Moving Forward to C++11

Howard Hinnant

May 15, 2012

Outline

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

Outline

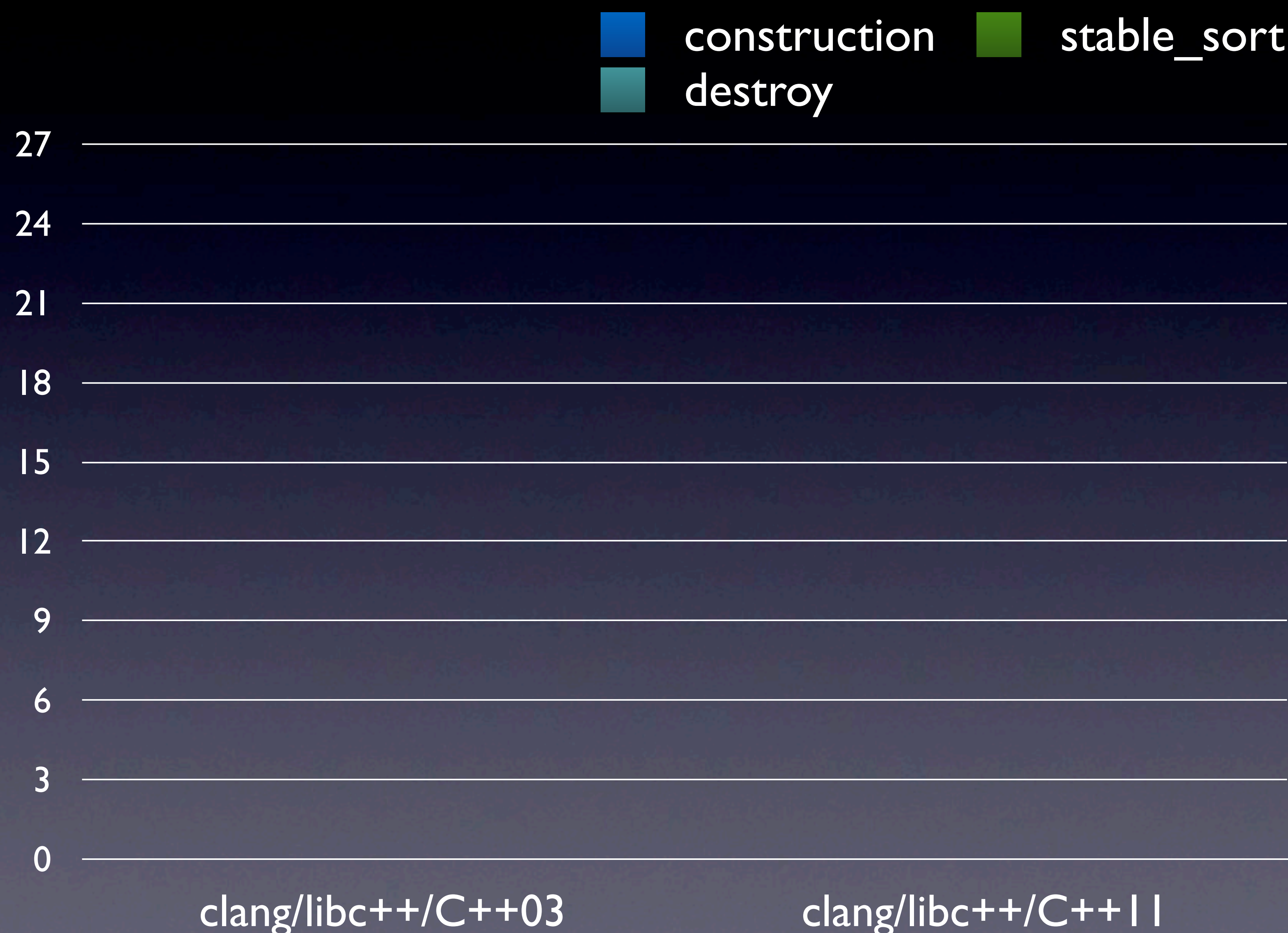
- The rvalue reference
- Move Semantics
- Factory Functions
- More rvalue ref rules
- “Perfect” forwarding

Motivation for Move

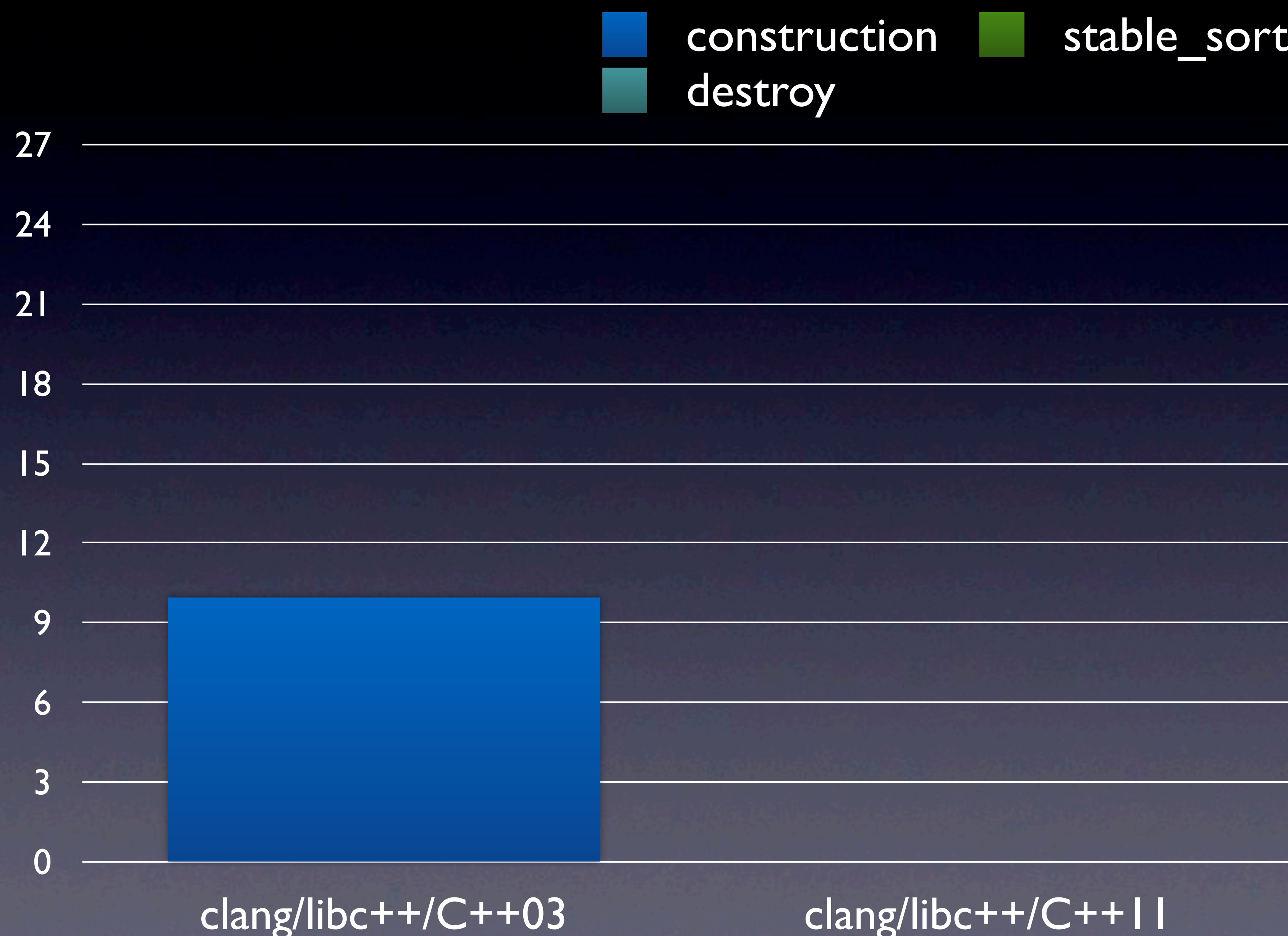
- In 2006, I wrote a benchmark to show off move semantics.
  - It manipulated the unlikely data structure vector<set<int>>:
  - Return it from factory functions.
  - Manipulate it with algorithms.

Motivation for Move

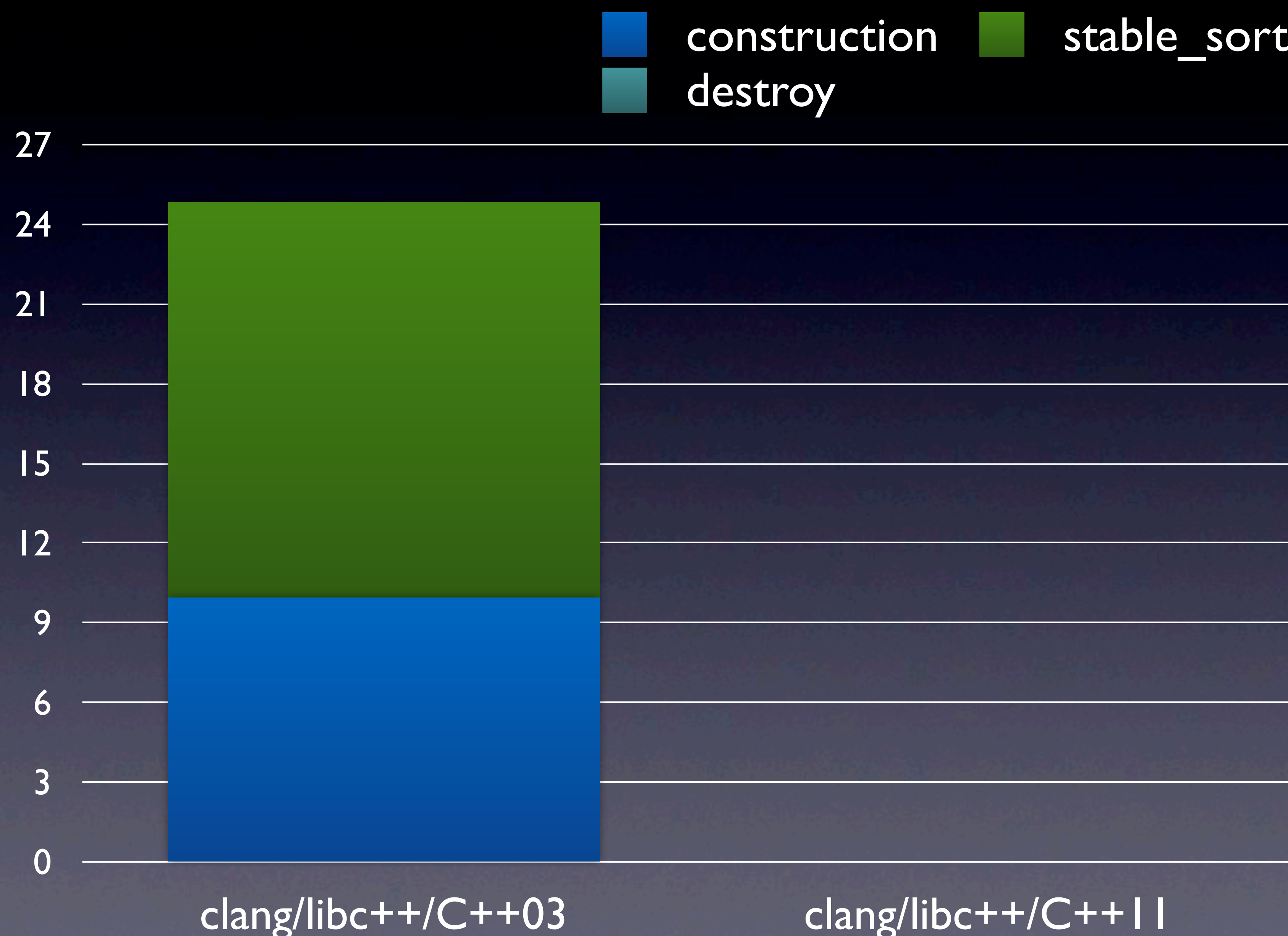
Motivation for Move



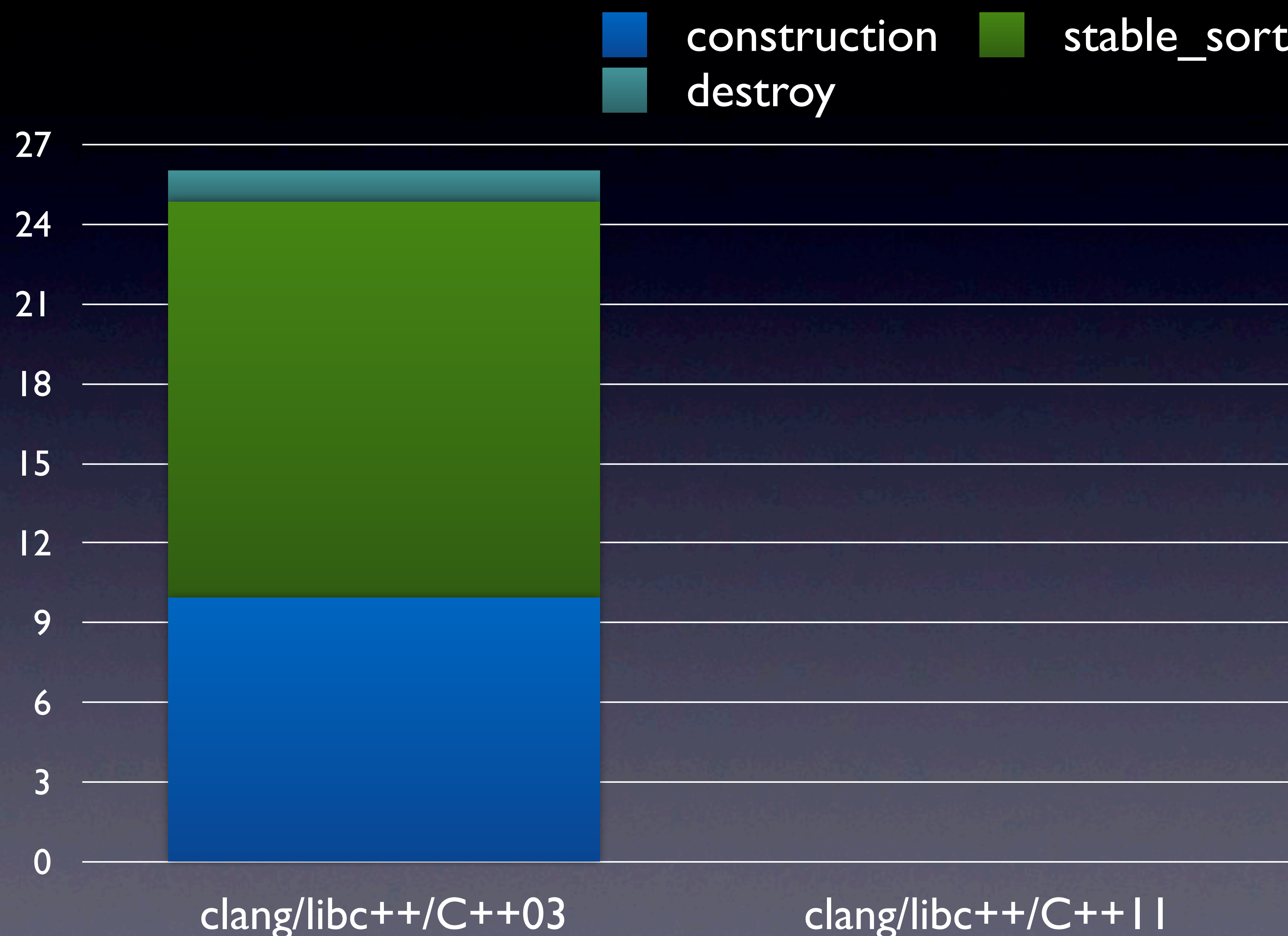
Motivation for Move



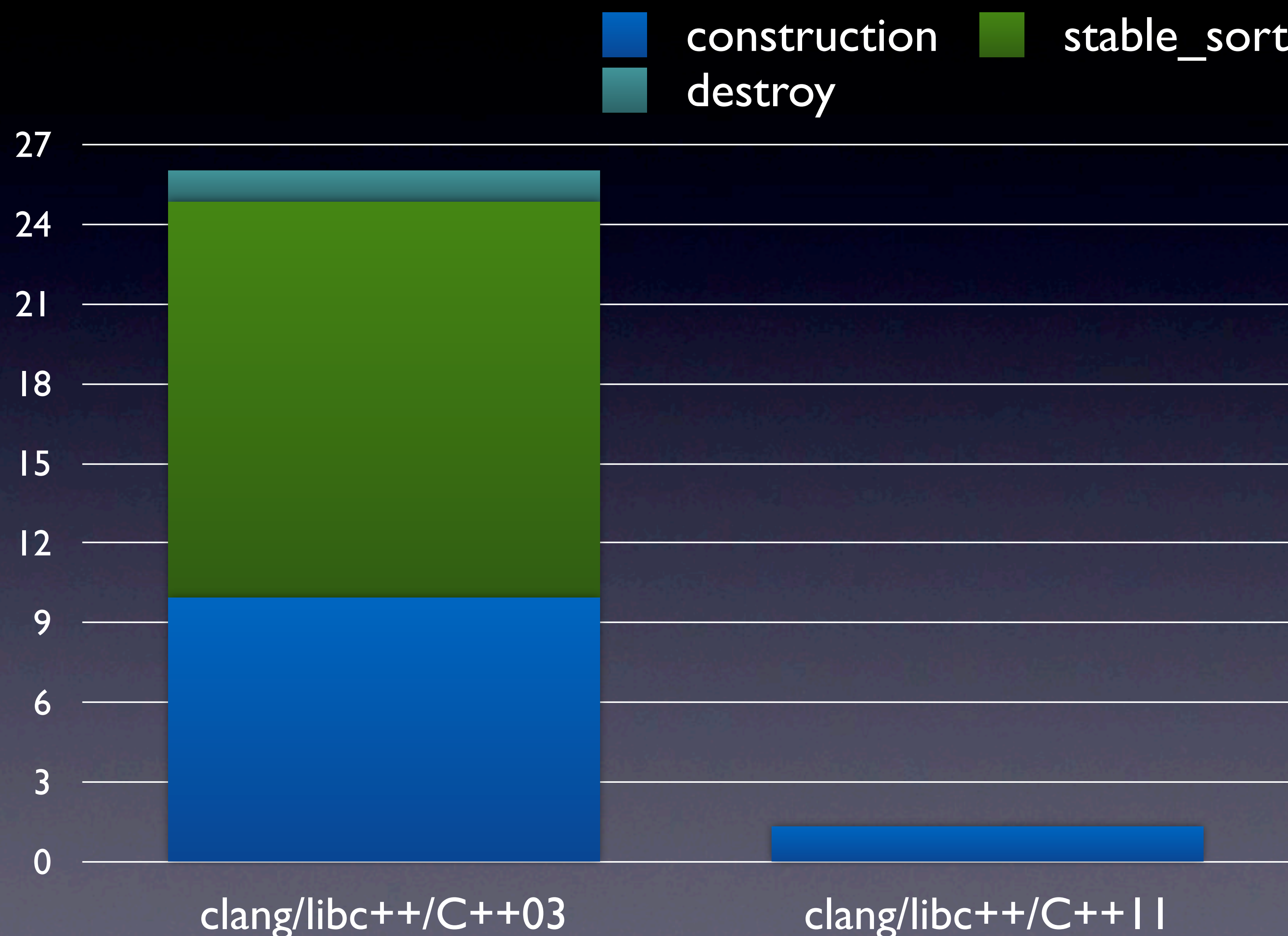
Motivation for Move



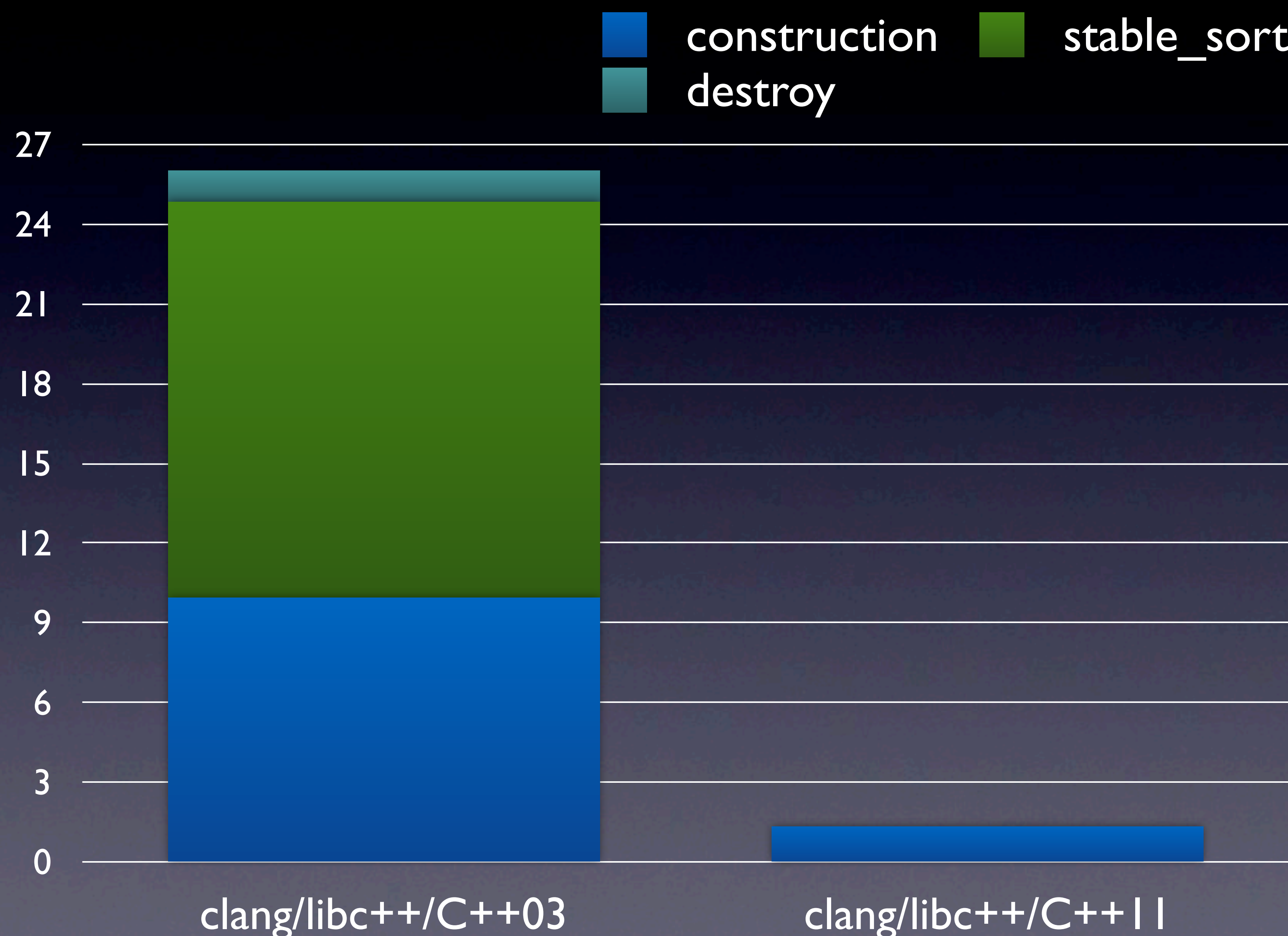
Motivation for Move



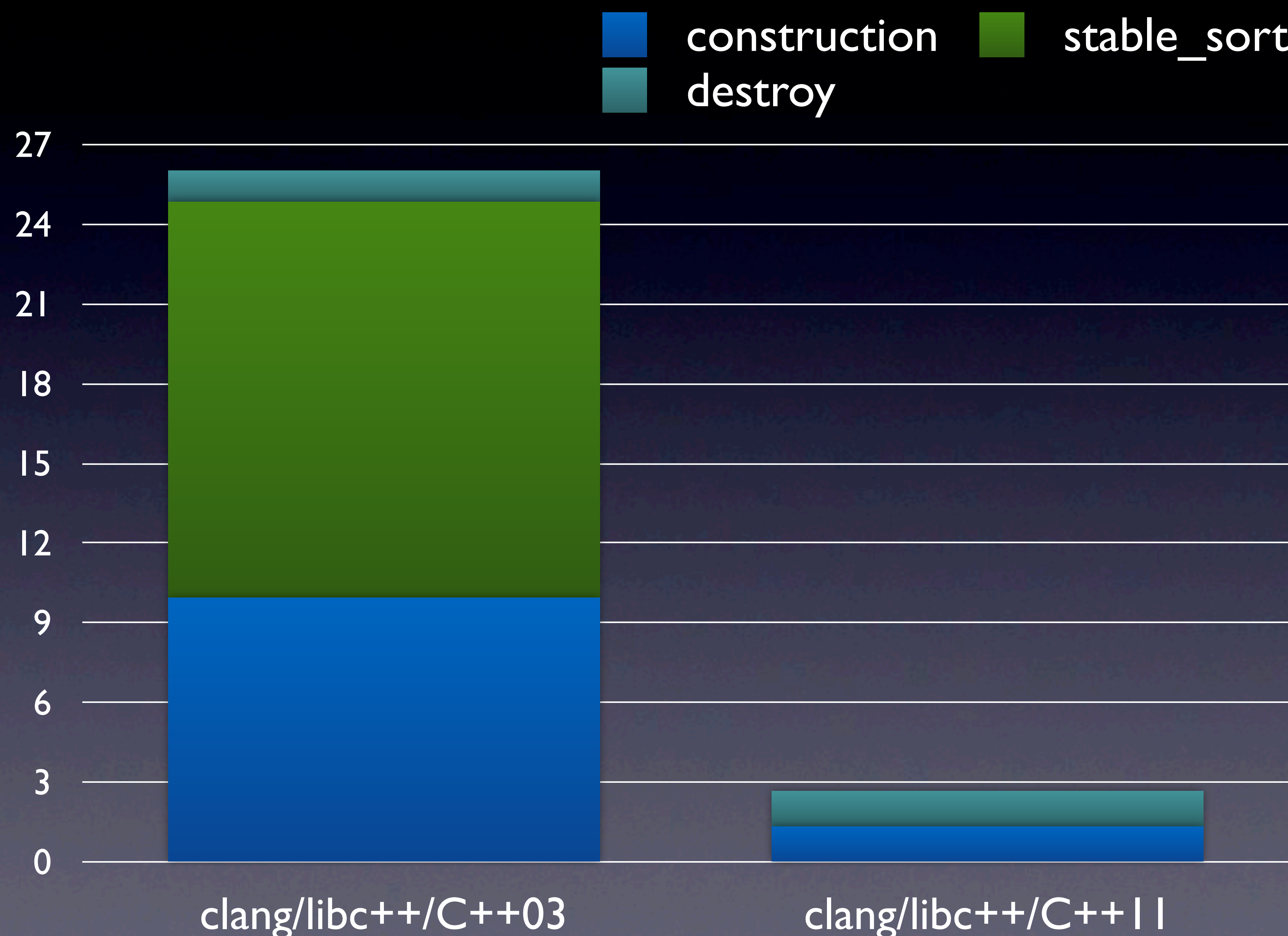
Motivation for Move



Motivation for Move



Motivation for Move



Motivation for Move

Motivation for Move

- With move semantics, vector<set<int>> does not have to be an unlikely data structure.

Motivation for Move

- 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.

Motivation for Move

- 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.”

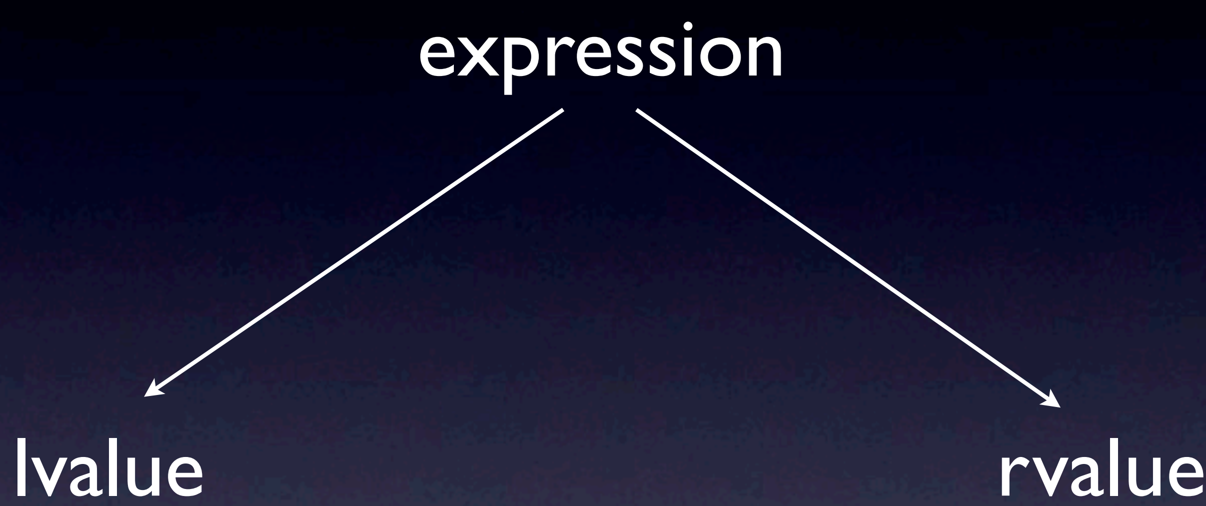
Rvalue reference syntax

A&

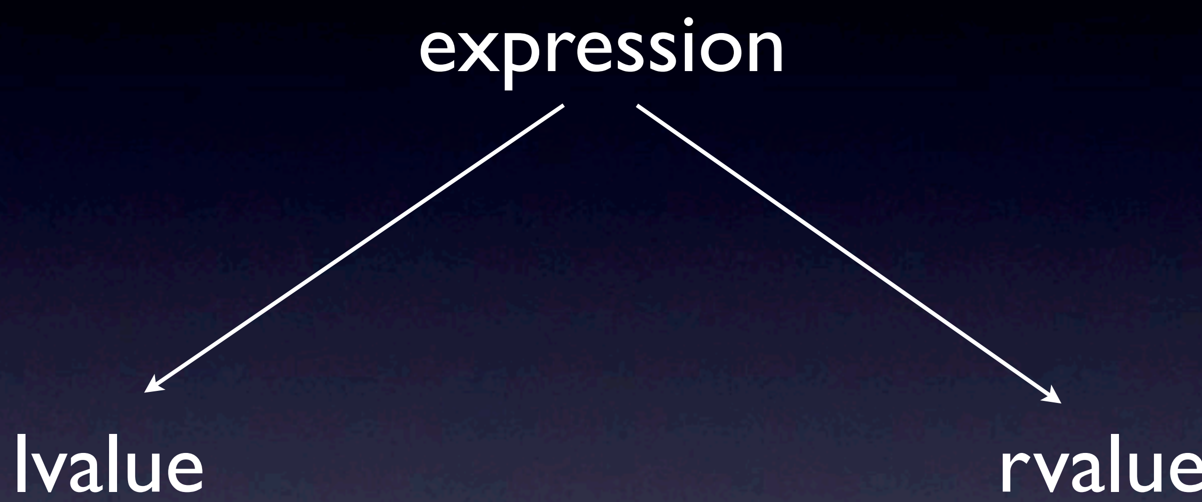
A&&

- 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

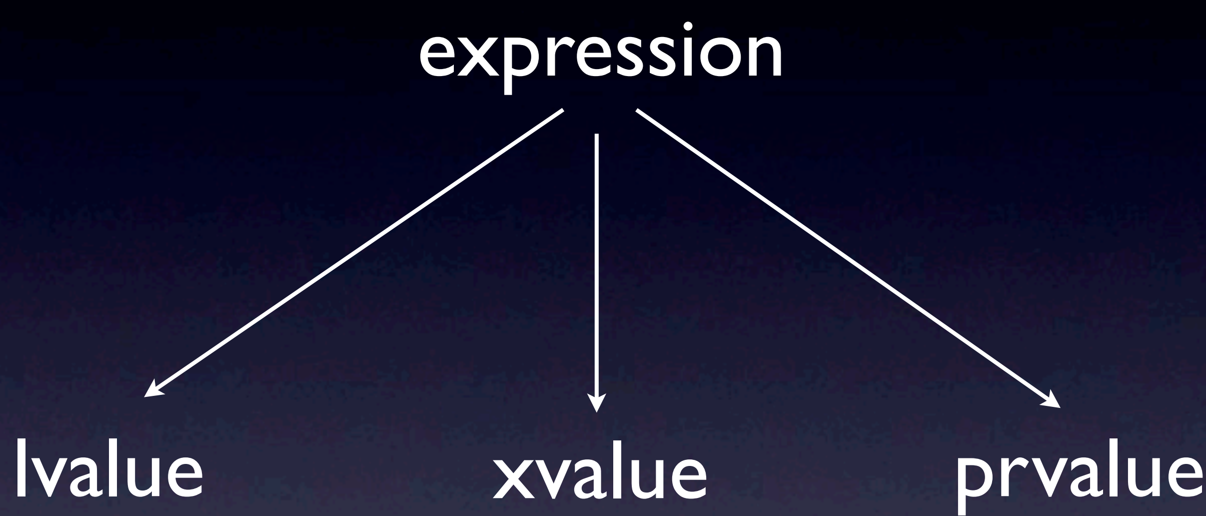
Expressions

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

Expressions

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

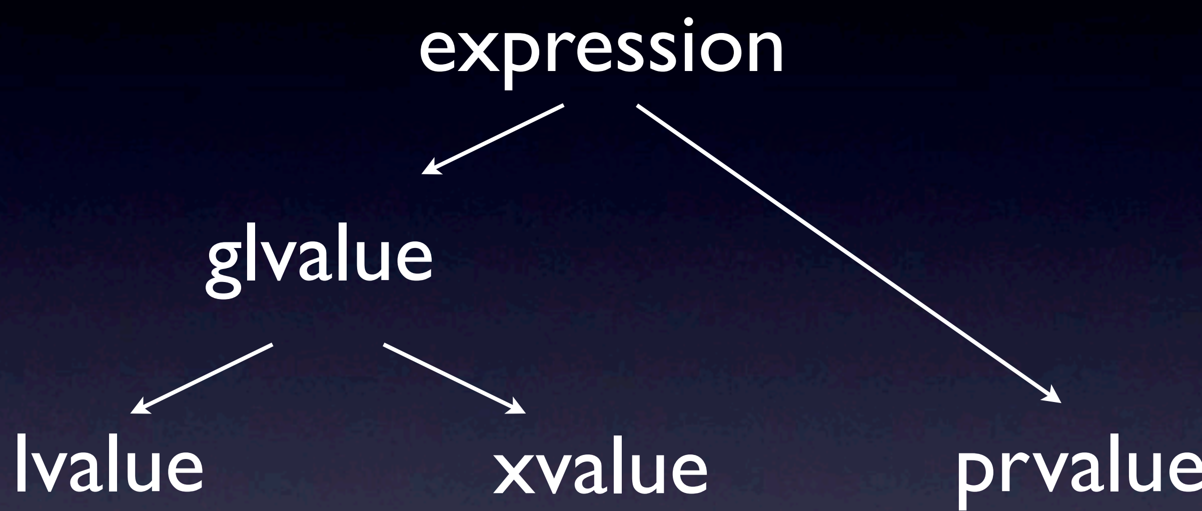
Expressions



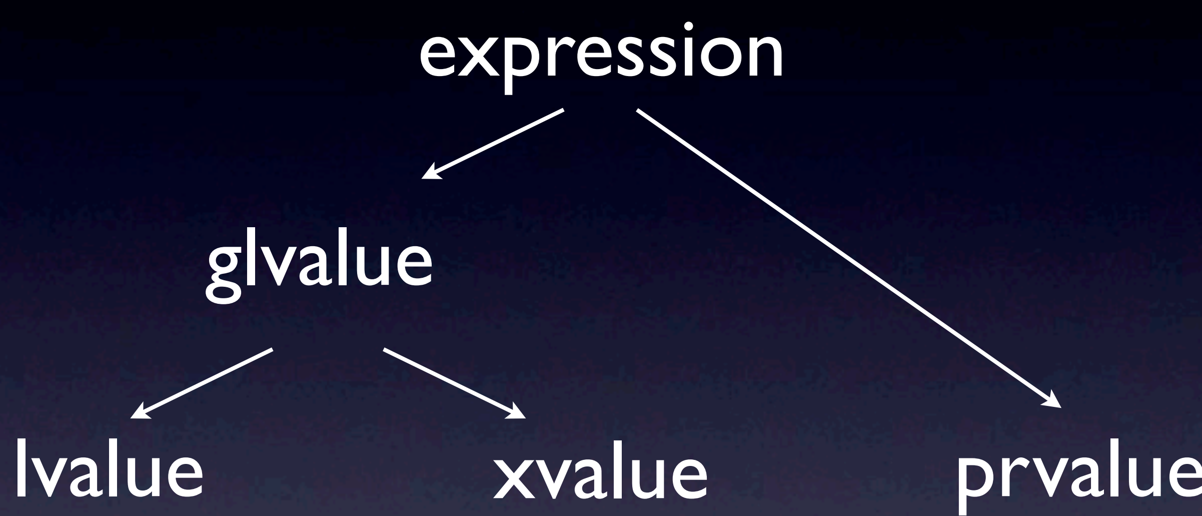

```
static_cast<A&&>(a)
```

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

Expressions

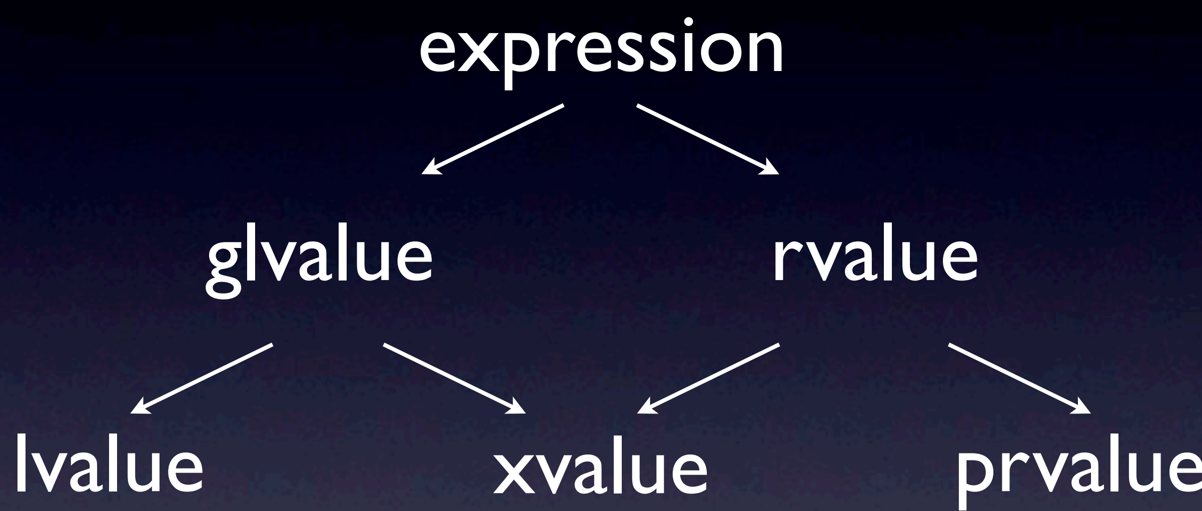


Expressions

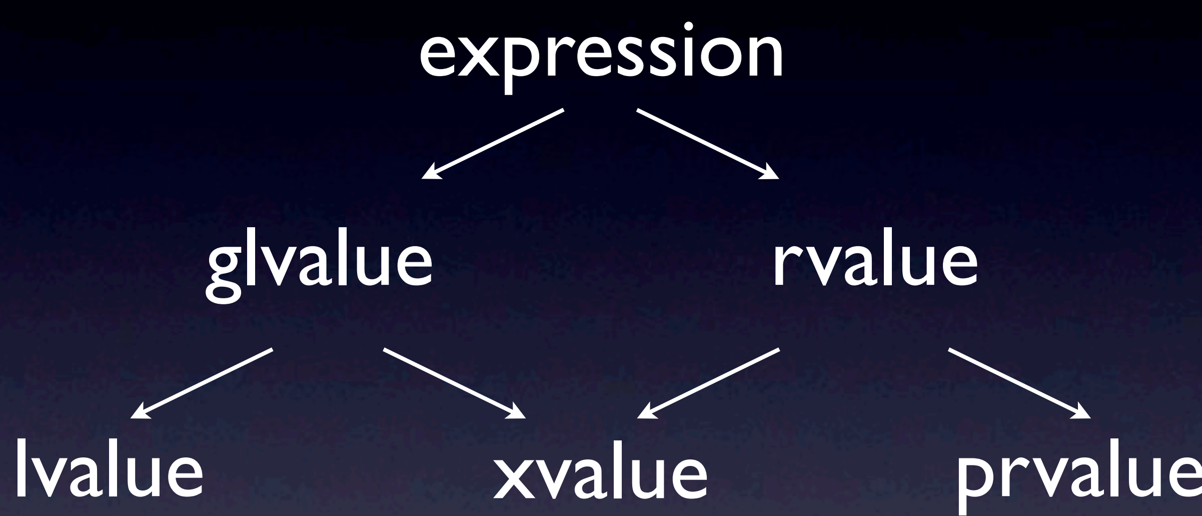


- A glvalue has a distinct address in memory.
  - I.e. it has an identity.

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);
```

Special case: Will bind to rvalue if const A&

Binding

Binds to lvalues and rvalues

Binds to lvalues

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

Special case: Will bind to rvalue if const A&

Binding

Binds to lvalues and rvalues

Binds to lvalues

```
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.

Outline

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

Outline

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

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)
{
  // 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.

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.

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
public:
    A(const A& a);       // copy constructor




};
```

- 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

```
A make_A();

A a1;
A a2 = a1;                // Calls copy ctor
A a3 = make_A();          // Calls (or elides)
                          //       move ctor
A a4 = std::move(a1);     // Calls move ctor
```

The move constructor

```
A make_A();

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

The move constructor

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

The move constructor

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

};
struct A
{
    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

```
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

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


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

noexcept is extension

deprecated

- Comments indicate compiler supplied definitions.

Implicit Special Members

```
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

noexcept is extension

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

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

- 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_;

};
```

Advice

- 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, "");
```

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!
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, "");
```

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

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




};
```

- 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;
}
```

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

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

```
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;
}
```

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

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

```
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;
}
```

```
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);
```

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

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.

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.

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.

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.