Moving Forward to C++11

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May 15, 2012

Outline

- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

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- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

Motivation for Move

- In 2006, I wrote a benchmark to show off move semantics.
- It manipulated the unlikely data structure vector<set<int>>:
- Return it from factory functions.
- Manipulate it with algorithms.

Motivation for Move

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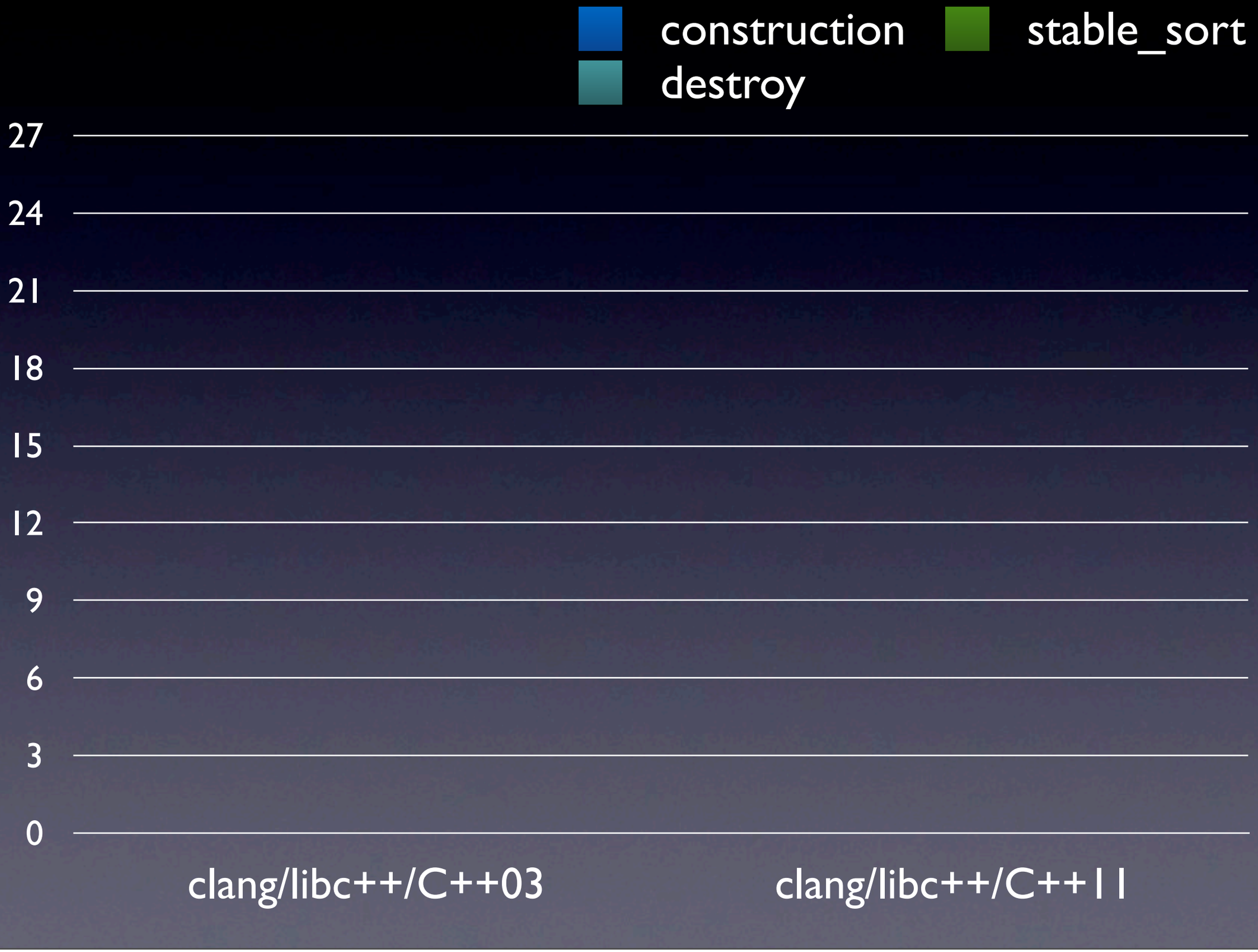

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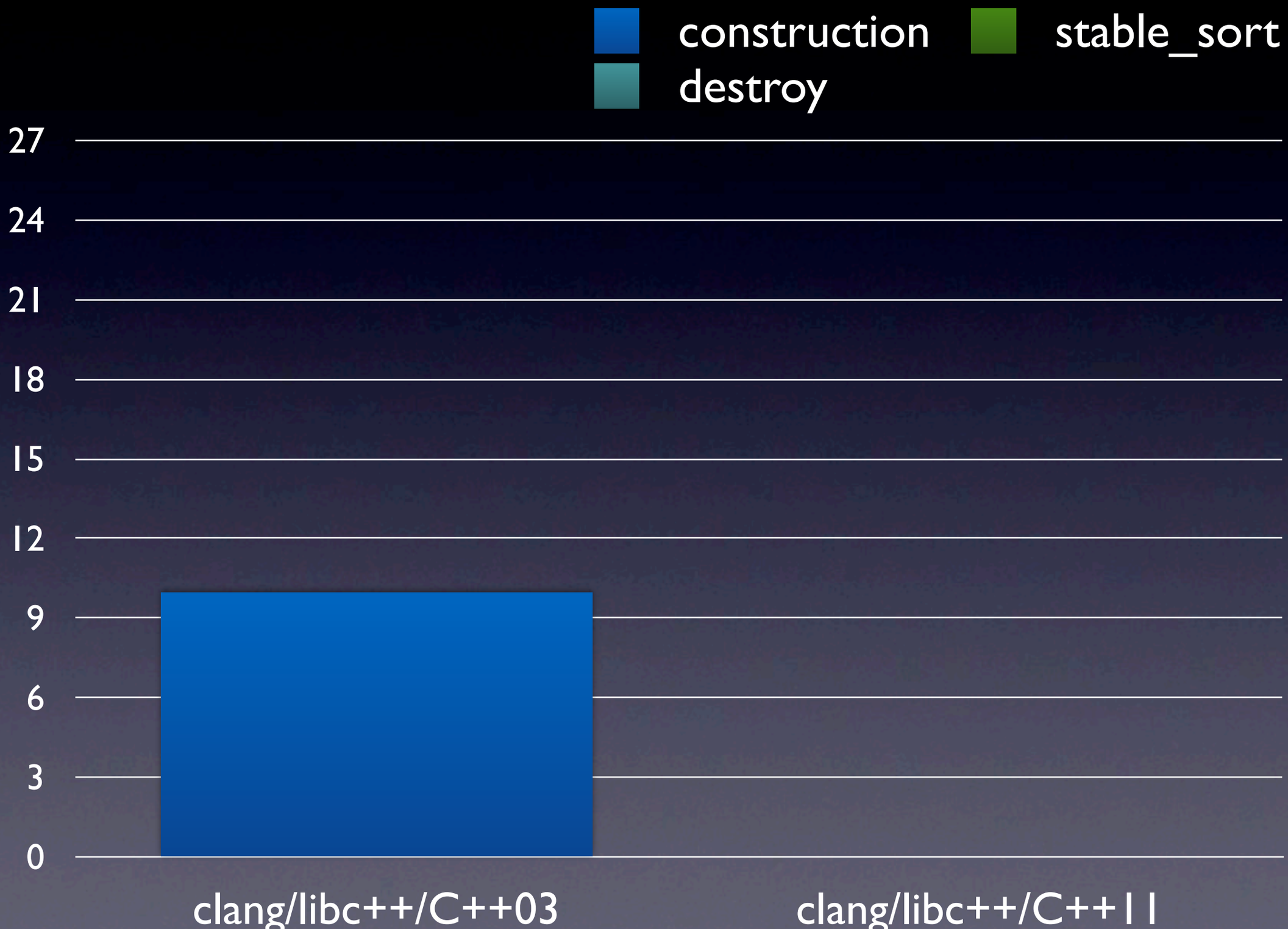

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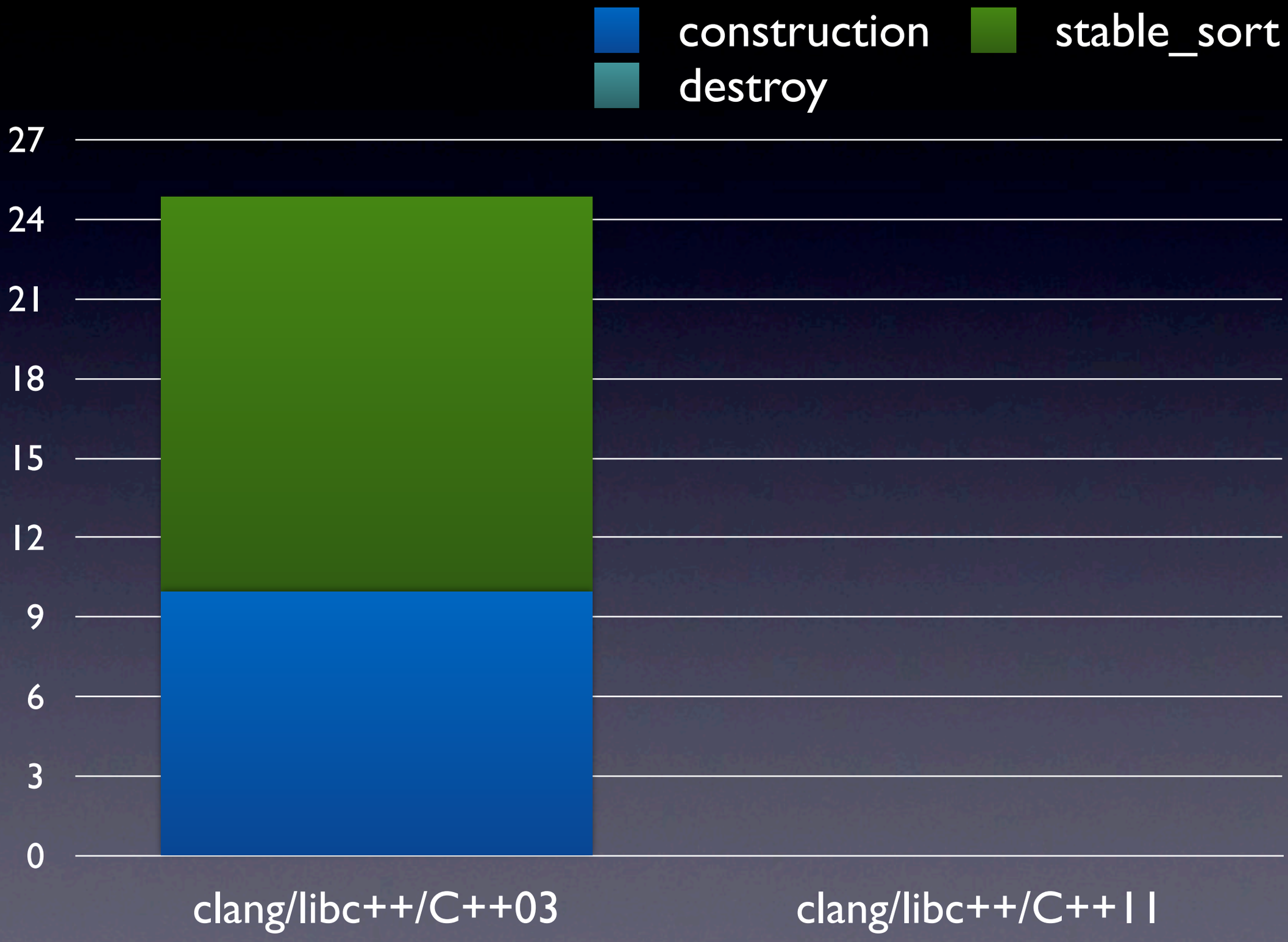

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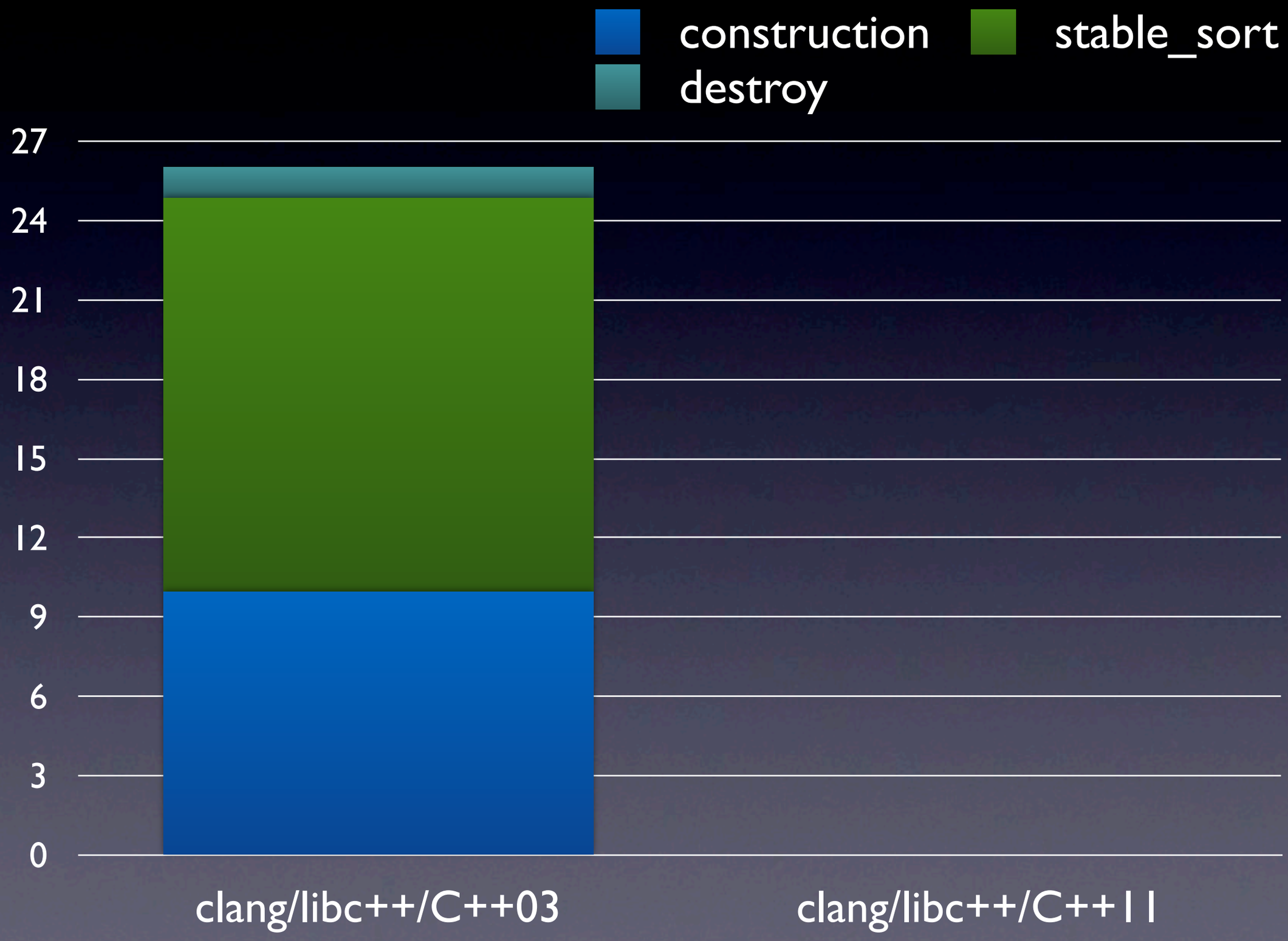
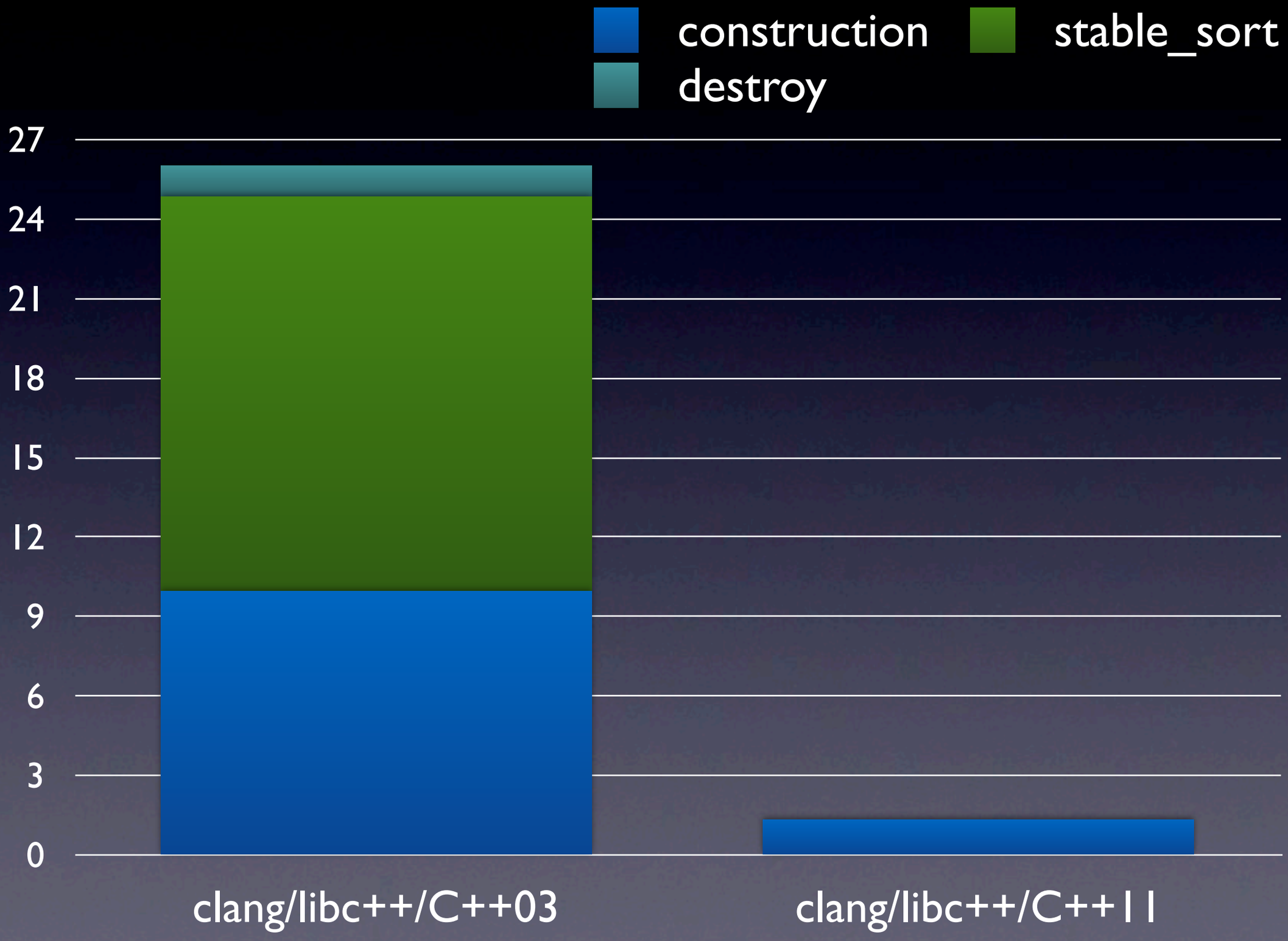


Motivation for Move



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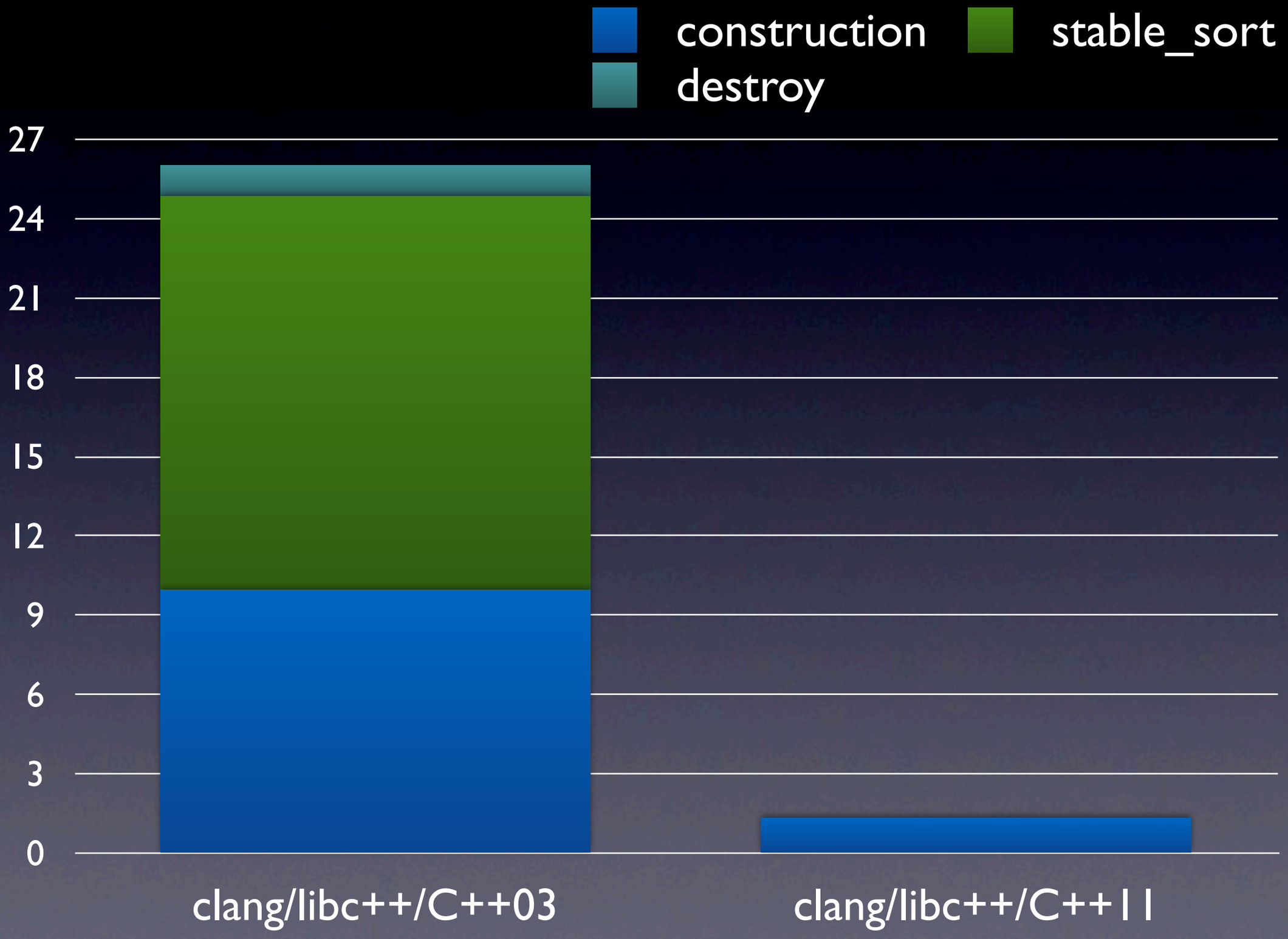
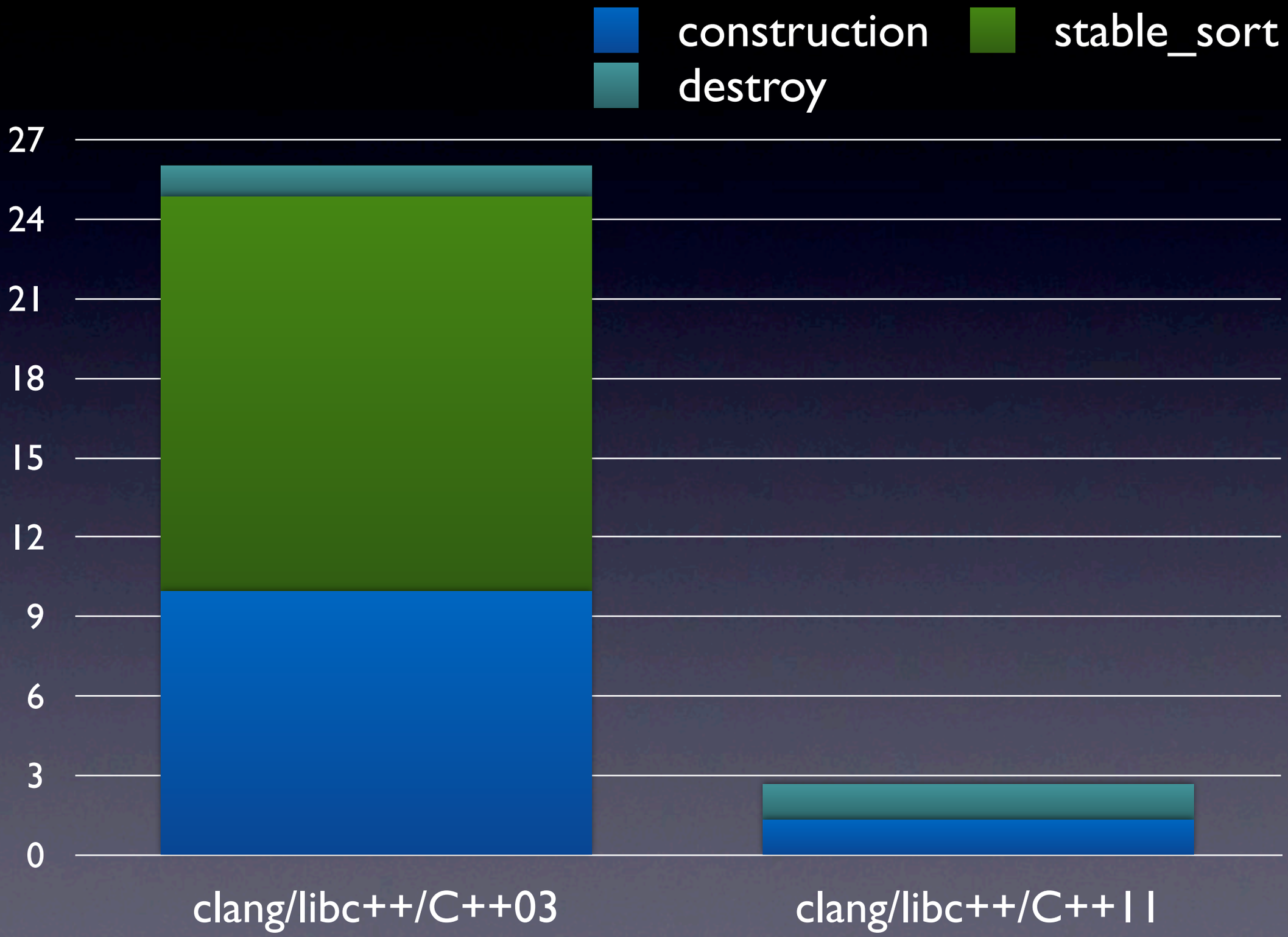


Motivation for Move



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- With move semantics, vector<set<int>> does not have to be an unlikely data structure.
- Containers and algorithms can move around set<int> almost as cheaply as moving around an int.
- And you can install move semantics in your "heavy" data structures.

Rvalue reference syntax

A&

Rvalue reference syntax

A&

- In C++03 we have the reference.

Rvalue reference syntax

A&

Rvalue reference syntax

A&

- In C++11 we renamed “reference” to “lvalue reference.”

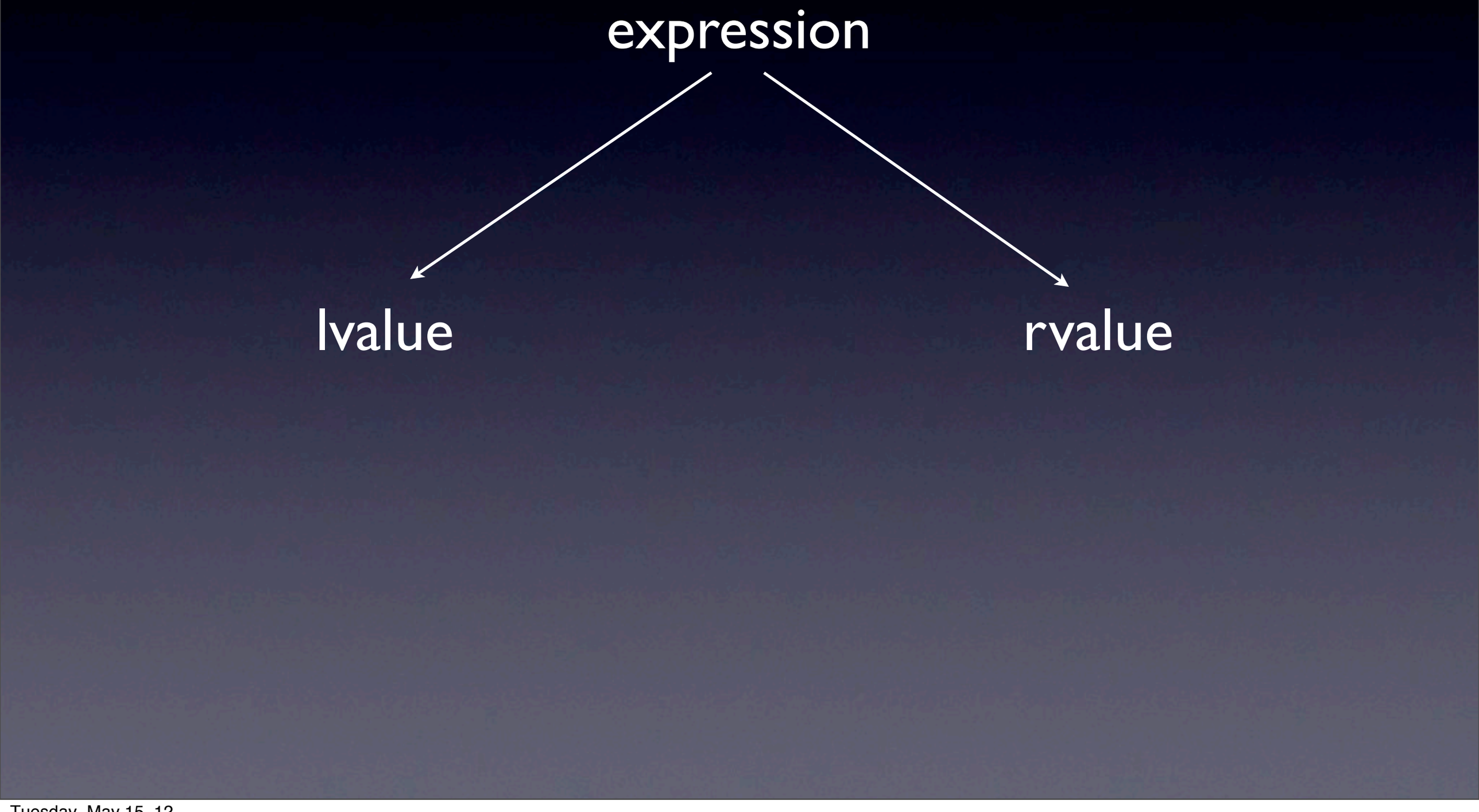
Rvalue reference syntax

A&

A&&

- In C++11 we renamed “reference” to “lvalue reference.”
- And we introduce a new kind of reference called “rvalue reference.”

Expressions

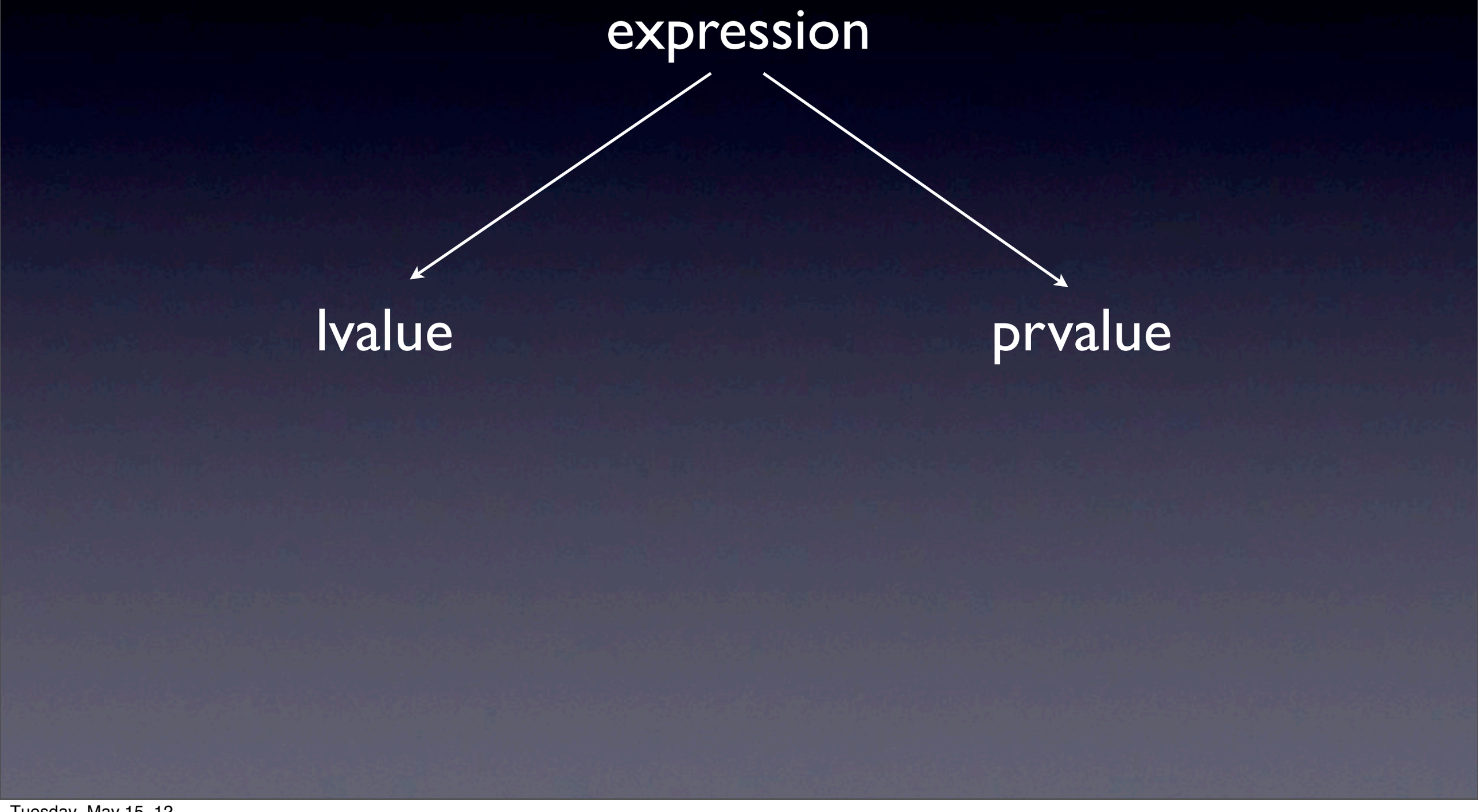


Expressions

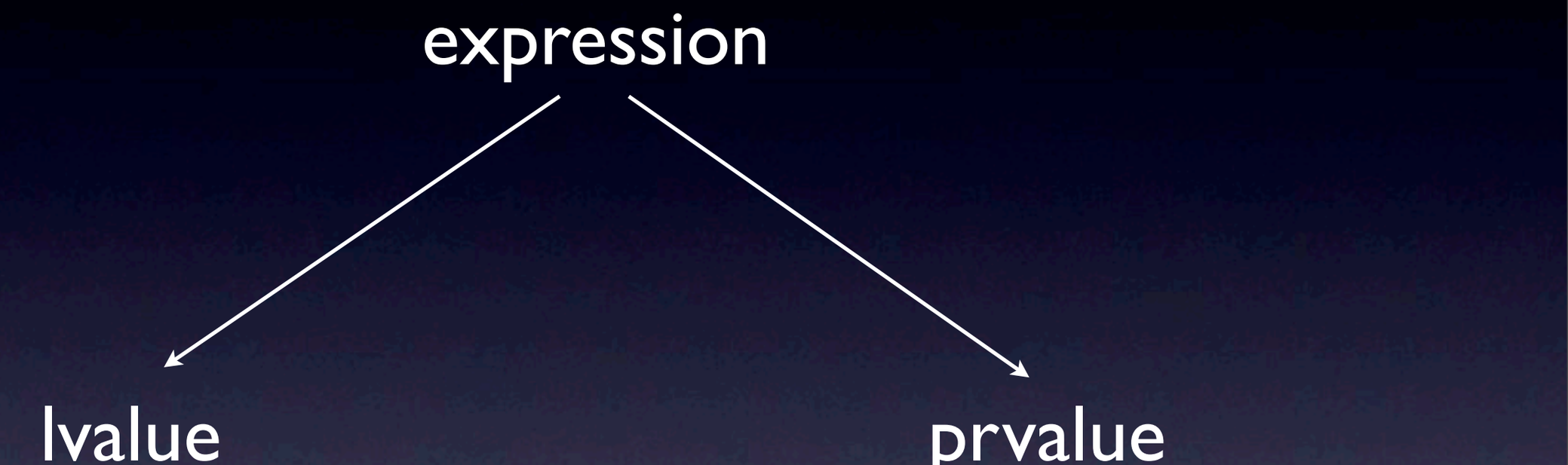
`static_cast<A&>(a)` `static_cast<A>(a)`

- In C++98/03 every expression is lvalue or rvalue.
- Expressions never have reference type.

Expressions

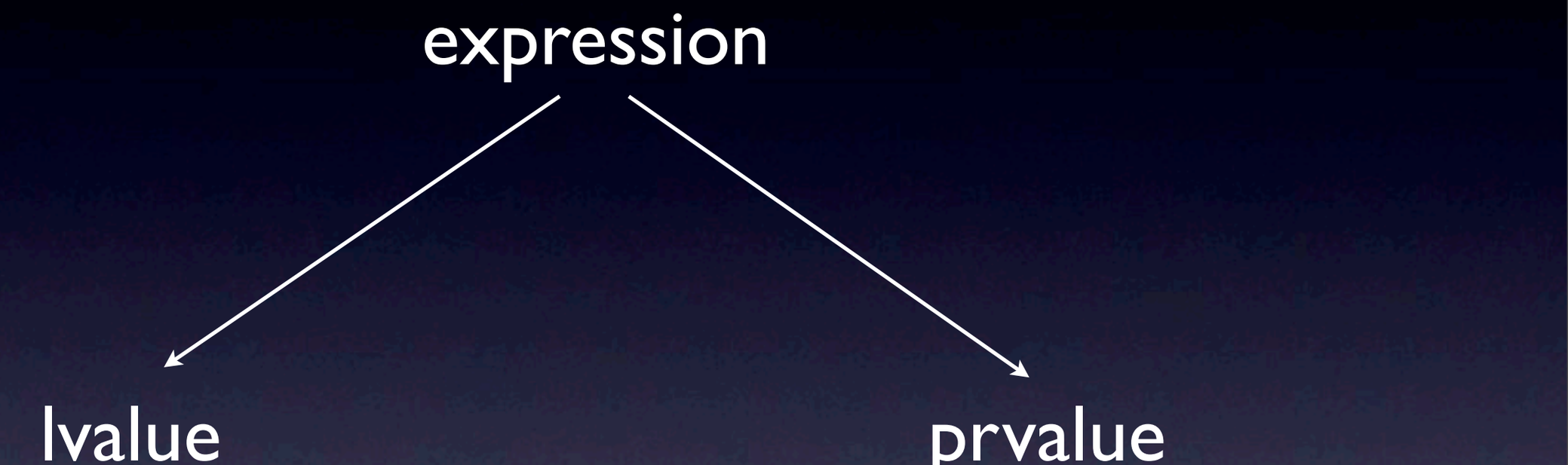


Expressions



- In C++11 we renamed rvalue to prvalue.

Expressions



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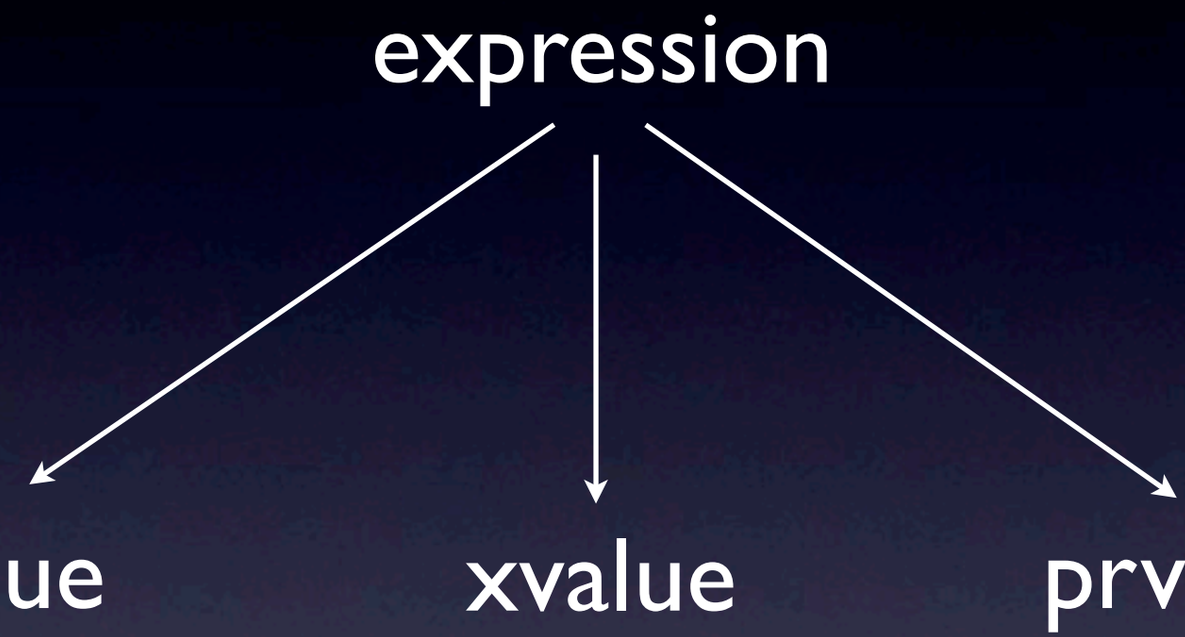
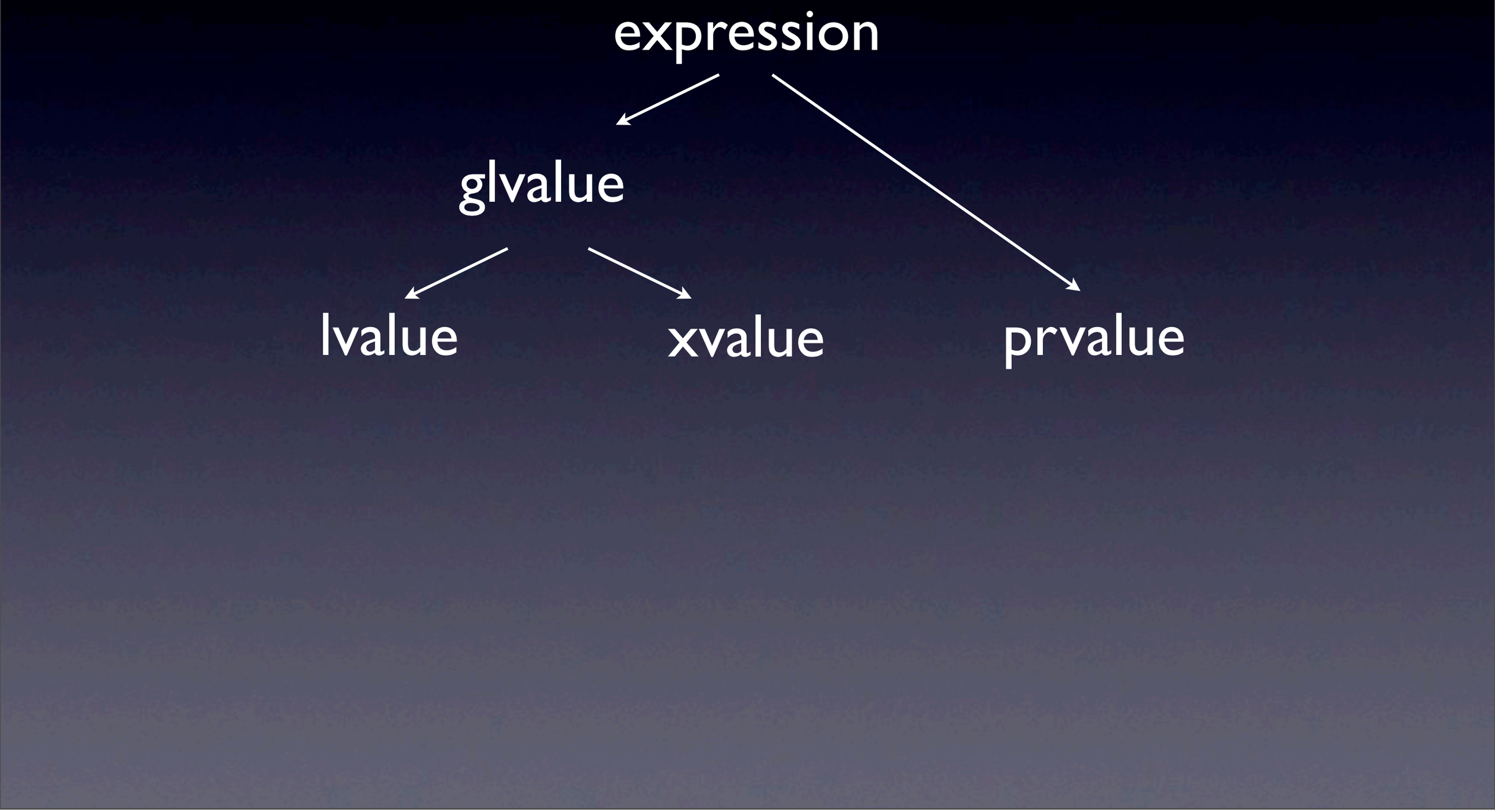
Expressions



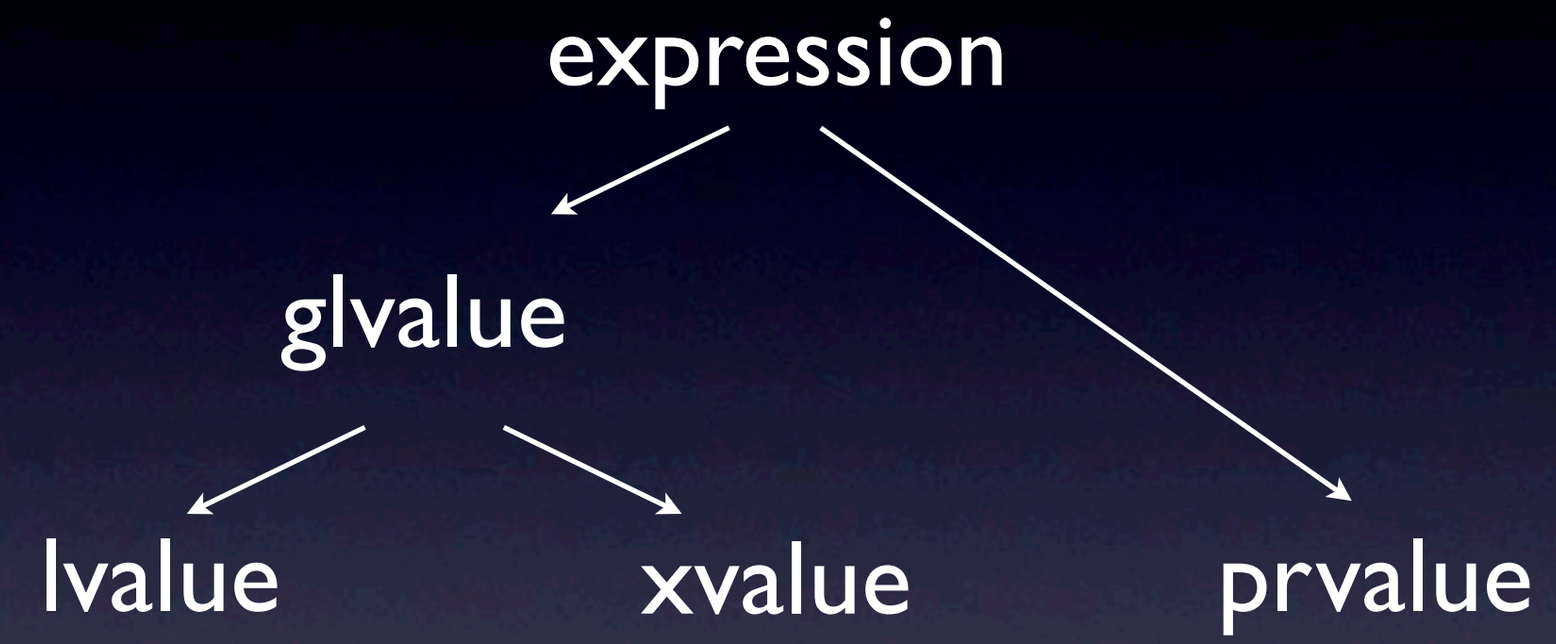
`static_cast<A&&>(a)`

- In C++11 we renamed rvalue to prvalue.
- And we added a new value category: xvalue.

Expressions

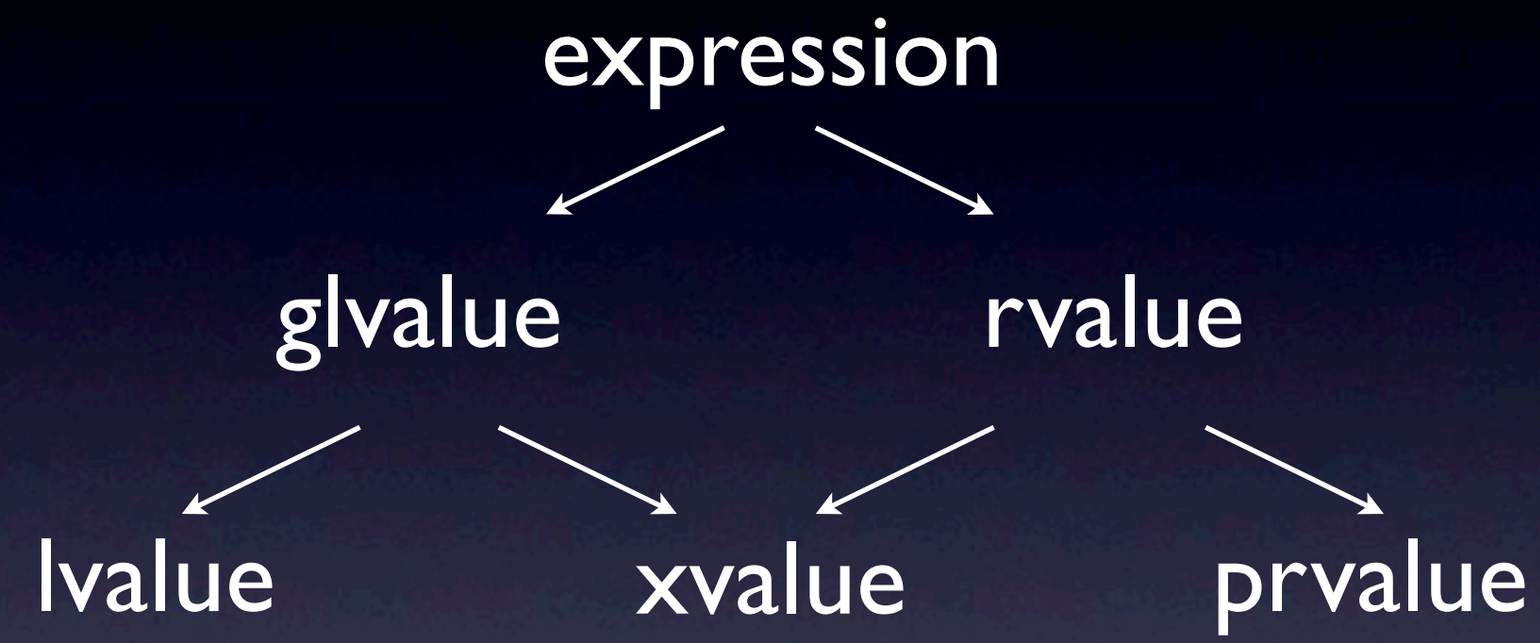


Expressions

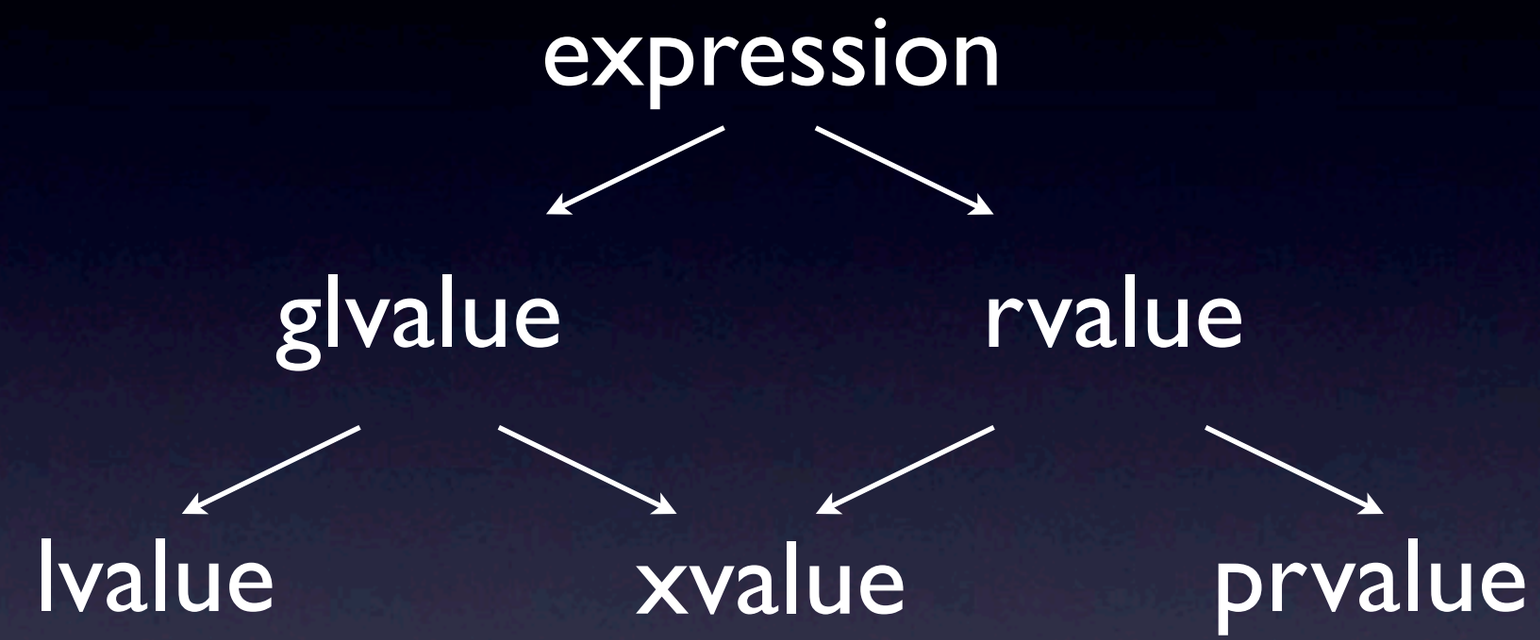


- A glvalue has a distinct address in memory.
- I.e. it has an identity.

Expressions



Expressions



- Only rvalues will bind to an rvalue reference.
- lvalues will not bind to an rvalue reference.

Binding

```
void f(A& i, A j, A&& k);
```

Binding

Binds to lvalues

```
void f(A& i, A j, A&& k);
```

Binding

Binds to lvalues

```
void f(A& i, A j, A&& k);
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Special case: Will bind to rvalue if const A&

Binding

Binds to lvalues
and rvalues

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void f(A& i, A j, A&& k);
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Binding

Binds to lvalues
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void f(A& i, A j, A&& k);
```

Special case: Will bind to rvalue if const A&

lvalues require copy
rvalues require move
(the move can be elided)

Binding

Binds to lvalues
and rvalues

Binds to lvalues

Binds to rvalues

```
void f(A& i, A j, A&& k);
```

prvalues
and
xvalues

Special case: Will
bind to rvalue if
const A&

lvalues require copy
rvalues require move
(the move can be elided)

Types & Expressions

```
void f(A& i, A j, A&& k)
{
}
```

Types & Expressions

```
void f(A& i, A j, A&& k)
{
}
```

- i is declared as type A&.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
    i; // lvalue A
}
```

- i is declared as type A&.
  - The **expression** i has type A and is an lvalue.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
    i; // lvalue A
}
```

- j is declared as type A.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
    i; // lvalue A
    j; // lvalue A
}
```

- j is declared as type A.
  - The **expression** j has type A and is an lvalue.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
    i; // lvalue A
    j; // lvalue A
}
```

- k is declared as type A&&.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
    i; // lvalue A
    j; // lvalue A
    k; // lvalue A
}
```

- k is declared as type A&&.
  - The **expression** k has type A and is an lvalue.

Types & Expressions

```
void f(A& i, A j, A&& k)
{
}
```

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2

void f(A& i, A j, A&& k)
{

}
```

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2
void f(A& i, A j, A&& k)
{
   g(i);  // calls #1
}
```

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2
void f(A& i, A j, A&& k)
{
    g(i);  // calls #1
    g(j);  // calls #1

}
```

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2
void f(A& i, A j, A&& k)
{
    g(i);  // calls #1
    g(j);  // calls #1
    g(k);  // calls #1
}
```

- The expression k is an lvalue A

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2
void f(A& i, A j, A&& k)
{
    g(static_cast<A&&>(i));  // calls #2
    g(static_cast<A&&>(j));  // calls #2
    g(static_cast<A&&>(k));  // calls #2
}
```

- An lvalue expression can be cast to an rvalue (xvalue) expression

Types & Expressions

```
void g(A&);   // #1
void g(A&&);  // #2
void f(A& i, A j, A&& k)
{
    g(std::move(i));  // calls #2
    g(std::move(j));  // calls #2
    g(std::move(k));  // calls #2
}
```

- Use std::move to perform the cast for better readability.

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Observation

```
void f(A& i, A j, A&& k)
{
  // i is not a unique reference
  // j is a unique reference
  // k is a reference to xvalue or prvalue
}
```

Observation

```
void f(A& i, A j, A&& k)
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- f() can do anything it wants to j, as long as the object remains destructible.

Observation

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void f(A& i, A j, A&& k)
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- f() can do anything it wants to j, as long as the object remains destructible.
- f() can do anything it wants to k, as long as k references a prvalue.

Observation

```
void f(A& i, A j, A&& k)
{
  // i is not a unique reference
  // j is a unique reference
  // k is a reference to xvalue or prvalue
}
```

- f() can do anything it wants to j, as long as the object remains destructible.
- f() can do anything it wants to k, as long as k references a prvalue.
- Convention: Do not cast an lvalue to an xvalue unless you want that object to be treated as a prvalue.

The move constructor

```
class A
{
    int* data_;          // heap allocated
public:
    A(const A& a);       // copy constructor
};
```

The move constructor

```
class A
{
    int* data_;          // heap allocated
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};
```

- copy constructor binds to an lvalue and copies resources.

The move constructor

```
class A
{
    int* data_;          // heap allocated
public:
    A(const A& a);       // copy constructor
    A(A&& a) noexcept // move constructor
      : data_(a.data_)
      { a.data_ = nullptr;}
};
```

- copy constructor binds to an lvalue and copies resources.
- move constructor binds to a rvalue and pilfers resources.

The move constructor

```
A make_A();

A a1;
A a2 = a1;                    // Calls copy ctor
```

The move constructor

```
A make_A();

A a1;
A a2 = a1;                  // Calls copy ctor
A a3 = make_A();            // Calls (or elides)
                            //       move ctor
```

The move constructor

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A make_A();

A a1;
A a2 = a1;                  // Calls copy ctor
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A a4 = std::move(a1);       // Calls move ctor
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The move constructor

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A a3 = make_A();            // Calls (or elides)
                            //       move ctor
A a4 = std::move(a1);       // Calls move ctor
```

- "Copies" from rvalues are made with the move constructor, which does nothing but trade pointers. *Fast!*

The move constructor

The move constructor

- If a class does not have a move constructor, its copy constructor will be used to copy from rvalues (just as in C++98/03).

The move constructor

- If a class does not have a move constructor, its copy constructor will be used to copy from rvalues (just as in C++98/03).
- Scalars move the same as they copy.

The move constructor

The move constructor

```
struct A
{
    A(const A& a);
    A(A&&) = default;
};
```

- Copy and move constructors can be explicitly defaulted.
  - The default copies/moves each base and data member (unless it is defined as deleted).

The move constructor

The move constructor

```
struct member
{
   member(const member&);

};
struct A
{
     member m_;
     A(A&&) = default; // deleted
};
```

- A defaulted move constructor is defined as deleted if:
  - there is a base or member with no move constructor and it is not trivially copyable.

The move constructor

```
struct member
{
   member(const member&)= default;

};
struct A
{
     member m_;
     A(A&&) = default;
};
```

- A defaulted move constructor is defined as deleted if:
  - there is a base or member with no move constructor and it is not trivially copyable.

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struct member
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    member(const member&);
    member(member&&);
};
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  - there is a base or member with no move constructor and it is not trivially copyable.

The move constructor

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struct member
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struct A
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     member m_;
     A(A&&) = default;
};
```

The move constructor

```
struct member
{
   member(const member&);

};
struct A
{
     member m_;
     A(A&&) = default;
};
```

- CWG issue 1402 (ready) changes the rules such that the defaulted move members will **not** be implicitly deleted, but instead copy the bases and members.

The move constructor

The move constructor

```
static_assert
(
  std::is_move_constructible<A>::value,
  "A should be move constructible"
);
```

- You can always test at compile time if a complete type is move constructible.

The move constructor

```
static_assert
(
  std::is_move_constructible<A>::value,
  "A should be move constructible"
);
```

- You can always test at compile time if a complete type is move constructible.
- This tests whether or not A is constructible from an rvalue A, not if A has a move constructor.
  - But a type with a deleted move constructor is never move constructible.

The move constructor

The move constructor

```
struct A
{
    A(const A& a) = delete;
    A(A&&)        = default;
};
```

- Copy and move constructors can be explicitly deleted.

The move constructor

```
struct A
{
    A(const A& a) = default;
    A(A&&)        = delete;
};
```

- Copy and move constructors can be explicitly deleted.
  - A deleted move constructor will prohibit copying from rvalues (rarely a good idea). Normally omit rather than delete a move constructor.

The move constructor

```
struct A
{
    A(const A& a) = default;

};
```

- Copy and move constructors can be explicitly deleted.
  - A deleted move constructor will prohibit copying from rvalues (rarely a good idea). Normally omit rather than delete a move constructor.

The move constructor

The move constructor

```
struct A
{
    // A(const A&) = delete;
    // A& operator=(const A&) = delete;
    A(A&&);
};
```

- A user-declared move constructor (defaulted or not) will implicitly create a deleted copy constructor and copy assignment.

Implicit Special Members

```
class A
{
   std::string s_;
public:
   // A() noexcept = default;
   // A(const A&) = default;
   // A& operator=(const A&) = default;
   // A(A&&) noexcept = default;
   // A& operator=(A&&) noexcept = default;
   // ~A() noexcept = default;
};
```

noexcept is extension

- Comments indicate compiler supplied definitions.

Implicit Special Members

```
class A
{
   std::string s_;
public:
   A();
   // A(const A&) = default;
   // A& operator=(const A&) = default;
   // A(A&&) noexcept = default;
   // A& operator=(A&&) noexcept = default;
   // ~A() noexcept = default;
};
```

- Comments indicate compiler supplied definitions.

Implicit Special Members

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class A
{
   std::string s_;
public:

   A(const A&);
   // A& operator=(const A&) = default;

   // ~A() noexcept = default;
};
```

deprecated

- Comments indicate compiler supplied definitions.

Implicit Special Members

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class A
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   std::string s_;
public:
   // A() noexcept = default;
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Implicit Special Members

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class A
{
   std::string s_;
public:
   // A() noexcept = default;
   // A(const A&) = default;
   // A& operator=(const A&) = default;

   ~A();
};
```

noexcept is extension

deprecated

- Comments indicate compiler supplied definitions.

Implicit Special Members

```
class A
{
   std::string s_;
public:

   // A(const A&) = delete;
   // A& operator=(const A&) = delete;
   A(A&&);

   // ~A() noexcept = default;
};
```

- Comments indicate compiler supplied definitions.

Implicit Special Members

```
class A
{
   std::string s_;
public:
   // A() noexcept = default;
   // A(const A&) = delete;
   // A& operator=(const A&) = delete;

   A& operator=(A&&);
   // ~A() noexcept = default;
};
```

noexcept is extension

- Comments indicate compiler supplied definitions.

Advice

- Put these (or other appropriate) tests right into your release code:

```
struct A
{
    std::string s_;
    std::vector<int> v_;
};
```

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- Put these (or other appropriate) tests right into your release code:

```
struct A
{
    std::string s_;
    std::vector<int> v_;
};

// Howard says put these tests in!
static_assert(std::is_nothrow_default_constructible<A>::value, "");
static_assert(std::is_copy_constructible<A>::value, "");
static_assert(std::is_copy_assignable<A>::value, "");
static_assert(std::is_nothrow_move_constructible<A>::value, "");
static_assert(std::is_nothrow_move_assignable<A>::value, "");
static_assert(std::is_nothrow_destructible<A>::value, "");
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{
    std::string s_;
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    A(const A&) = default;
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static_assert(std::is_nothrow_destructible<A>::value, "");
```

Advice

- Put these (or other appropriate) tests right into your release code:

```
struct A
{
    std::string s_;
    std::vector<int> v_;
    A(const A&) = default;
};

// Howard says put these tests in! Or else!!!

static_assert(std::is_copy_constructible<A>::value, "");
static_assert(std::is_copy_assignable<A>::value, "");


static_assert(std::is_nothrow_destructible<A>::value, "");
```

The move assignment operator

The move assignment operator

- Everything that's been said about the move constructor applies to the move assignment operator.

The move assignment operator

```
class A
{
    int* data_;          // heap allocated
public:
    A& operator=(const A& a);    // copy
};
```

The move assignment operator

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```

- copy assignment binds to lvalue rhs and copies resources.

The move assignment operator

```
class A
{
    int* data_;          // heap allocated
public:
    A& operator=(const A& a);    // copy
    A& operator=(A&& a) noexcept // move
    {
       std::swap(data_, a.data_);
       return *this;
    }
};
```

- copy assignment binds to lvalue rhs and copies resources.
- move assignment binds to rvalue rhs and does whatever is fastest to assume value of rhs.

The move assignment operator

The move assignment operator

```
class A
{
    fstream f_;
public:
    A& operator=(A&& a) noexcept
    {
        f_ = std::move(a.f_);
        return *this;
    }
};
```

- If your type holds std::lib components, move assigning those data members will generally do the right thing.

The move assignment operator

```
class A
{
    fstream f_;
public:
    A& operator=(A&& a) = default;
};
```

- If all you need to do is move assign bases and members, consider doing it with “= default”.

The move assignment operator

```
class A
{
    fstream f_;
public:

};
```

- Or doing it implicitly.

The move assignment operator

```
template <class T>
class A {
    T* data_;          // heap allocated
public:
    A& operator=(A&& a) noexcept {
        delete data_;
        data_ = a.data_;
        a.data_ = nullptr;
        return *this;
    }
};
```

- Does the move assignment operator need to check for self-assignment?

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- Convention: Do not cast an lvalue to an xvalue unless you want that object to be treated as a prvalue.

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- Convention: Do not cast an lvalue to an xvalue unless you want that object to be treated as a prvalue.
- If ‘a’ refers to a prvalue, then it is not possible for ‘this’ and ‘a’ to refer to the same object.

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}

a = std::move(a);
```

- However if ‘a’ refers to an xvalue, then it is possible for ‘this’ and ‘a’ to refer to the same object.

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}

a = std::move(a);
```

- However if ‘a’ refers to an xvalue, then it is possible for ‘this’ and ‘a’ to refer to the same object.
- But you’ve arguably broken convention.

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- Self-swap is one place where this can happen.

```
template <class T>
void swap(T& x, T& y) {
  T tmp(std::move(x));
  x = std::move(y);
  y = std::move(tmp);
}

std::swap(a, a);
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

```
template <class T>
void swap(T& x, T& y) {
  T tmp(std::move(x));
  x = std::move(y);
  y = std::move(tmp);
}

  std::swap(a, a);
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- However in this case, the self-move assignment happens only on a moved-from value.

```
template <class T>
void swap(T& x, T& y) {
  T tmp(std::move(x));
  x = std::move(y);
  y = std::move(tmp);
}

  std::swap(a, a);
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

```
template <class T>
void swap(T& x, T& y) {
  T tmp(std::move(x));
  x = std::move(y);
  y = std::move(tmp);
}

  std::swap(a, a);
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- Self-move assignment from a moved-from value is most often naturally safe.

```
template <class T>
void swap(T& x, T& y) {
  T tmp(std::move(x));
  x = std::move(y);
  y = std::move(tmp);
}

  std::swap(a, a);
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

The move assignment operator

```
A& operator=(A&& a) noexcept {
    delete data_;
    data_ = a.data_;
    a.data_ = nullptr;
    return *this;
}
```

- Indeed, in all permutation rearrangement algorithms (those that do not “remove” elements), the target of a move assignment is always in a “moved-from” state.

The move assignment operator

The move assignment operator

- I treat self-move assignment and self-swap as a performance bug in my code.

The move assignment operator

- I treat self-move assignment and self-swap as a performance bug in my code.
- My move assignment operators are "self-safe" only when in a moved-from state.

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- I treat self-move assignment and self-swap as a performance bug in my code.
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- Feel free to check for self-move assignment in your code.

The move assignment operator

- I treat self-move assignment and self-swap as a performance bug in my code.
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- Feel free to check for self-move assignment in your code.
  - Either with an if - to ignore the bug.

The move assignment operator

- I treat self-move assignment and self-swap as a performance bug in my code.
- My move assignment operators are "self-safe" only when in a moved-from state.
- Feel free to check for self-move assignment in your code.
  - Either with an if - to ignore the bug.
  - Or with an assert - to catch the bug.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- In C++98/03 it became popular to define assignment using a copy/swap pattern.
- This is very good if you need strong exception safety.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
        swap(a);
        return *this;
    }
};
```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- It is very efficient when assigning from rvalues.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- It is very efficient when assigning from rvalues.
- It is not so efficient when assigning from lvalues.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
        swap(a);
        return *this;
    }
};
```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- Strong exception safety is good, but it is not free.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- Strong exception safety is good, but it is not free.
- Do not pay for it (performance) if you do not need it.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
        swap(a);
        return *this;
    }
};
```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
    A& operator=(A a) {
       swap(a);
       return *this;
    }
};
```

- The fatal assumption here is that:

  ```
  A& operator=(const A&) = default;
  ```

  is always about the same speed as:

  ```
  A(const A&) = default;
  ```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
   A& operator=(const A& a) = default;
   A& operator=(A&& a) = default;

};
```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
   A& operator=(const A& a) = default;
   A& operator=(A&& a) = default;

};
```

- This copy assignment can be much faster! (2X, 5X, even 7X)

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
   A& operator=(const A& a) = default;
   A& operator=(A&& a) = default;

};
```

- This copy assignment can be much faster! (2X, 5X, even 7X)
- This move assignment is just as fast.

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
   A& operator=(const A& a) = default;
   A& operator=(A&& a) = default;

};
```

Assignment boo boo's

```
class A
{
   std::vector<int> v_;
   std::string s_;
public:
   A& operator=(const A& a) = default;
   A& operator=(A&& a) = default;

};
```

- Prefer defaulted assignment operators.

Outline

- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

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- The rvalue reference
- Move Semantics
- Factory Functions
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Return By Value

```
A
make()
{
   A a;
   // ...
   return a;
}
```

Return By Value

```
A
make()
{
   A a;
   // ...
   return a; // 1. RVO.
}
```

Return By Value

```
A
make()
{
   A a;
   // ...
   return a; // 1. RVO.
}            // 2. Return as if an rvalue.
```

Return By Value

```
A
make()
{
   A a;
   // ...
   return a;  // 1. RVO.
}             // 2. Return as if an rvalue.
              // 3. Return as if an lvalue.
```

- Move semantics makes factory functions efficient.

Return By Value

```
A&&
make()
{
   A a;
   // ...
   return a;
}
```

Return By Value

```
A&&   // Wrong!!
make()
{
   A a;
   // ...
   return a;
}
```

- Do not return a reference to a local object.
  - Not even an rvalue reference.

Return By Value

```
A
make()
{
   A a;
   // ...
   return std::move(a);
}
```

Return By Value

```
A
make()
{
   A a;
   // ...
   return std::move(a);   // Wrong!!
}
```

- Explicitly using std::move will inhibit RVO.

Return By Value

```
template <class ...T>
ifstream
prepare(const string& filename,
        const T& ...t)
{
  create(filename, t...);
  return ifstream(filename);
}
```

- Now you can return “move-only” types from factory functions.

Return a Modified Copy

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

```
A
modify(A a)
{
   a.modify();
   return a;   // 1. Return as if an rvalue.
}              // 2. Return as if an lvalue.
```

- Returning a by-value parameter by-value will also implicitly move.

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

- There has been a lot of talk lately about which of these designs is “better.”

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

- There has been a lot of talk lately about which of these designs is “better.”
- Today we will measure and provide quantitative results.

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

- How many copy constructions?
- How many move constructions?

Return a Modified Copy

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

```
A
modify(const A& a)
{
  A tmp(a);
  tmp.modify();
  return tmp;
}
```

```
A
modify(A a)
{
  a.modify();
  return a;
}
```

- How does the value category (lvalue/rvalue) of the argument impact the results?
- Is the answer different in C++03 than in C++11?

Return a Modified Copy

in C++03

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

Return a Modified Copy

in C++03

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

here

Assuming RVO for all cases

- lvalue: 1 copy construction
- rvalue: 1 copy construction

Return a Modified Copy

C++03	lvalue	rvalue
const A&	1 copy	1 copy
A		

Return a Modified Copy

C++03	lvalue	rvalue
const A&	1 copy	1 copy
A		

- Keep score here

Return a Modified Copy

in C++03

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

in C++03

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

in C++03

```
A
modify(A a) <-------------- here (lvalue only)
{
   a.modify();
   return a; <-------------- here
}
```

- lvalue: 2 copy constructions
- rvalue: 1 copy construction

Return a Modified Copy

C++03	lvalue	rvalue
const A&	1 copy	1 copy
A	2 copies	1 copy

Return a Modified Copy

C++03	lvalue	rvalue
const A&	1 copy	1 copy
A	2 copies	1 copy

- const A& is usually better in C++03

Return a Modified Copy

C++03	lvalue	rvalue
const A&	1 copy	1 copy
A	2 copies	1 copy

- const A& is usually better in C++03
- (perhaps except when A is small and trivial)

Return a Modified Copy

in C++11

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

Return a Modified Copy

in C++11

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

here

- lvalue: 1 copy construction
- xvalue: 1 copy construction
- prvalue: 1 copy construction

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A			

Return a Modified Copy

in C++11

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

in C++11

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

Return a Modified Copy

in C++11

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

copy lvalue here

move here

- lvalue: 1 copy construction + 1 move construction

Return a Modified Copy

in C++11

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

copy lvalue here

move xvalue here

move here

- lvalue: 1 copy construction + 1 move construction
- xvalue: 2 move constructions

Return a Modified Copy

in C++11

```
A
modify(A a)
{
   a.modify();
   return a;
}
```

copy lvalue here

move xvalue here

move here

- lvalue: 1 copy construction + 1 move construction
- xvalue: 2 move constructions
- prvalue: 1 move construction

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move

- Pass by value is better in C++11 if move is much faster than copy, and if the argument is not always an lvalue.

Return a Modified Copy

in C++11

```
A
modify(const A& a)
{
   A tmp(a);
   tmp.modify();
   return tmp;
}
```

Return a Modified Copy

in C++11

```
A                                   A
modify(const A& a)                  modify(A&& a)
{                                   {
   A tmp(a);                           a.modify();
   tmp.modify();                       return std::move(tmp);
   return tmp;                      }
}
```

- Consider overloading on rvalue reference.

Return a Modified Copy

in C++11

```
A                                   A
modify(const A& a)                  modify(A&& a)
{                                   {
   A tmp(a);                           a.modify();
   tmp.modify();                       return std::move(tmp);
   return tmp;                      }
}
```

Return a Modified Copy

in C++11

```
A
modify(const A& a)
{
  A tmp(a);
  tmp.modify();
  return tmp;
}
```

```
A
modify(A&& a)
{
  a.modify();
  return std::move(tmp);
}
```

- lvalue: 1 copy construction
- xvalue: 1 move construction
- prvalue: 1 move construction

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move
const A& + A&&	1 copy	1 move	1 move

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move
const A& + A&&	1 copy	1 move	1 move

- If you pass by reference (and have fast moves), overload on rvalue reference.

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move
const A& + A&&	1 copy	1 move	1 move

- If you pass by reference (and have fast moves), overload on rvalue reference.
- This ideal may or may not be worth overloading.

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move
const A& + A&&	1 copy	1 move	1 move

- Take away: If you hear: "always pass by value" or "never pass by value", you're getting bad information.

Return a Modified Copy

C++11	lvalue	xvalue	prvalue
const A&	1 copy	1 copy	1 copy
A	1 copy 1 move	2 moves	1 move
const A& + A&&	1 copy	1 move	1 move

- Take away: If you hear: "always pass by value" or "never pass by value", you're getting bad information.
- You are not excused from the design process.

Outline

- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

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Reference Collapsing

```
template <class T>
void
f(T& t);
```

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&>(i);` T is int&

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&>(i);` T is int&

This calls: `f<int&>(int& & t);`

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&>(i);` T is int&

This calls: `f<int&>(int& & t);`

Which collapses to: `f<int&>(int& t);`

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&&>(i);` T is int&&

This calls:

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&&>(i);` T is int&&

This calls: `f<int&&>(int&& & t);`

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T& t);
```

Consider: `f<int&&>(i);` T is int&&

This calls: `f<int&&>(int&& & t);`

Which collapses to: `f<int&&>(int& t);`

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&>(i);` T is int&

This calls:

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&>(i);` T is int&

This calls: `f<int&>(int& && t);`

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&>(i);` T is int&

This calls: `f<int&>(int& && t);`

Which collapses to: `f<int&>(int& t);`

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&&>(2);` T is int&&

This calls:

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&&>(2);` T is int&&

This calls: `f<int&&>(int&& && t);`

Which collapses to:

Reference Collapsing

```
template <class T>
void
f(T&& t);
```

Consider: `f<int&&>(2);` T is int&&

This calls: `f<int&&>(int&& && t);`

Which collapses to: `f<int&&>(int&& t);`

Reference Collapsing

This

Collapses to this

Reference Collapsing

This	Collapses to this
T& &	T&
T& &&	T&
T&& &	T&
T&& &&	T&&

The Set Up

```
template <class T>
void
f(T& t);
```

- What is the declared type of t?

The Set Up

```
template <class T>
void
f(T& t);
```

- What is the declared type of t?
  - A reference.

The Set Up

```
template <class T>
void
f(T& t);
```

- What is the declared type of t?
  - An lvalue reference.

The Set Up

```
template <class T>
void
f(T& t);
```

- What is the declared type of t?
  - A non-const lvalue reference.

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void
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```

- What is the declared type of t?
  - A non-const lvalue reference.

```
void g(const int& i)
{
    f(i); // f<const int>(const int& t);
}
```

The Set Up

```
template <class T>
void
f(T& t);
```

- What is the declared type of t?
  - A lvalue reference.

Just because it looks like T&, you can not assume it is a non-const lvalue reference.

Special Deduction for rvalue reference

```
template <class T>
void
f(T&& t);
```

Special Deduction for rvalue reference

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```

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Special Deduction for rvalue reference

```
template <class T>
void
f(T&& t);
```

t is an rvalue reference to int

```
f(3);  // f<int>(int&& t);
```

Just because it looks like T&&, you can not assume it is an rvalue reference.

Special Deduction for rvalue reference

```
template <class T>
void
f(T&& t);
```

t is an rvalue reference to int

```
f(3);   // f<int>(int&& t);

f(i);   // f<int&>(int& && t);
```

Just because it looks like T&&, you can not assume it is an rvalue reference.

Special Deduction for rvalue reference

```
template <class T>
void
f(T&& t);
```

```
f(3);   // f<int>(int&& t);
```

t is an rvalue reference to int

```
f(i);   // f<int&>(int& t);
```

t is an lvalue reference to int

Just because it looks like T&&, you can not assume it is an rvalue reference.

Special Deduction for rvalue reference

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void
f(T&& t);
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- The “T&&” template pattern is special.
- “const T&&” does not behave this way.
- If the argument is an lvalue A, T deduces as A&, otherwise T deduces as A.

Special Deduction for rvalue reference

```
template <class T>
void
f(T&& t);
```

- The “T&&” template pattern is special.
- “const T&&” does not behave this way.
- If the argument is an lvalue A, T deduces as A&, otherwise T deduces as A.
- cv-qualifiers will also deduce into T just as in the T& case.

Outline

- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

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The Forwarding Problem

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- A forwarding function forwards one or more arguments to some other function.
- A forwarding function should preserve cv-qualifiers and value category.
- If the destination function is overloaded on cv-qualifiers or value category, getting the forwarding wrong can be catastrophic.

The Forwarding Problem

```
template <class T, class U>
void f(T& t, U& u);
```

The Forwarding Problem

```
template <class T, class U>
void f(T& t, U& u);

template <class T, class U>
void g(T& t, U& u)
{f(t,u);}
```

```
int i = 2;
const int j = 3;
g(i, j);
```

Good!

f sees: t is an lvalue int,
u is an lvalue const int

The Forwarding Problem

```
template <class T, class U>
void f(T& t, U& u);

template <class T, class U>
void g(T& t, U& u)
{f(t,u);}
```

```
int i = 2;
const int j = 3;
g(i, j);
```

Good!

f sees: t is an lvalue int,
u is an lvalue const int

But: `g(i, 3);  // Doesn't compile!`

The Forwarding Problem

```
template <class T, class U>
void f(T& t, U& u);
```

```
int i = 2;
const int j = 3;
g(i, j);
```

f sees:

```
g(i, 3);
```

The Forwarding Problem

```
template <class T, class U>
void f(T& t, U& u);

template <class T, class U>
void g(const T& t, const U& u)
{f(t,u);}
```

```
int i = 2;
const int j = 3;
g(i, j);
```

But const unnecessarily added.

f sees:
```
t is an lvalue const int,
u is an lvalue const int
```

Now:
```
g(i, 3);  // Compiles!
```

The Forwarding Problem

The Forwarding Problem

```
template <class T, class U>
void g(T& t, U& u)
{f(t,u);}

template <class T, class U>
void g(const T& t, U& u)
{f(t,u);}

template <class T, class U>
void g(T& t, const U& u)
{f(t,u);}

template <class T, class U>
void g(const T& t, const U& u)
{f(t,u);}
```

The Forwarding Problem

Too Many Overloads!!!

The Forwarding Solution

The Forwarding Solution

```
template <class T, class U, class V>
void f(T&& t, U&& u, V&& v);

template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
    f(t, u, v);
}
```

```
const A i = A();
A j;
g(i, j, A());
```

v should be an rvalue

f sees:

```
t is an lvalue const A
u is an lvalue A
v is an lvalue A
```

The Forwarding Solution

```
template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
       f(static_cast<T&&>(t),
         u,
         v);
}
```

```
const A i = A();
A j;
g(i, j, A());
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The Forwarding Solution

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template <class T, class U, class V>
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template <class T, class U, class V>
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```

```
const A i = A();T is const A&
A j;
g(i, j, A());
```

The Forwarding Solution

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template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
        f(static_cast<T&&>(t),
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const A i = A();
A j;
g(i, j, A());
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T is const A&

T&& is const A&

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template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
       f(static_cast<T&&>(t),
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}
```

```
const A i = A();      T is const A&
A j;                  T&& is const A&
g(i, j, A());
```

f sees: t is an lvalue const A ✓

The Forwarding Solution

```
template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
       f(static_cast<T&&>(t),
         static_cast<U&&>(u),
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const A i = A();
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A j;                          U is A&
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const A i = A();
A j;                        U is A&
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       f(static_cast<T&&>(t),
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}
```

```
const A i = A();
A j;
g(i, j, A());          V is A
```

f sees: t is an lvalue const A
u is an lvalue A

The Forwarding Solution

```
template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
       f(static_cast<T&&>(t),
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}
```

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A j;
g(i, j, A());
```

V is A

f sees: t is an lvalue const A
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template <class T, class U, class V>
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const A i = A();
A j;
g(i, j, A());
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V is A
V&& is A&&

f sees: t is an lvalue const A
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The Forwarding Solution

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template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
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}
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const A i = A();
A j;
g(i, j, A());
```

V is A
V&& is A&&

f sees: t is an lvalue const A
u is an lvalue A
v is an rvalue A

✓

The Forwarding Solution

```
template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
       f(static_cast<T&&>(t),
         static_cast<U&&>(u),
         static_cast<V&&>(v));
}
```

```
const A i = A();
A j;
g(i, j, A());
```

Perfect!

f sees:
```
t is an lvalue const A
u is an lvalue A
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```

The Forwarding Solution

```
const A i = A();
A j;
g(i, j, A());
```

Perfect!

```
f sees:  t is an lvalue const A
         u is an lvalue A
         v is an rvalue A
```

The Forwarding Solution

```
template <class T, class U, class V>
void g(T&& t, U&& u, V&& v) {
    f(std::forward<T>(t),
      std::forward<U>(u),
      std::forward<V>(v));
}
```

Use `std::forward` for better readability.

```
const A i = A();
A j;
g(i, j, A());
```

Perfect!

f sees:
- `t` is an lvalue `const A`
- `u` is an lvalue `A`
- `v` is an rvalue `A`

The Forwarding Solution

```
const A i = A();
A j;
g(i, j, A());
```

Perfect!

```
f sees:  t is an lvalue const A
         u is an lvalue A
         v is an rvalue A
```

The Forwarding Solution

```
template <class ...T>
void g(T&& ...t) {
    f(std::forward<T>(t)...);
}
```

```
const A i = A();
A j;
g(i, j, A());
```

f sees:
```
t is an lvalue const A
u is an lvalue A
v is an rvalue A
```

Perfect!
And easy!

Summary

- The rvalue reference has been introduced to support:
- Move semantics.
- Perfect forwarding.