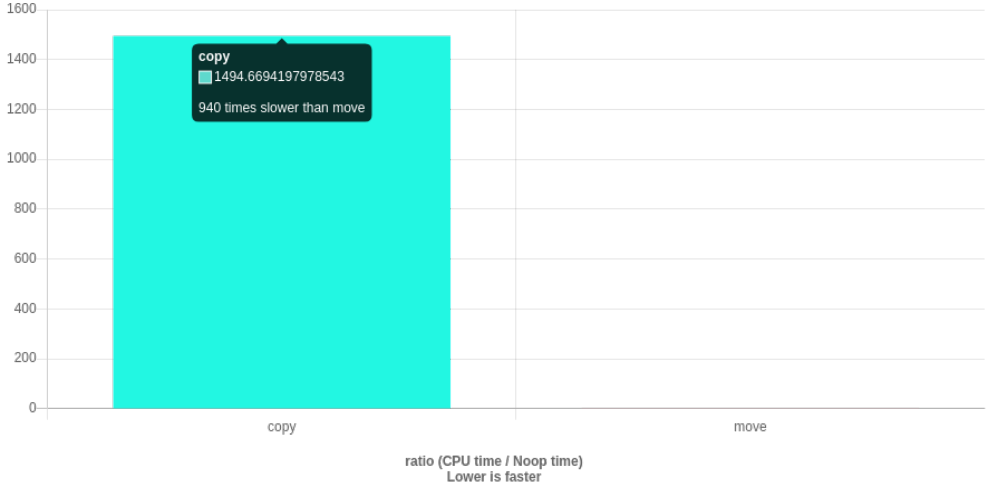
- → does not *move*
- → does not destroy
- → does nothing at all during runtime
- → **unconditionally casts** its argument to an rvalue

Quick Bench: tinyurl.com/y67sg7to

```
1  std::vector<int> x(1000, 42);
2  std::vector<int> y(1000, 42);
3  for (auto _ : state) {
4      auto tmp = x;
5      x = y;
6      y = tmp;
7      benchmark::DoNotOptimize(x[345] + y[678]);
8  }
```

```
1  std::vector<int> x(1000, 42);
2  std::vector<int> y(1000, 42);
3  for (auto _ : state) {
4      auto tmp = std::move(x);
5      x = std::move(y);
6      y = std::move(tmp);
7      benchmark::DoNotOptimize(x[345] + y[678]);
8  }
```

Quick Bench: tinyurl.com/y67sg7to



Universal References

Rvalue ref. or no rvalue ref.?

Rvalue refs are declared using “&&”: reasonable to assume that the presence of “&&” in a type declaration indicates an rvalue reference?

```
struct S{};

S&& s = S{};                    // (1)

auto&& s2 = s;                  // (2)

void f(S&& s);                  // (3)

template <typename T>
void f(T&& t);                  // (4)

template <typename T>
void f(const T&& t);            // (5)

template <typename T>
void f(std::vector<T>&& v); // (6)
```

Does “&&” mean rvalue reference?

- → (1): ???
- → (2): ???
- → (3): ???
- → (4): ???
- → (5): ???
- → (6): ???

Rvalue ref. or no rvalue ref.?

Rvalue refs are declared using “&&”: reasonable to assume that the presence of “&&” in a type declaration indicates an rvalue reference?

```
struct S{};

S&& s = S{};                          // (1)

auto&& s2 = s;                        // (2)

void f(S&& s);                        // (3)

template <typename T>
void f(T&& t);                        // (4)

template <typename T>
void f(const T&& t);                  // (5)

template <typename T>
void f(std::vector<T>&& v);           // (6)
```

Does “&&” mean rvalue reference?

- → (1):
- → (2):
- → (3):
- → (4):
- → (5):
- → (6):

* albeit questionable: `move` changes object in most cases ⇏ `const`

`std::move` and `const`

* albeit questionable: `move` changes object in most cases ⇏ `const`

```
1  #include <iostream>
2
3  struct S {
4      S() {}
5      S(const S&) { std::cout << 'A'; }
6      S(S&&) { std::cout << 'B'; }
7  };
8
9  int main() {
10     const S s;
11     auto s2 = std::move(s);
12 }
```

godbolt.org/z/r9hv8K

…prints A

(cf. https://stackoverflow.com/a/28595415)

Universal references

Universal references[†]

- Syntax (`x` is a universal reference):
  - `auto&& x`
  - `template <typename T> f(T&& x…`
- Rule of thumb: substitute fully qualified type into `auto` or `T` and reduce:
  - `&&` ↦ `&&`
  - `&&&` ↦ `&`
  - `&&&&` ↦ `&&`

```
std::vector<S> v;
auto&& s = v[0]; // S&&& -> S&

auto&& s2 = S{}; // S&&&& -> S&&
auto&& s3 = s2;  // S&&&  -> S&

// S&&&& -> S&&
auto&& s3 = std::move(s2);

/* Exception */
S s4{};
auto&& s5 = s4; // S&& -> S&
```

Universal reference are always references!

[†] *Universal reference*: term introduced by Scott Meyers

Q: What is the output of the program?

```cpp
#include <iostream>
#include <type_traits>

struct S {
    S() { std::cout << 'a'; }
    S(const S&) { std::cout << 'b'; }
    S(S&&) { std::cout << 'c'; }
};

template <typename T>
S f(T&& t) { return t; }

int main() {
    S s{};
    f(s);
    f(std::move(s));
}
```

godbolt.org/z/6xn1n3

Q: What is the output of the program?

```cpp
#include <iostream>
#include <type_traits>

struct S{};

void f(S&) { std::cout << 'a'; }
void f(S&&) { std::cout << 'b'; }

int main() {
    auto&& r1 = S{};
    static_assert(std::is_same_v<decltype(r1), S&&>);
    f(r1);
    f(static_cast<S&&>(r1));

    S s;
    auto&& r2 = s;
    static_assert(std::is_same_v<decltype(r2), S&>);
    f(r2);
}
```

godbolt.org/z/zTExze

Q: What is the output of the program?

```cpp
#include <iostream>

struct S{
    void f() & { std::cout << 'a'; }
    void f() && { std::cout << 'b'; }
};

int main() {
    auto&& r1 = S{};
    r1.f();
    static_cast<decltype(r1)>(r1).f();

    auto&& r2 = r1;
    r2.f();
    static_cast<decltype(r2)>(r2).f();
}
```

godbolt.org/z/WcYYsd

How do we fuse these implementations?

```cpp
// if `t` is an lvalue of type `T`
template <typename T> T& forward(T& t) {
    return t;
}

// if `t` is an rvalue of type `T`
template <typename T> T&& forward(T& t) {
    return std::move(t); // static_cast<T&&>(t)
}
```

```cpp
#include <type_traits>

template <typename T>
T&& forward(std::remove_reference_t<T>& t) {
    return static_cast<T&&>(t);
}
```

godbolt.org/z/EjPnPr

Q: What is the output of the program?

```
#include <iostream>
#include <type_traits>

struct S {
    S() { std::cout << 'a'; }
    S(const S&) { std::cout << 'b'; }
    S(S&&) { std::cout << 'c'; }
};

template <typename T>
S f(T&& t) { return std::forward<T>(t); }

int main() {
    S s{};
    f(s);
    f(std::move(s));
}
```

godbolt.org/z/7Worb3

A: abc

```
1  #include <iostream>
2  #include <type_traits>
3
4  struct S {
5      S() { std::cout << 'a'; }
6      S(const S&) { std::cout << 'b'; }
7      S(S&&) { std::cout << 'c'; }
8  };
9
10 template <typename T>
11 S f(T&& t) { return std::forward<T>(t); }
12
13 int main() {
14     S s{};
15     f(s);
16     f(std::move(s));
17 }
```

godbolt.org/z/7Worb3

Rule of thumb: Use `std::move` for rvalues and `std::forward` for universal references

Q: Why can't we use perfect forwarding here?

```
1  #include <functional>
2
3  template <typename Iter, typename Callable, typename... Args>
4  void foreach (Iter current, Iter end, Callable op, const Args&... args) {
5      while (current != end) {
6          std::invoke(op, args..., *current);
7          ++current;
8      }
9  }
```

godbolt.org/z/TvnEfT

Reading x86-64 Assembly

…for fun and profit

Function Prologue & Epilogue

- Few lines of code at the beginning (*prologue*) and end (*epilogue*) of a function, which **prepares** (and eventually restores)
  - the **stack** and
  - **registers**
- Not part of assembly: **convention** (defined & interpreted differently by different OS and compilers)

Prologue

```
1 push rbp     ; rbp: frame pointer
2 mov rbp, rsp ; rsp: stack pointer
3 sub rsp, N
```

alternatively

```
1 enter N, 0
```

(reserve N bytes on stack for local use)

Epilogue

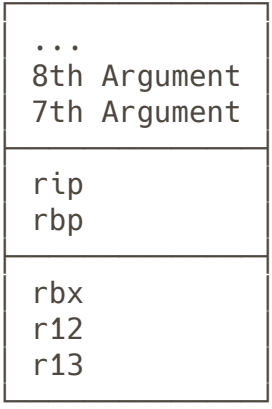
```
1 mov rsp, rbp
2 pop rbp
3 ret
```

alternatively

```
1 leave
2 ret
```

Stack frame for function call

- CALL = PUSH *address of next instruction* + JMP *target*
- RET pops return address and transfers control there
- pass arguments 1 …6 in registers (`rsi`, `rdx`, …)



(stack frame for function call with 8 arguments and local registers `rbx`, `r12` and `r13`)

`lea` vs. `mov`

- `lea`: load effective address
- puts memory address from `src` into the destination `dest`
- Example: `lea eax, [ebx+8]`
  - put `[ebx+8]` into `eax`
  - value of `eax` after instruction: `0x00403A48`
- …whereas: `mov eax, [ebx+8]`
  - value of `eax` after instruction: `0x0012C140`

Registers
EAX = 0x00000000
EBX = 0x00403A40

	Memory
0x00403A40	0x7C81776F
0x00403A44	0x7C911000
0x00403A48	0x0012C140
0x00403A4C	0x7FFDB000

Reading assembly for fun and profit

```
1  int f(int x, int y, int z) {
2      int sum = x + y + z;
3      return sum;
4  }
```

godbolt.org/z/MaWcP9

```
# g92 -O0
  | f(int, int, int):
 1|   push rbp
 1|   mov rbp, rsp
 1|   mov DWORD PTR [rbp-20], edi
 1|   mov DWORD PTR [rbp-24], esi
 1|   mov DWORD PTR [rbp-28], edx
 2|   mov edx, DWORD PTR [rbp-20]
 2|   mov eax, DWORD PTR [rbp-24]
 2|   add edx, eax
 2|   mov eax, DWORD PTR [rbp-28]
 2|   add eax, edx
 2|   mov DWORD PTR [rbp-4], eax
 3|   mov eax, DWORD PTR [rbp-4]
 4|   pop rbp
 4|   ret
```

godbolt.org/z/MaWcP9

Reading assembly for fun and profit

```
1  int f(int x, int y, int z) {
2      int sum = x + y + z;
3      return sum;
4  }
```

godbolt.org/z/MaWcP9

```
# g92 -O1
  | f(int, int, int):
 2|   add edi, esi
 2|   lea eax, [rdi+rdx]
 4|   ret
```

godbolt.org/z/67WsqT

```
# g92 -O0
  | f(int, int, int):
 1|   push rbp
 1|   mov rbp, rsp
 1|   mov DWORD PTR [rbp-20], edi
 1|   mov DWORD PTR [rbp-24], esi
 1|   mov DWORD PTR [rbp-28], edx
 2|   mov edx, DWORD PTR [rbp-20]
 2|   mov eax, DWORD PTR [rbp-24]
 2|   add edx, eax
 2|   mov eax, DWORD PTR [rbp-28]
 2|   add eax, edx
 2|   mov DWORD PTR [rbp-4], eax
 3|   mov eax, DWORD PTR [rbp-4]
 4|   pop rbp
 4|   ret
```

godbolt.org/z/MaWcP9

Reading assembly for fun and profit

```
1  int f(int x) {
2      return x + 1;
3  }
4
5  int g(int x) {
6      return f(x + 2);
7  }
```

godbolt.org/z/87GK4q

```
# g92 -O0
  | f(int):
 1|   push rbp
 1|   mov rbp, rsp
 1|   mov DWORD PTR [rbp-4], edi
 2|   mov eax, DWORD PTR [rbp-4]
 2|   add eax, 1
 3|   pop rbp
 3|   ret
  | g(int):
 5|   push rbp
 5|   mov rbp, rsp
 5|   sub rsp, 8
 5|   mov DWORD PTR [rbp-4], edi
 6|   mov eax, DWORD PTR [rbp-4]
 6|   add eax, 2
 6|   mov edi, eax
 6|   call f(int)
 7|   leave
 7|   ret
```

godbolt.org/z/87GK4q

Reading assembly for fun and profit

```
1  int f(int x) {
2      return x + 1;
3  }
4
5  int g(int x) {
6      return f(x + 2);
7  }
```

godbolt.org/z/87GK4q

```
# g92 -O1
  | f(int):
 2|   lea eax, [rdi+1]
 3|   ret
  | g(int):
 2|   lea eax, [rdi+3]
 7|   ret
```

godbolt.org/z/Yxbb6q

```
# g92 -O0
  | f(int):
 1|   push rbp
 1|   mov rbp, rsp
 1|   mov DWORD PTR [rbp-4], edi
 2|   mov eax, DWORD PTR [rbp-4]
 2|   add eax, 1
 3|   pop rbp
 3|   ret
  | g(int):
 5|   push rbp
 5|   mov rbp, rsp
 5|   sub rsp, 8
 5|   mov DWORD PTR [rbp-4], edi
 6|   mov eax, DWORD PTR [rbp-4]
 6|   add eax, 2
 6|   mov edi, eax
 6|   call f(int)
 7|   leave
 7|   ret
```

godbolt.org/z/87GK4q

Reading assembly for fun and profit

```
1  void side_effect();
2
3  int f(int x) {
4      auto a = x;
5      side_effect();
6      return a - x;
7  }
```

godbolt.org/z/5xq5n5

```
# g92 -O0
  | f(int):
 3|   push rbp
 3|   mov rbp, rsp
 3|   sub rsp, 32
 3|   mov DWORD PTR [rbp-20], edi
 4|   mov eax, DWORD PTR [rbp-20]
 4|   mov DWORD PTR [rbp-4], eax
 5|   call side_effect()
 6|   mov eax, DWORD PTR [rbp-4]
 6|   sub eax, DWORD PTR [rbp-20]
 7|   leave
 7|   ret
```

godbolt.org/z/5xq5n5

Implicit costs of using `const&`

```
1  void side_effect();
2
3  int f(int x) {
4      auto a = x;
5      side_effect();
6      return a - x;
7  }
```

godbolt.org/z/5xq5n5

```
1  void side_effect();
2
3  int f(const int& x) {
4      auto a = x;
5      side_effect();
6      return a - x;
7  }
```

godbolt.org/z/333ME7

Implicit costs of using `const&`

```
# g92 -O0
  | f(int):
 3|   push rbp
 3|   mov rbp, rsp
 3|   sub rsp, 32
 3|   mov DWORD PTR [rbp-20], edi
 4|   mov eax, DWORD PTR [rbp-20]
 4|   mov DWORD PTR [rbp-4], eax
 5|   call side_effect()
 6|   mov eax, DWORD PTR [rbp-4]
 6|   sub eax, DWORD PTR [rbp-20]
 7|   leave
 7|   ret
```

godbolt.org/z/5xq5n5

```
# g92 -O0
  | f(int const&):
 3|   push rbp
 3|   mov rbp, rsp
 3|   sub rsp, 32
 3|   mov QWORD PTR [rbp-24], rdi
 4|   mov rax, QWORD PTR [rbp-24]
 4|   mov eax, DWORD PTR [rax]
 4|   mov DWORD PTR [rbp-4], eax
 5|   call side_effect()
 6|   mov rax, QWORD PTR [rbp-24]
 6|   mov eax, DWORD PTR [rax]
 6|   mov edx, DWORD PTR [rbp-4]
 6|   sub edx, eax
 6|   mov eax, edx
 7|   leave
 7|   ret
```

godbolt.org/z/333ME7

Implicit costs of using `const&`

```
# g92 -O3
  | f(int):
 3|   sub rsp, 8
 5|   call side_effect()
 7|   xor eax, eax
 7|   add rsp, 8
 7|   ret
```

godbolt.org/z/od8v6e

NB #1: adjusting `rsp` in function prologue necessary when function is not a leaf function since callee have to know where to start saving variables on stack. (Adjusting `rsp` can be ommitted in leaf functions.)

```
# g92 -O3
  | f(int const&):
 3|   push rbp
 3|   push rbx
 3|   mov rbx, rdi
 3|   sub rsp, 8
 4|   mov ebp, DWORD PTR [rdi]
 5|   call side_effect()
 6|   mov eax, ebp
 6|   sub eax, DWORD PTR [rbx]
 7|   add rsp, 8
 7|   pop rbx
 7|   pop rbp
 7|   ret
```

godbolt.org/z/cr8f9b

Implicit costs of using `const&`

```
# g92 -O3
  | f(int):
 3|   sub rsp, 8
 5|   call side_effect()
 7|   xor eax, eax
 7|   add rsp, 8
 7|   ret
```

godbolt.org/z/od8v6e

NB #2: Offset `x` in `sub rsp, x` is objective of optimizations such as alignment: ABI requires stack to be aligned to 16 bytes.

```
# g92 -O3
  | f(int const&):
 3|   push rbp
 3|   push rbx
 3|   mov rbx, rdi
 3|   sub rsp, 8
 4|   mov ebp, DWORD PTR [rdi]
 5|   call side_effect()
 6|   mov eax, ebp
 6|   sub eax, DWORD PTR [rbx]
 7|   add rsp, 8
 7|   pop rbx
 7|   pop rbp
 7|   ret
```

godbolt.org/z/cr8f9b

Implicit costs of using `const&`

```
1  #include <string>
2  #include <string_view>
3
4  auto get_size(const std::string& s) {
5          return s.size();
6  }
7
8  auto get_size(std::string_view sv) {
9      return sv.size();
10 }
```

godbolt.org/z/br9Mfz

```
# clang900 -O3 -std=c++2a -stdlib=libc++
  | get_size(std::string const&):
xx|   movzx eax, byte ptr [rdi]
xx|   test al, 1
xx|   je .LBB0_1
 0|   mov rax, qword ptr [rdi + 8]
 5|   ret
  | .LBB0_1:
 0|   shr rax
 5|   ret
  | get_size(std::string_view):
 8|   mov rax, rsi
 9|   ret
  |
```

godbolt.org/z/br9Mfz

Even though we *only* pass a reference, we pay the cost of the complex object `std::string` (i.e., first bit is tested for short string optimization)

↪ prefer views such as `std::string_view` or `std::span`

Implicit costs of using `const&`

```
1  #include <string>
2  #include <string_view>
3
4  auto get_size(const std::string& s) {
5          return s.size();
6  }
7
8  auto get_size(std::string_view sv) {
9      return sv.size();
10 }
```

godbolt.org/z/br9Mfz

```
# clang900 -O3 -std=c++2a -stdlib=libc++
   | get_size(std::string const&):
xx|   movzx eax, byte ptr [rdi]
xx|   test al, 1
xx|   je .LBB0_1
 0|   mov rax, qword ptr [rdi + 8]
 5|   ret
   | .LBB0_1:
 0|   shr rax
 5|   ret
   | get_size(std::string_view):
 8|   mov rax, rsi
 9|   ret
   |
```

godbolt.org/z/br9Mfz

*Confession: switching to `libstdc++` resolves this issue here

Will it compile?

```cpp
#include <array>
#include <span>

int main() {
    constexpr std::array x{
        4, 8, 15, 16, 23, 42
    };
    constexpr std::span x_view{x};
}
```

godbolt.org/z/66exs6

```cpp
template <typename T, std::size_t N>
constexpr span(const std::array<T, N>& arr) noexcept;
```

cppreference.com/w/cpp/container/span/span

Will it compile?

```
1  #include <array>
2  #include <span>
3
4  int main() {
5      constexpr std::array x{
6          4, 8, 15, 16, 23, 42
7      };
8      constexpr std::span x_view{x};
9  }
```

godbolt.org/z/66exs6

No!

- → Constructor takes by reference
- → References to automatic storage objects are not constant expressions!
- → Solutions?

```
1  template <typename T, std::size_t N>
2  constexpr span(const std::array<T, N>& arr) noexcept;
```

cppreference.com/w/cpp/container/span/span

Will it compile?

```
1  #include <array>
2  #include <span>
3
4  int main() {
5      constexpr static std::array x{
6          4, 8, 15, 16, 23, 42
7      };
8      constexpr std::span x_view{x};
9  }
```

godbolt.org/z/Ga5Ysv

Nota bene …

this will work though, since reference / pointer does not *escape* constant expression …

```cpp
#include <array>
#include <span>

constexpr auto f() {
    std::array x{4, 8, 15, 16, 23, 42};
    std::span x_view{x};
    return 0;
}

int main() {
    static_assert(f() == 0);
}
```

godbolt.org/z/rso3na

PART II

Dangling References

Will it compile?

```
1  struct S {
2      int x;
3  };
4
5  auto f() {
6      S s{.x = 42};
7      return s;
8  }
9
10 int main() {
11     S& s = f();
12     return s.x;
13 }
```

godbolt.org/z/x4rWKj

Will it invoke undefined behavior?

```
1  struct S {
2      int x;
3  };
4
5  auto f() {
6      S s{.x = 42};
7      return s;
8  }
9
10 int main() {
11     const S& s = f();
12     return s.x;
13 }
```

godbolt.org/z/avGMPa

…binding a reference to a temporary???

Temporary object lifetime extension

```
1  struct S {
2      int x;
3  };
4
5  auto f() {
6      S s{.x = 42};
7      return s;
8  }
9
10 int main() {
11     const S& s = f();
12     return s.x;
13 }
```

godbolt.org/z/avGMPa

cppreference.com: “The lifetime of a temporary object may be extended by binding to a const lvalue reference or to an rvalue reference (since C++11).”

Q: What is the output of the program?

```
1  #include <iostream>
2
3  template <char id> struct Log {
4      Log() { std::cout << id << 1; }
5      virtual ~Log() { std::cout << id << 2; }
6  };
7  struct A: Log<'a'> {
8      int x;
9      A(int x): x(x) {};
10 };
11 struct B: Log<'b'> {
12     const A& a;
13     B(const A& a): a(a) {}
14 };
15
16 int main() {
17     const B& b = B{A{42}};
18     std::cout << 'x';
19     return b.a.x;
20 }
```

godbolt.org/z/hcods4

A: a1b1a2xb2

```
1  #include <iostream>
2
3  template <char id> struct Log {
4      Log() { std::cout << id << 1; }
5      virtual ~Log() { std::cout << id << 2; }
6  };
7  struct A: Log<'a'> {
8      int x;
9      A(int x): x(x) {};
10 };
11 struct B: Log<'b'> {
12     const A& a;
13     B(const A& a): a(a) {}
14 };
15
16 int main() {
17     const B& b = B{A{42}};
18     std::cout << 'x';
19     return b.a.x;
20 }
```

godbolt.org/z/hcods4

Dangling reference!!!

- → lifetime extension only for result of the temporary expression, **not any sub-expression**
- → use address sanitizer!

contrived?

Reference lifetime extension

(derived from `abseil.io`: Tip of the Week #107: “Reference Lifetime Extension”)

```
1 std::vector<std::string_view> explode(const std::string& s);
2
3 for (std::string_view s: explode(str_cat("oo", "ps"))) { // WRONG!
4     [...]
```

Q: What is the output of the program?

```
1  #include <vector>
2
3  int main() {
4      std::vector<int> v;
5      v.push_back(1);
6      auto& x = v[0];
7      v.push_back(2);
8      return x;
9  }
```

godbolt.org/z/M6bx1Y

Q: What is the output of the program?

```
1  #include <vector>
2
3  int main() {
4      std::vector<int> v;
5      v.push_back(1);
6      auto& x = v[0];
7      v.push_back(2);
8      return x;
9  }
```

godbolt.org/z/M6bx1Y

Dangling reference!!!

- → `std::vector` needs to reallocate all the space the second time an element is pushed
- → use address sanitizer!

`std::move` in the wild

Moving `std::string`

(derived from CppCon 2019: *Ben Deane* “Everyday Efficiency: In-Place Construction (Back to Basics?)”)

```
1  static void cp_small_str(benchmark::State& state) {
2      for (auto _ : state) {
3          std::string original("small");
4          benchmark::DoNotOptimize(original);
5          std::string copied = original;
6          benchmark::DoNotOptimize(copied);
7      }
8  }
9  BENCHMARK(cp_small_str);
```

```
1  static void mv_small_str(benchmark::State& state) {
2      for (auto _ : state) {
3          std::string original("small");
4          benchmark::DoNotOptimize(original);
5          std::string moved = std::move(original);
6          benchmark::DoNotOptimize(moved);
7      }
8  }
9  BENCHMARK(mv_small_str);
```

Moving `std::string`

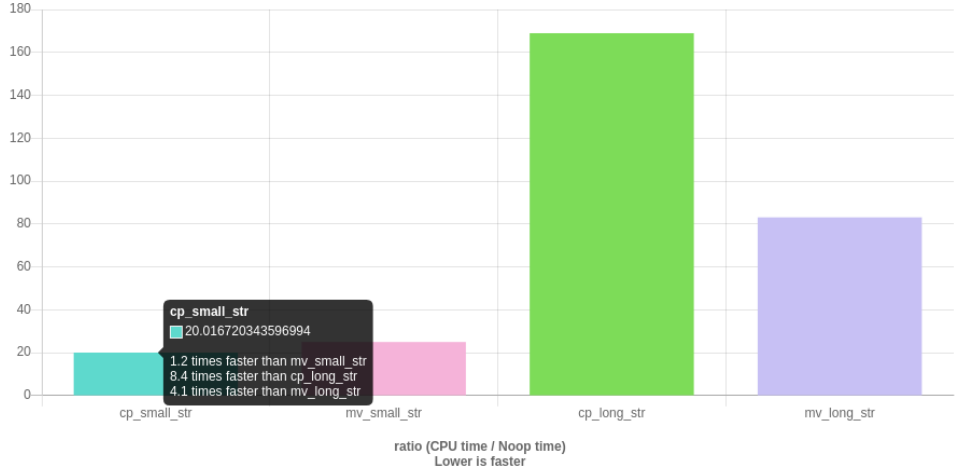
(derived from CppCon 2019: *Ben Deane* “Everyday Efficiency: In-Place Construction (Back to Basics?)”)

```
1  static void cp_long_str(benchmark::State& state) {
2      for (auto _ : state) {
3          std::string original("this is too long for short string optimization");
4          benchmark::DoNotOptimize(original);
5          std::string copied = original;
6          benchmark::DoNotOptimize(copied);
7      }
8  }
9  BENCHMARK(cp_long_str);
```

```
1  static void mv_long_str(benchmark::State& state) {
2      for (auto _ : state) {
3          std::string original("this is too long for short string optimization");
4          benchmark::DoNotOptimize(original);
5          std::string moved = std::move(original);
6          benchmark::DoNotOptimize(moved);
7      }
8  }
9  BENCHMARK(mv_long_str);
```

Moving `std::string`

Quick Bench result



Quick Bench: `tinyurl.com/yybmdngv`

Moving `std::string`

Copy small `std::string`

1. copy stack allocated data

Move small `std::string`

1. copy stack allocated data
2. set string length of moved string to zero

$\hookrightarrow$ moving is not necessarily better than copying!

Moving `std::map`

Did they forget to mark the move ctor `noexcept`?

```
// since C++11
std::map(const std::map&&)

// until C++17
std::map& operator=(std::map&&)

// since C++17
std::map& operator=(std::map&&) noexcept
```

Moving `std::map`

Did they forget to mark the move ctor `noexcept`? No!

```
// since C++11
std::map(const std::map&&)

// until C++17
std::map& operator=(std::map&&)

// since C++17
std::map& operator=(std::map&&) noexcept
```

- → Move ctor needs to allocate new sentinel node, because moved from container must still be a valid container (albeit in an unspecified state)
- → Move assignment can swap, thus no need to allocate

↪ move ctor of `std::map` allocates heap space!

(Billy O'Neal: `twitter.com/MalwareMinigun/status/1165310509022736384`)

Moving `std::map`

```cpp
static void rvo(benchmark::State& state) {
    for (auto _ : state) {
        auto m = []() -> std::map<int, int> {
            std::map<int, int> m{{0, 42}};
            return m;
        }();
        benchmark::DoNotOptimize(m);
    }
}
BENCHMARK(rvo);
```

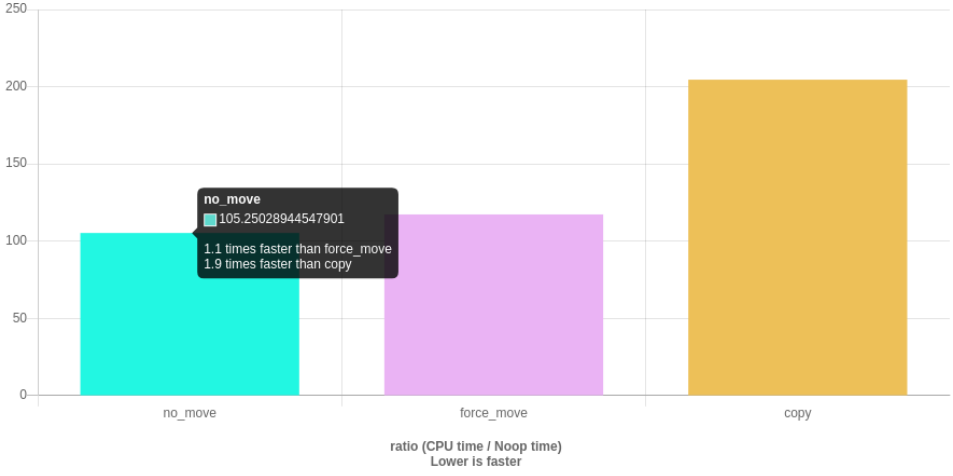
```cpp
static void fmove(benchmark::State& state) {
    for (auto _ : state) {
        auto m = []() -> std::map<int, int> {
            std::map<int, int> m{{0, 42}};
            return std::move(m);
        }();
        benchmark::DoNotOptimize(m);
    }
}
BENCHMARK(fmove);
```

Moving `std::map`

```
1  static void copy(benchmark::State& state) {
2      for (auto _ : state) {
3          std::map<int, int> m{{0, 42}};
4          benchmark::DoNotOptimize(m);
5          auto m2 = m;
6          benchmark::DoNotOptimize(m2);
7      }
8  }
9  BENCHMARK(copy);
```

Moving `std::map`

Quick Bench result



Quick Bench: `tinyurl.com/y57egvjp`

Why?

Does this code bother anyone?

```cpp
#include <cstddef>
#include <type_traits>
#include <utility>

template <typename T>
struct Data final {
    T *data;
    explicit Data(const std::size_t size): data(new T[size]) {}
    ~Data() { delete [] data; }
};

auto init() {
    Data<int> d(3);
    d.data[0] = 1; d.data[1] = 2; d.data[2] = 3;
    return d;
}

int main() { return init().data[2]; }
```

godbolt.org/z/j19Pbq

Interlude

What happens on `return`?

Will it compile?

```
1  struct A {
2      int x;
3      A(int x, int y = 0) : x(x + y) {}
4  };
5
6  struct B {
7      int x;
8      explicit B(int x, int y = 0) : x(x + y) {}
9  };
10
11 template <typename T>
12 T init() { return 42; }
13
14 int main() {
15   auto x = init<A>().x;
16   auto y = init<B>().x;
17 }
```

godbolt.org/z/vYab6f

Implicit conversion to the function return type

Implicit conversion

- …if ctor is **not** marked `explicit`
- Examples:
  - `std::optional(T&&)`
  - `std::string(const char*)`

```
1  #include <optional>
2  #include <string>
3
4  std::optional<int> f() {
5      return 42;
6  }
7
8  std::string g() {
9      return "foo";
10 }
```

godbolt.org/z/bh4svz

Q: What is the output of the program?

Compiler flags: `-std=c++14 -fno-elide-constructors`

```
1  #include <iostream>
2
3  struct S {
4      S() { std::cout << 'a'; }
5      S(const S&) { std::cout << 'b'; }
6      S(const S&&) { std::cout << 'c'; }
7      S& operator=(const S&) { std::cout << 'd'; return *this; }
8      S& operator=(const S&&) { std::cout << 'e'; return *this; }
9  };
10
11 S f() { return S{}; }
12
13 int main() {
14     S s(S{}); std::cout << ", ";
15     auto s1 = f(); std::cout << ", ";
16     auto s2{f()};
17 }
```

godbolt.org/z/xxb9xe

Q: What is the output of the program?

Compiler flags: `-std=c++17`

```
1  #include <iostream>
2
3  struct S {
4      S() { std::cout << 'a'; }
5      S(const S&) { std::cout << 'b'; }
6      S(const S&&) { std::cout << 'c'; }
7      S& operator=(const S&) { std::cout << 'd'; return *this; }
8      S& operator=(const S&&) { std::cout << 'e'; return *this; }
9  };
10
11 S f() { return S{}; }
12
13 int main() {
14     S s(S{}); std::cout << ", ";
15     auto s1 = f(); std::cout << ", ";
16     auto s2{f()};
17 }
```

godbolt.org/z/7oPa4Y

Why?

Ben Deane: “Perhaps the most important optimization the compiler does”

Copy Elision

```
1  struct S {
2      S() = default;
3      S(const S&) = delete;
4      S& operator=(const S&) = delete;
5  };
6
7  S f() { return S{}; }
8
9  int main() {
10     S s(S{});
11     auto s1 = f();
12     auto s2{f()};
13 }
```

godbolt.org/z/ThqjzP

Mandatory elision of copy/move operations since C++17):

- → Return statement: when operand is a `prvalue` of same class type as return type
- → Initialization of a variable: when initializer expression is a `prvalue` of same class type as the variable type

…even if the copy/move constructor and the destructor has observable side-effects!

Rule of thumb: avoid naming return values

RVO in Depth

C++ Objects in Assembly

```
1  struct S final {
2      int a, b, c;
3
4      S(int a, int b, int c) noexcept:
5          a(a), b(b), c(c) {}
6
7      ~S() noexcept {}
8
9      auto sum() noexcept {
10         return a + b + c;
11     }
12 };
13
14 int main() {
15     S s(1, 2, 3);
16     return s.sum();
17 }
```

godbolt.org/z/4oWTr6

```
   | main:
14|   push rbp
14|   mov rbp, rsp
14|   sub rsp, 16
14|   mov dword ptr [rbp - 4], 0
15|   lea rdi, [rbp - 16]
15|   mov esi, 1
15|   mov edx, 2
15|   mov ecx, 3
15|   call S::S(int, int, int)
16|   lea rdi, [rbp - 16]
16|   call S::sum()
16|   mov dword ptr [rbp - 4], eax
17|   lea rdi, [rbp - 16]
17|   call S::~S()
17|   mov eax, dword ptr [rbp - 4]
17|   add rsp, 16
17|   pop rbp
17|   ret
```

C++ Objects in Assembly

```
1  struct S final {
2      int a, b, c;
3
4      S(int a, int b, int c) noexcept:
5          a(a), b(b), c(c) {}
6
7      ~S() noexcept {}
8
9      auto sum() noexcept {
10         return a + b + c;
11     }
12 };
13
14 int main() {
15     S s(1, 2, 3);
16     return s.sum();
17 }
```

godbolt.org/z/4oWTr6

```
  | S::S(int, int, int):
5|   push rbp
5|   mov rbp, rsp
5|   mov qword ptr [rbp - 8], rdi
5|   mov dword ptr [rbp - 12], esi
5|   mov dword ptr [rbp - 16], edx
5|   mov dword ptr [rbp - 20], ecx
5|   mov rax, qword ptr [rbp - 8]
5|   mov ecx, dword ptr [rbp - 12]
5|   mov dword ptr [rax], ecx
5|   mov ecx, dword ptr [rbp - 16]
5|   mov dword ptr [rax + 4], ecx
5|   mov ecx, dword ptr [rbp - 20]
5|   mov dword ptr [rax + 8], ecx
5|   pop rbp
5|   ret
```

C++ Objects in Assembly

```
1  struct S final {
2      int a, b, c;
3
4      S(int a, int b, int c) noexcept:
5          a(a), b(b), c(c) {}
6
7      ~S() noexcept {}
8
9      auto sum() noexcept {
10         return a + b + c;
11     }
12 };
13
14 int main() {
15     S s(1, 2, 3);
16     return s.sum();
17 }
```

godbolt.org/z/4oWTr6

```
   | S::sum():
 9|   push rbp
 9|   mov rbp, rsp
 9|   mov qword ptr [rbp - 8], rdi
 9|   mov rax, qword ptr [rbp - 8]
10|   mov ecx, dword ptr [rax]
10|   add ecx, dword ptr [rax + 4]
10|   add ecx, dword ptr [rax + 8]
10|   mov eax, ecx
10|   pop rbp
10|   ret
```

RVO in Assembly

```
1  struct S final {
2      int x;
3      explicit S(int x) noexcept;
4      S(const S&) noexcept;
5      S(S&&) noexcept;
6      ~S() noexcept;
7  };
8
9  S f() {
10     return S{42};
11 }
12
13 auto g() {
14     auto s = f();
15     return s.x;
16 }
```

godbolt.org/z/z86r3d

```
# g92 -fno-elide-constructors
  | g():
  |   [...]
14|   lea rax, [rbp-20]
14|   mov rdi, rax
14|   call f()
14|   lea rdx, [rbp-20]
14|   lea rax, [rbp-24]
14|   mov rsi, rdx
14|   mov rdi, rax
14|   call S::S(S&&)
14|   lea rax, [rbp-20]
14|   mov rdi, rax
14|   call S::~S()
15|   mov ebx, DWORD PTR [rbp-24]
14|   lea rax, [rbp-24]
14|   mov rdi, rax
14|   call S::~S()
15|   mov eax, ebx
  |   [...]
```

RVO in Assembly

```
1  struct S final {
2      int x;
3      explicit S(int x) noexcept;
4      S(const S&) noexcept;
5      S(S&&) noexcept;
6      ~S() noexcept;
7  };
8
9  S f() {
10     return S{42};
11 }
12
13 auto g() {
14     auto s = f();
15     return s.x;
16 }
```

godbolt.org/z/z86r3d

```
# g92 -fno-elide-constructors
  | f():
  |   [...]
 9|   mov QWORD PTR [rbp-24], rdi
10|   lea rax, [rbp-4]
10|   mov esi, 42
10|   mov rdi, rax
10|   call S::S(int)
10|   lea rdx, [rbp-4]
10|   mov rax, QWORD PTR [rbp-24]
10|   mov rsi, rdx
10|   mov rdi, rax
10|   call S::S(S&&)
10|   lea rax, [rbp-4]
10|   mov rdi, rax
10|   call S::~S()
  |   [...]
```

RVO in Assembly

```
1  # g92 -fno-elide-constructors
2  f():
3    [...]
4    mov QWORD PTR [rbp-24], rdi
5    lea rax, [rbp-4]
6    mov esi, 42
7    mov rdi, rax
8    call S::S(int)
9    lea rdx, [rbp-4]
10   mov rax, QWORD PTR [rbp-24]
11   mov rsi, rdx
12   mov rdi, rax
13   call S::S(S&&)
14   lea rax, [rbp-4]
15   mov rdi, rax
16   call S::~S()
17   nop
18   mov rax, QWORD PTR [rbp-24]
19   leave
20   ret
```

```
1  # g92
2  f():
3    [...]
4    mov QWORD PTR [rbp-8], rdi
5    mov rax, QWORD PTR [rbp-8]
6    mov esi, 42
7    mov rdi, rax
8    call S::S(int)
9    mov rax, QWORD PTR [rbp-8]
10   leave
11   ret
```

RVO in Assembly

```
1  # g92 -fno-elide-constructors
2  g():
3    [...]
4    lea rax, [rbp-20]
5    mov rdi, rax
6    call f()
7    lea rdx, [rbp-20]
8    lea rax, [rbp-24]
9    mov rsi, rdx
10   mov rdi, rax
11   call S::S(S&&)
12   lea rax, [rbp-20]
13   mov rdi, rax
14   call S::~S()
15   mov ebx, DWORD PTR [rbp-24]
16   lea rax, [rbp-24]
17   mov rdi, rax
18   call S::~S()
19   mov eax, ebx
20   [...]
```

```
1  # g92
2  g():
3    [...]
4    lea rax, [rbp-20]
5    mov rdi, rax
6    call f()
7    mov ebx, DWORD PTR [rbp-20]
8    lea rax, [rbp-20]
9    mov rdi, rax
10   call S::~S()
11   mov eax, ebx
```

(N)RVO or no (N)RVO?

```
1  #include <utility>
2
3  struct S final {
4      S() noexcept;
5      S(const S&) noexcept;
6      S(S&&) noexcept;
7      ~S() noexcept;
8  };
9
10 S f1() { S s; return s; }
11 S f2() { S s; return std::move(s); }
12 S f3() { const S s; return s; }
13 S f4() { const S s; return std::move(s); }
```

godbolt.org/z/6Es7Ys

- → f1: ???
- → f2: ???
- → f3: ???
- → f4: ???

(N)RVO or no (N)RVO?

```
1  struct S {
2      S() noexcept;
3      S(const S&) noexcept;
4      S(const S&&) noexcept;
5      ~S() noexcept;
6  };
7
8  S f1(S s) { return s; }
9  S f2(S& s) { return s; }
10 S f3(const S& s) { return s; }
```

godbolt.org/z/7sf6jY

- f1: ???
- f2: ???
- f3: ???

(N)RVO or no (N)RVO?

```
1  struct S final {
2      S() noexcept;
3      S(const S&) noexcept;
4      S(S&&) noexcept;
5      ~S() noexcept;
6  };
7
8  S f() {
9      S s;
10     auto& t = s;
11     return t;
12 }
```

godbolt.org/z/a6hrE1

(N)RVO or no (N)RVO?

```
1  struct S {
2      S(int) noexcept;
3      S(const S&) noexcept;
4      S(const S&&) noexcept;
5      ~S() noexcept;
6  };
7
8  S f1(bool x) { return x ? S{1} : S{2}; }
9  S f2(bool x) { S s{1}; return x ? s : S{2}; }
```

godbolt.org/z/TEcq1o

- → f1: ???
- → f2: ???

(N)RVO or no (N)RVO?

```
1  #include <utility>
2
3  struct S final {
4      S() noexcept;
5      S(const S&) noexcept;
6      S(S&&) noexcept;
7      ~S() noexcept;
8  };
9  auto f() { return std::pair<S, S>{}; }
10 S g1() { auto [s1, s2] = f(); return s1; }
11 S g2() { auto&& [s1, s2] = f(); return s1; }
12 S g3() { auto [s1, s2] = f(); return std::move(s1); }
13 S g4() { auto&& [s1, s2] = f(); return std::move(s1); }
```

godbolt.org/z/v5ro3q

- → g1: ???
- → g2: ???
- → g3: ???
- → g4: ???

(N)RVO or no (N)RVO?

(derived from CppCon 2019: *Jason Turner* “Great C++ is_trivial”)

No (N)RVO in any of these examples!

```
1 S g1() { auto [s1, s2] = f(); return s1; } // copy
2 S g2() { auto&& [s1, s2] = f(); return s1; } // copy: no implicit move yet (?)
3 S g3() { auto [s1, s2] = f(); return std::move(s1); } // move
4 S g4() { auto&& [s1, s2] = f(); return std::move(s1); } // move
```

…`return std::move` is not always bad

Why? Structured bindings:

- → Creation of temporary object `e`
- → Like a reference: structured binding is an alias into `e`

Implicit move

`return std::move` is not yet necessarily a code smell

(use `-Wpessimizing-move`)

Automatic move from local variables and parameters if:

- return expression names a variable whose type is either
  - an object type or (since C++11)
  - an rvalue reference to object type (since C++20*)
- …and that variable is declared
  - in the body or
  - as a parameter of
- …the innermost enclosing function or lambda expression

* P1825R0 (not yet implemented in GCC or Clang: cppreference.com/w/cpp/compiler_support)

Perfect Backwarding

Forwarding Values and Preserving Value Category

(derived from CppCon 2018: *Hayun Ezra Chung* “Forwarding Values... and Backwarding Them Too?”)

```cpp
#include <iostream>
#include <memory>

struct Resource {};

struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

auto make_target(??? resource) {
    return std::make_unique<Target>(???);
}

int main() {
    Resource resource;
    make_target(resource);            // should print 'a'
    make_target(Resource(resource));  // should print 'b'
    make_target(std::move(resource)); // should print 'b'
}
```

godbolt.org/z/WMPGGq

Forwarding Values and Preserving Value Category

(derived from CppCon 2018: *Hayun Ezra Chung* “Forwarding Values... and Backwarding Them Too?”)

```cpp
#include <iostream>
#include <memory>

struct Resource {};

struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

template <typename T> auto make_target(T&& resource) {
    return std::make_unique<Target>(std::forward<T>(resource));
}

int main() {
    Resource resource;
    make_target(resource);            //  lvalue: T = Resource&
    make_target(Resource(resource));  // prvalue: T = Resource
    make_target(std::move(resource)); //  xvalue: T = Resource
}
```

godbolt.org/z/nbd6P4

Forwarding Values and Preserving Value Category

(derived from CppCon 2018: *Hayun Ezra Chung* “Forwarding Values... and Backwarding Them Too?”)

```cpp
#include <iostream>
#include <memory>

struct Resource {};

struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

auto make_target(auto&& resource) {
    return std::make_unique<Target>(std::forward<decltype(resource)>(resource));
}

int main() {
    Resource resource;
    make_target(resource);
    make_target(Resource(resource));
    make_target(std::move(resource));
}
```

godbolt.org/z/znq1K4

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    decltype(auto) visit(auto visitor) { return visitor(resource); }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource& { return r; }));
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/f56vaP

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    // what if we want to do sth. with the result before returning?
    decltype(auto) visit(auto visitor) { return visitor(resource); }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource& { return r; }));
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/35zbYW

Backwarding Values and Preserving Value Category

Q: Why is this a bad idea?

```
1 auto&& visit(auto visitor) {
2     auto&& result = visitor(resource);
3     return result;
4 }
```

Backwarding Values and Preserving Value Category

Q: Why is this a bad idea?

```
1 auto&& visit(auto visitor) {
2     auto&& result = visitor(resource);
3     return result;
4 }
```

A: Dangling reference for

```
visit([](Resource& r) -> Resource { return r; }));
```

`auto&&` is always a reference!

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    ??? visit(auto visitor) {
        ??? result = visitor(resource);
        return ???;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
}
```

godbolt.org/z/d1WeqT

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    Resource visit(auto visitor) {
        Resource result = visitor(resource);
        return result;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
}
```

godbolt.org/z/9joq3h

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    ??? visit(auto visitor) {
        ??? result = visitor(resource);
        return ???;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource& { return r; }));
}
```

godbolt.org/z/MzGGqc

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    Resource& visit(auto visitor) {
        Resource& result = visitor(resource);
        return result;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource& { return r; }));
}
```

godbolt.org/z/Y6437o

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    ??? visit(auto visitor) {
        ??? result = visitor(resource);
        return ???;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; };
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/rj4xqz

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    Resource&& visit(auto visitor) {
        Resource&& result = visitor(resource);
        return result;
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; };
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/a7rq34

Backwarding Values and Preserving Value Category

error: cannot bind rvalue reference of type “Resource&&” to lvalue of type “Resource”

```
1  #include <iostream>
2
3  struct Resource {};
4  struct ResourceManager {
5      Resource resource;
6
7      Resource&& visit(auto visitor) {
8          Resource&& result = visitor(resource);
9          return result;
10     }
11 };
12 struct Target {
13     Target(const Resource&) { std::cout << 'a'; };
14     Target(Resource&&) { std::cout << 'b'; }
15 };
16
17 int main() {
18     ResourceManager rm;
19     Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
20 }
```

godbolt.org/z/a7rq34

Backwarding Values and Preserving Value Category

```cpp
#include <iostream>

struct Resource {};
struct ResourceManager {
    Resource resource;

    Resource&& visit(auto visitor) {
        Resource&& result = visitor(resource);
        return std::move(result); // static_cast<Resource&&>(result)
    }
};
struct Target {
    Target(const Resource&) { std::cout << 'a'; };
    Target(Resource&&) { std::cout << 'b'; }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/T91Tbq

How do we fuse these implementations?

```
1  Resource visit(auto visitor) {
2      Resource result = visitor(resource);
3      return result;
4  }
5
6  Resource& visit(auto visitor) {
7      Resource& result = visitor(resource);
8      return result;
9  }
10
11 Resource&& visit(auto visitor) {
12     Resource&& result = visitor(resource);
13     return static_cast<Resource&&>(result);
14 }
```

```
1  Target(rm.visit([](Resource& r) -> Resource { return r; }));
2  Target(rm.visit([](Resource& r) -> Resource& { return r; }));
3  Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
```

How do we fuse these implementations?

```
1  Resource visit(auto visitor) {
2      Resource result = visitor(resource);
3      return result;
4  }
5
6  Resource& visit(auto visitor) {
7      Resource& result = visitor(resource);
8      return result;
9  }
10
11 Resource&& visit(auto visitor) {
12     Resource&& result = visitor(resource);
13     return static_cast<Resource&&>(result);
14 }
```

```
1  decltype(auto) visit(auto visitor) {
2      decltype(auto) result = visitor(resource);
3      return static_cast<decltype(result)>(result);
4  }
```

(derived from CppCon 2018: *Hayun Ezra Chung* “Forwarding Values... and Backwarding Them Too?”)

```cpp
#include <iostream>

struct Resource {};
struct Target {
    Target(const Resource&) { std::cout << 'a'; }
    Target(Resource&&) { std::cout << 'b'; }
};
struct ResourceManager {
    Resource resource;

    decltype(auto) visit(auto visitor) {
        decltype(auto) result = visitor(resource);
        return static_cast<decltype(result)>(result);
    }
};

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource& { return r; }));
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
    Target(rm.visit([](Resource& r) -> Resource&& { return std::move(r); }));
}
```

godbolt.org/z/96rjsq

Q: What is the output of the program?

```cpp
#include <iostream>

struct Resource {
    Resource() {}
    Resource(const Resource&) { std::cout << 'a'; }
};
struct ResourceManager {
    Resource resource;

    Resource visit(auto visitor) {
        Resource result = visitor(resource);
        return result;
    }
};
struct Target { Target(const Resource&) {}; };

int main() {
    ResourceManager rm;
    Target(rm.visit([](Resource& r) -> Resource { return r; }));
}
```

godbolt.org/z/aK8f4x

Q: What is the output of the program?

```
1  #include <iostream>
2
3  struct Resource {
4      Resource() {}
5      Resource(const Resource&) { std::cout << 'a'; }
6  };
7  struct ResourceManager {
8      Resource resource;
9
10     Resource visit(auto visitor) {
11         Resource result = visitor(resource);
12         return static_cast<Resource>(result);
13     }
14 };
15 struct Target { Target(const Resource&) {}; };
16
17 int main() {
18     ResourceManager rm;
19     Target(rm.visit([](Resource& r) -> Resource { return r; }));
20 }
```

godbolt.org/z/rhhM8a

Missing (N)RVO

```
1  struct Resource {
2      [...]
3      Resource(const Resource&) { std::cout << 'a'; }
4  };
5
6  Resource visit(auto visitor) {
7      Resource result = visitor(resource);
8      return static_cast<Resource>(result);
9  }
```

Neither RVO nor NRVO!

- → `static_cast` is not the name of a variable (c-style cast does not work either)
- → compiler cannot elide observable side effects of copy construction
- → “Solution”
  - → remove explicit cast, or
  - → remove side effect (`std::cout`)

Missing (N)RVO

```
1 template <typename T>
2 decltype(auto) visit(T visitor) {
3     decltype(auto) result = visitor(resource);
4     if constexpr (std::is_same_v<decltype(result), Resource&&>) {
5         return std::move(result);
6     } else {
7         return result;
8     }
9 }
```

…works for GCC (without `auto` concept), not for Clang though

Missing (N)RVO

```cpp
template <typename T>
static constexpr bool returns_rref = std::is_same_v<std::invoke_result_t<T,
    ↪ Resource&>, Resource&&>;

template <typename T, std::enable_if_t<returns_rref<T>, int> = 0>
decltype(auto) visit(T visitor) {
    decltype(auto) result = visitor(resource);
    return std::move(result);
}

template <typename T, std::enable_if_t<not returns_rref<T>, int> = 0>
decltype(auto) visit(T visitor) {
    decltype(auto) result = visitor(resource);
    return result;
}
```

…still, no NRVO with Clang but this time due to the deduced return type!

Missing (N)RVO

```cpp
template <typename T>
static constexpr bool returns_rref = std::is_same_v<std::invoke_result_t<T,
    ↪ Resource&>, Resource&&>;

template <typename T, std::enable_if_t<returns_rref<T>, int> = 0>
decltype(auto) visit(T visitor) {
    decltype(auto) result = visitor(resource);
    return std::move(result);
}

template <typename T, std::enable_if_t<not returns_rref<T>, int> = 0>
auto visit(T visitor) -> decltype(visitor(resource)) {
    decltype(auto) result = visitor(resource);
    return result;
}
```

…now works for GCC and Clang!

```cpp
#include <iostream>

struct Resource {
    Resource() {}
    Resource(const Resource&) { std::cout << 'a'; }
};
struct ResourceManager {
    Resource resource;

    template <typename T>
    static constexpr bool returns_rref = std::is_same_v<std::invoke_result_t<T,
        ↪ Resource&>, Resource&&>;

    template <typename T, std::enable_if_t<returns_rref<T>, int> = 0>
    decltype(auto) visit(T visitor) {
        decltype(auto) result = visitor(resource);
        return std::move(result);
    }

    template <typename T, std::enable_if_t<not returns_rref<T>, int> = 0>
[...]
```

godbolt.org/z/97jdrs

More things that don’t work

Missing (N)RVO

```
#include <iostream>

struct Resource {
    Resource() {}
    Resource(const Resource&) { std::cout << 'a'; }
};
struct ResourceManager {
    Resource resource;

    template <typename T>
    auto visit(T visitor) -> decltype(visitor(resource)) {
        using R = std::invoke_result_t<T, Resource&>;

        decltype(auto) result = visitor(resource);
        if constexpr (std::is_same_v<R, Resource&&>) {
            return std::move(result);
        } else {
            return result;
        }
[...]
```

godbolt.org/z/P9n1o8

…works with GCC, fails with Clang

Missing (N)RVO

```
#include <iostream>

struct Resource {
    Resource() {}
    Resource(const Resource&) { std::cout << 'a'; }
};
struct ResourceManager {
    Resource resource;

    template <typename T>
    auto visit(T visitor) -> decltype(visitor(resource)) {
        using R = std::invoke_result_t<T, Resource&>;
        if constexpr (std::is_same_v<R, Resource&&>) {
            decltype(auto) result = visitor(resource);
            return std::move(result);
        } else {
            decltype(auto) result = visitor(resource);
            return result;
        }
[...]
```

godbolt.org/z/8heP76

…works with Clang, fails with GCC

Missing (N)RVO

```
#include <iostream>

struct Resource {
    Resource() {}
    Resource(const Resource&) { std::cout << 'a'; }
};
struct ResourceManager {
    Resource resource;

    template <typename T>
    auto visit(T visitor) -> decltype(visitor(resource)) {
        using R = std::invoke_result_t<T, Resource&>;
        if constexpr (decltype(auto) result = visitor(resource);
                      std::is_same_v<R, Resource&&>) {
            return std::move(result);
        } else {
            return result;
        }
    }
[...]
```

godbolt.org/z/e48EeT

…fails with GCC and Clang

Conclusion

(shamelessly copied from CppCon 2018: *Hayun Ezra Chung* “Forwarding Values... and Backwarding Them Too?”)

Forwarding

- Parameter Type: `T&&`
- Function Argument: `std::forward<E>(e)`
- Alternatively: `static_cast<decltype(e)&&>(e)`

Backwarding

- Parameter Type: `decltype(auto)`
- Function Argument: `decltype(e)(e)`
- Alternatively: `static_cast<decltype(e)>(e)`*