Writing good std::future<C++>

Anton Bikineev, 2016

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C++17 Standardization process. What we wanted and expected…

- concepts
- ranges
- modules
- parallel algorithms
- *.then* on futures and other concurrency features
- executors
- coroutines with *await*
- transactional memory
- contracts
- fold expressions
- uniform function call syntax
- constexpr lambdas
- filesystem library
- networking library
- library features, e.g. *any*, *optional*, etc…
- etc…

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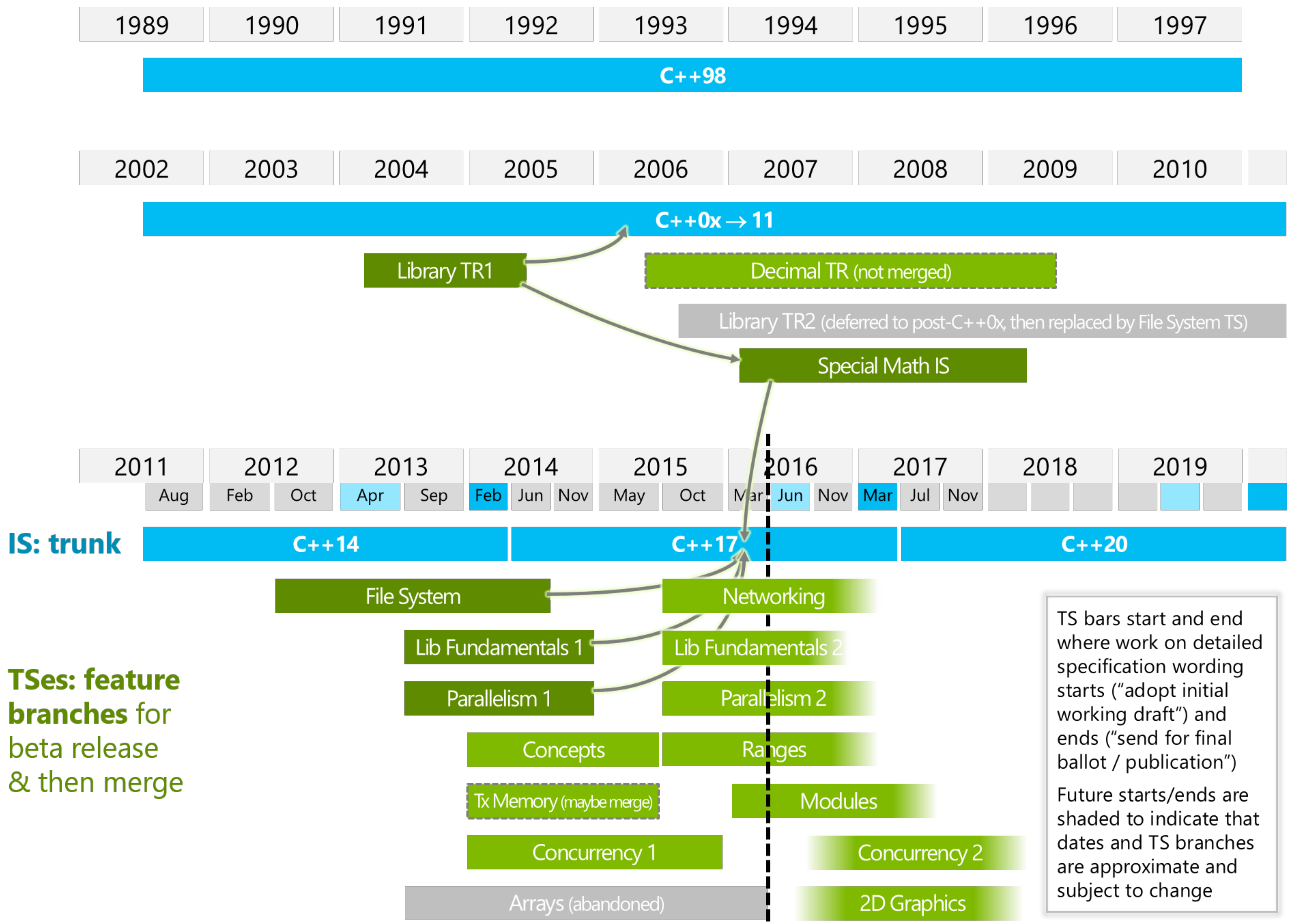
- library features, e.g. *any*, *optional*, etc…
- etc…

Kenny Kerr @kennykerr 7 march
C++11 attempted too much. C++14 fixed that.
C++17 attempts too little. We need to fix that.


1989
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C++0x → 11
Library TR1
Decimal TR (not merged)
Library TR2 (deferred to post-C++0x, then replaced by File System TS)
Special Math IS
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IS: trunk
C++14
C++17
C++20
File System
Networking
Lib Fundamentals 1
Lib Fundamentals 2
Parallelism 1
Parallelism 2
Concepts
Ranges
Tx Memory (maybe merge)
Modules
Concurrency 1
Concurrency 2
Arrays (abandoned)
2D Graphics
TSes: feature branches for beta release & then merge
TS bars start and end where work on detailed specification wording starts ("adopt initial working draft") and ends ("send for final ballot / publication")
Future starts/ends are shaded to indicate that dates and TS branches are approximate and subject to change

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C++’s view on polymorphism

C++'s view on polymorphism

```
class Factory
{
public:
    virtual AbstractButton* createButton() = 0;
};
```

C++’s view on polymorphism

```
class Factory
{
public:
    virtual std::unique_ptr<AbstractButton> createButton() = 0;
};
```

C++'s view on polymorphism

```
class Factory
{
public:
    virtual std::unique_ptr<AbstractButton> createButton() = 0;
};


// use of polymorphic code
void createForm(Factory* factory)
{
    auto button = factory->createButton();
}
```

C++'s view on polymorphism

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void createForm(Factory* factory)
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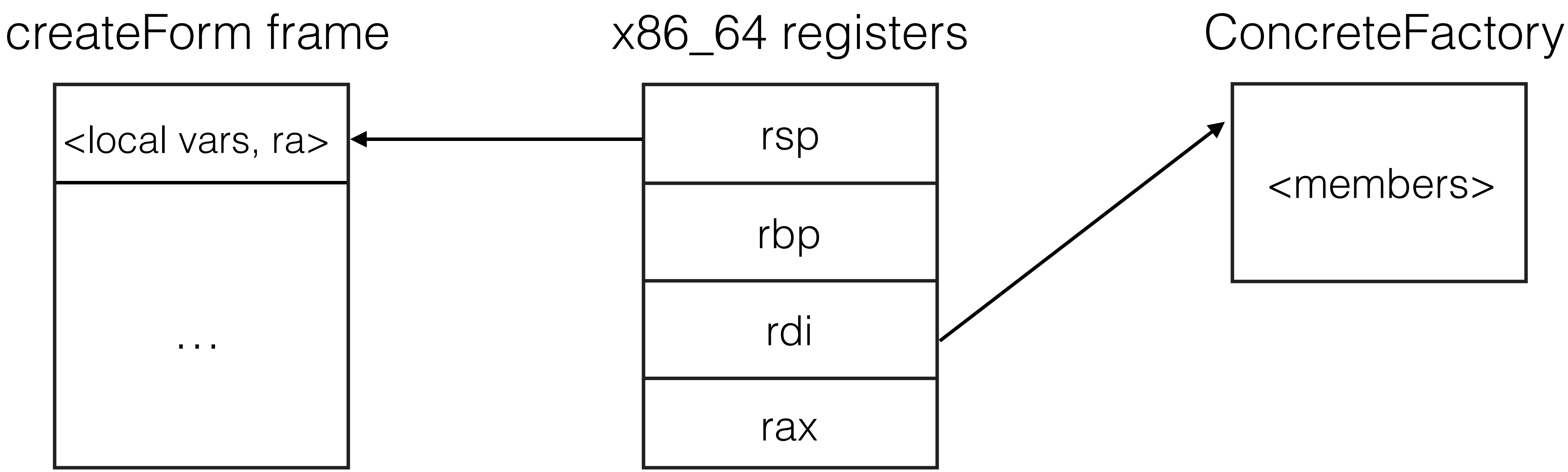
}
```

C++’s view on polymorphism

```
// use of polymorphic code
void createForm(Factory* factory)
{
    auto button = factory->createButton();
}
```

```
__Z10createFormP7Factory:
LFB2560:
    pushq   %rbp
LCFI0:
    movq    %rsp, %rbp
LCFI1:
    subq    $32, %rsp
    movq    %rdi, -24(%rbp)
    movq    -24(%rbp), %rax
    movq    (%rax), %rax
    addq    $8, %rax
    movq    (%rax), %rax
    leaq    -16(%rbp), %rdx
    movq    -24(%rbp), %rcx
    movq    %rcx, %rsi
    movq    %rdx, %rdi
    call    *%rax
    leaq    -16(%rbp), %rax
    movq    %rax, %rdi
    call    __ZNSt10unique_ptrI14AbstractButtonSt14default_deleteIS0_EED1Ev
    nop
    leave
LCFI2:
    ret
```

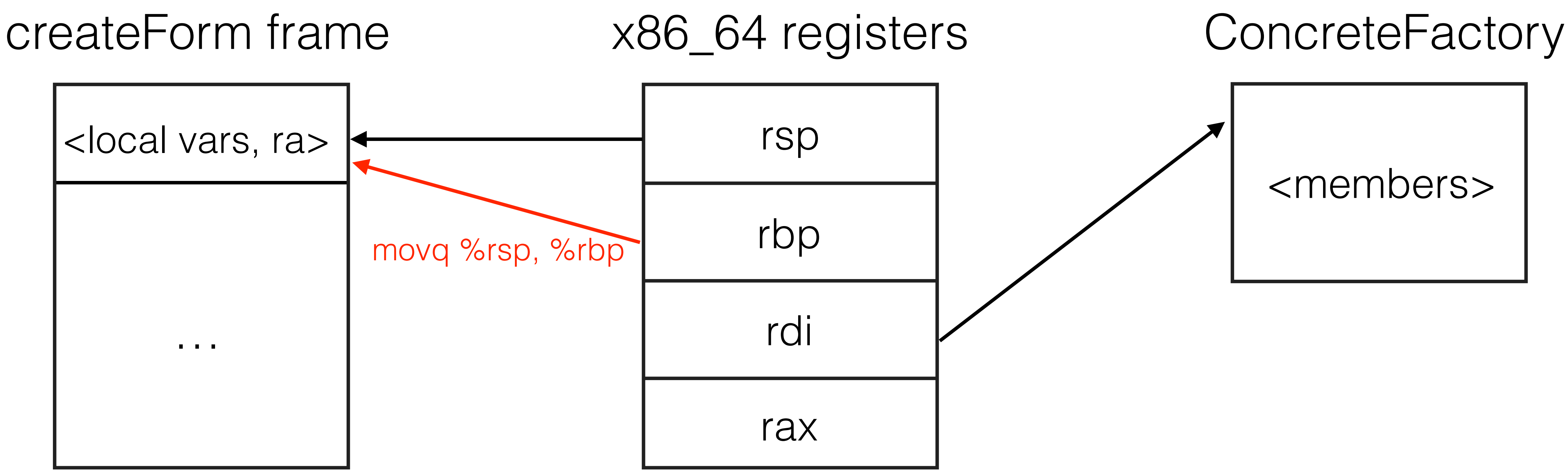
Dynamic polymorphism



the function itself

```
__ZN15ConcreteFactory12createButtonEv:
    pushq   %rbp
    ... ; some asm instrs
```

Dynamic polymorphism



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__ZN15ConcreteFactory12createButtonEv:
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    ... ; some asm instrs
```


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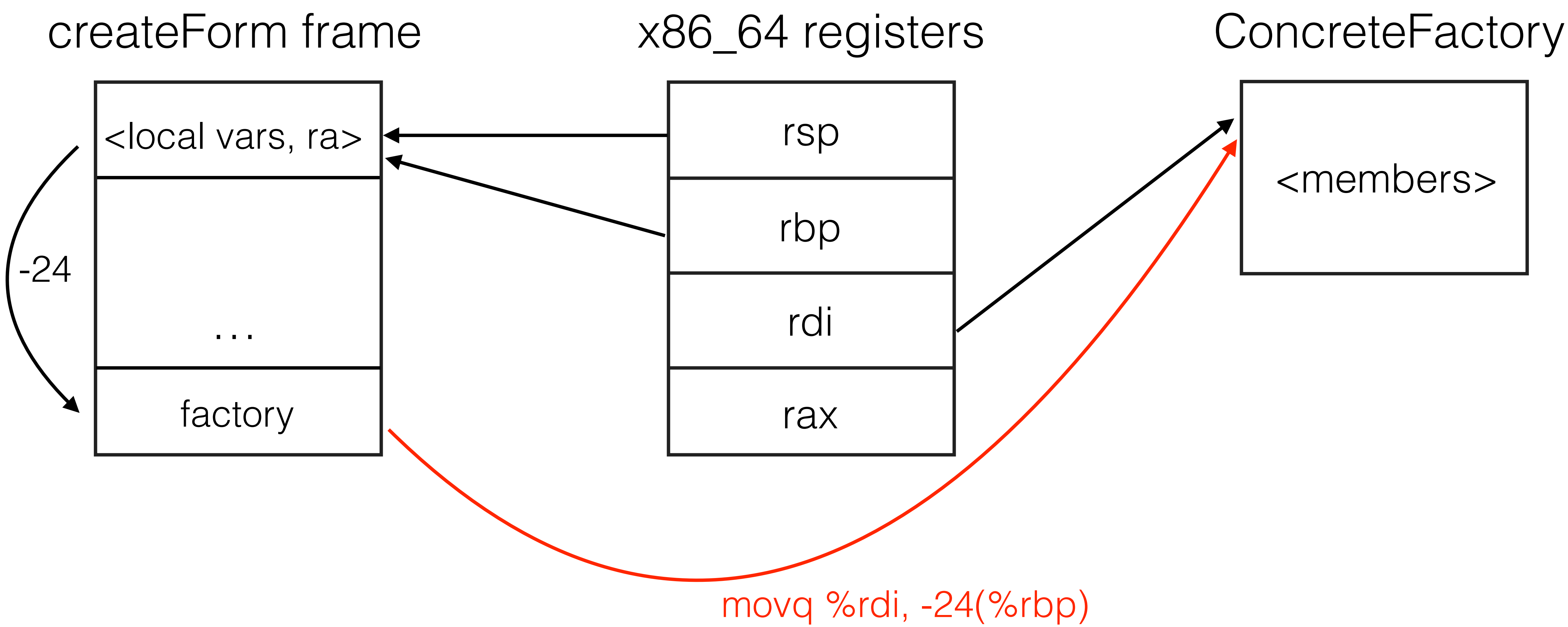
Dynamic polymorphism



the function itself

```
__ZN15ConcreteFactory12createButtonEv:
    pushq   %rbp
    ... ; some asm instrs
```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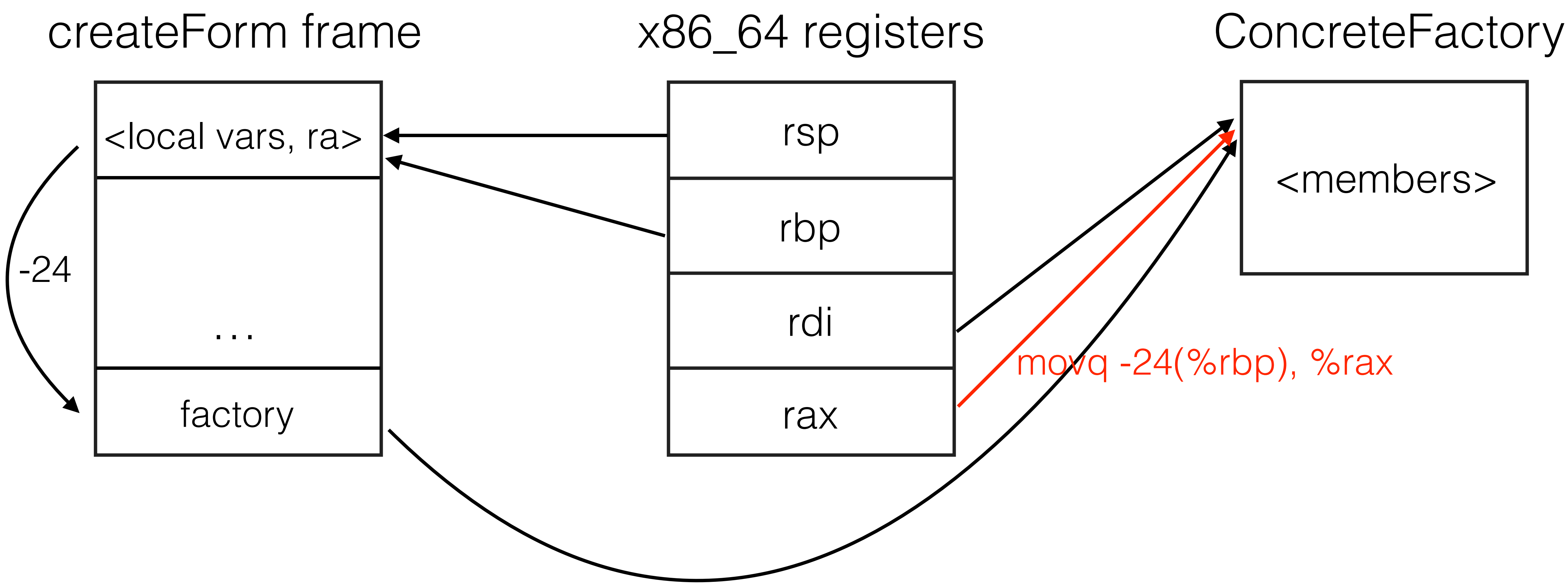
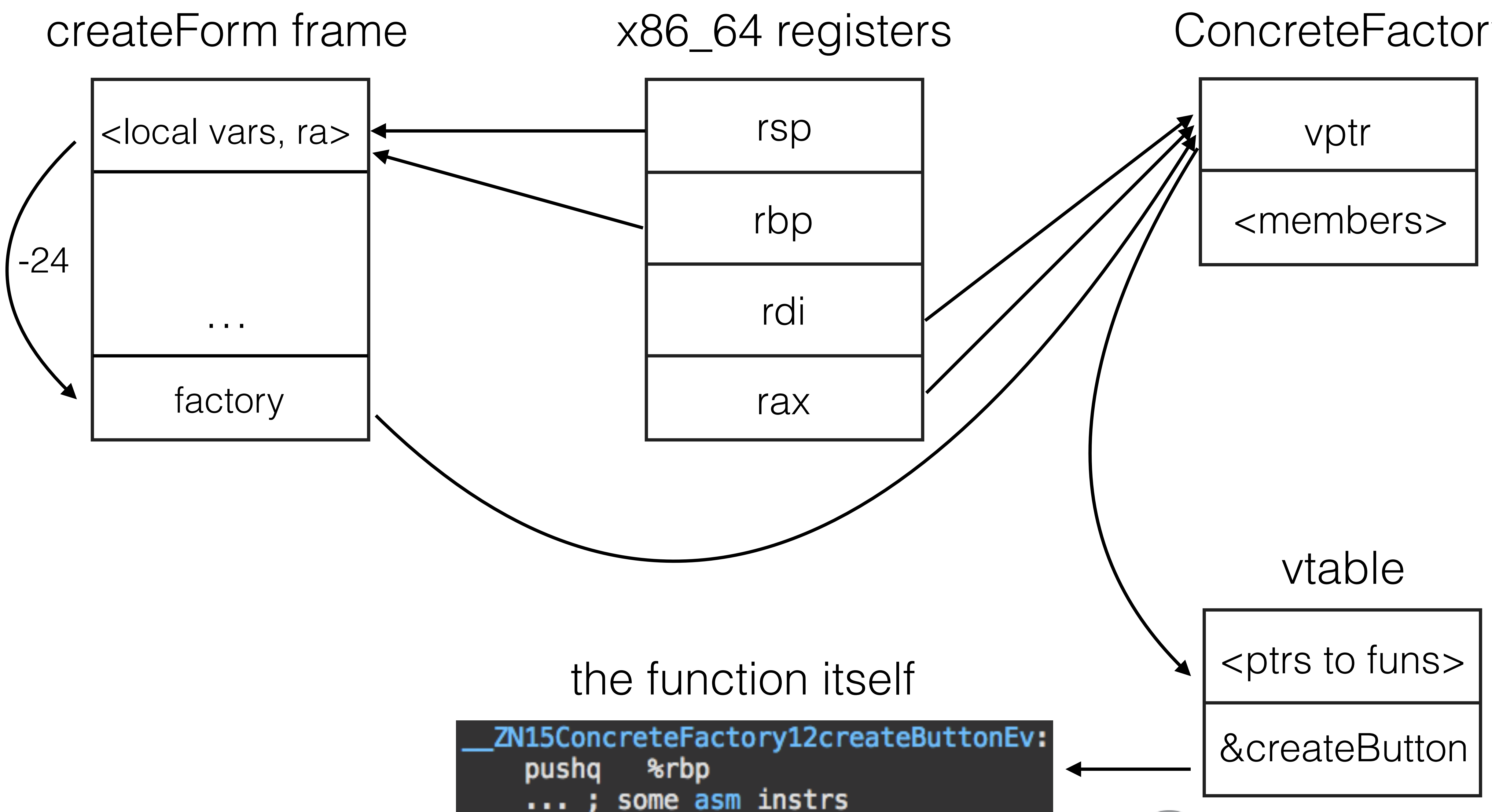
Dynamic polymorphism



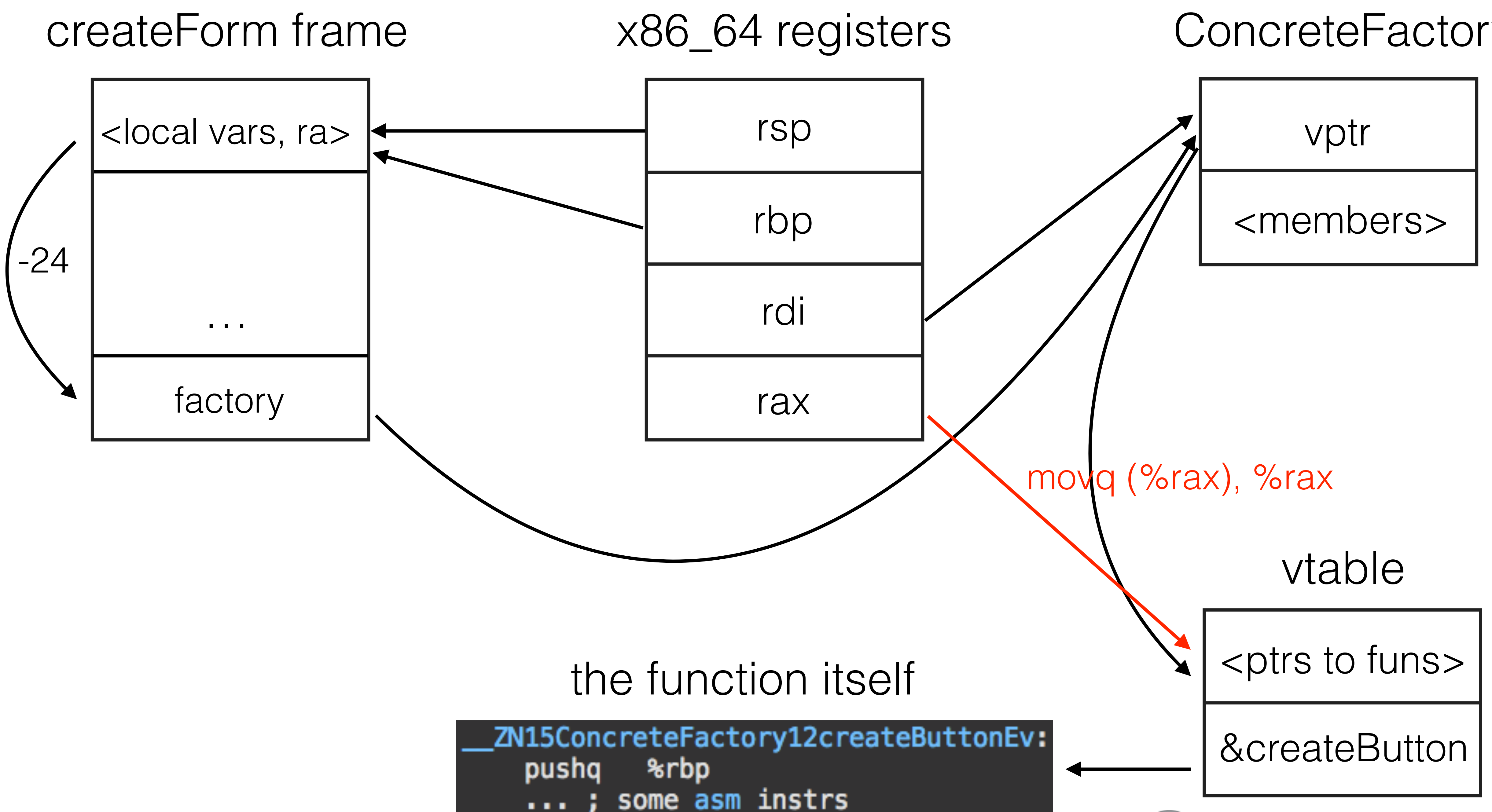
the function itself

```
__ZN15ConcreteFactory12createButtonEv:
    pushq   %rbp
    ... ; some asm instrs
```

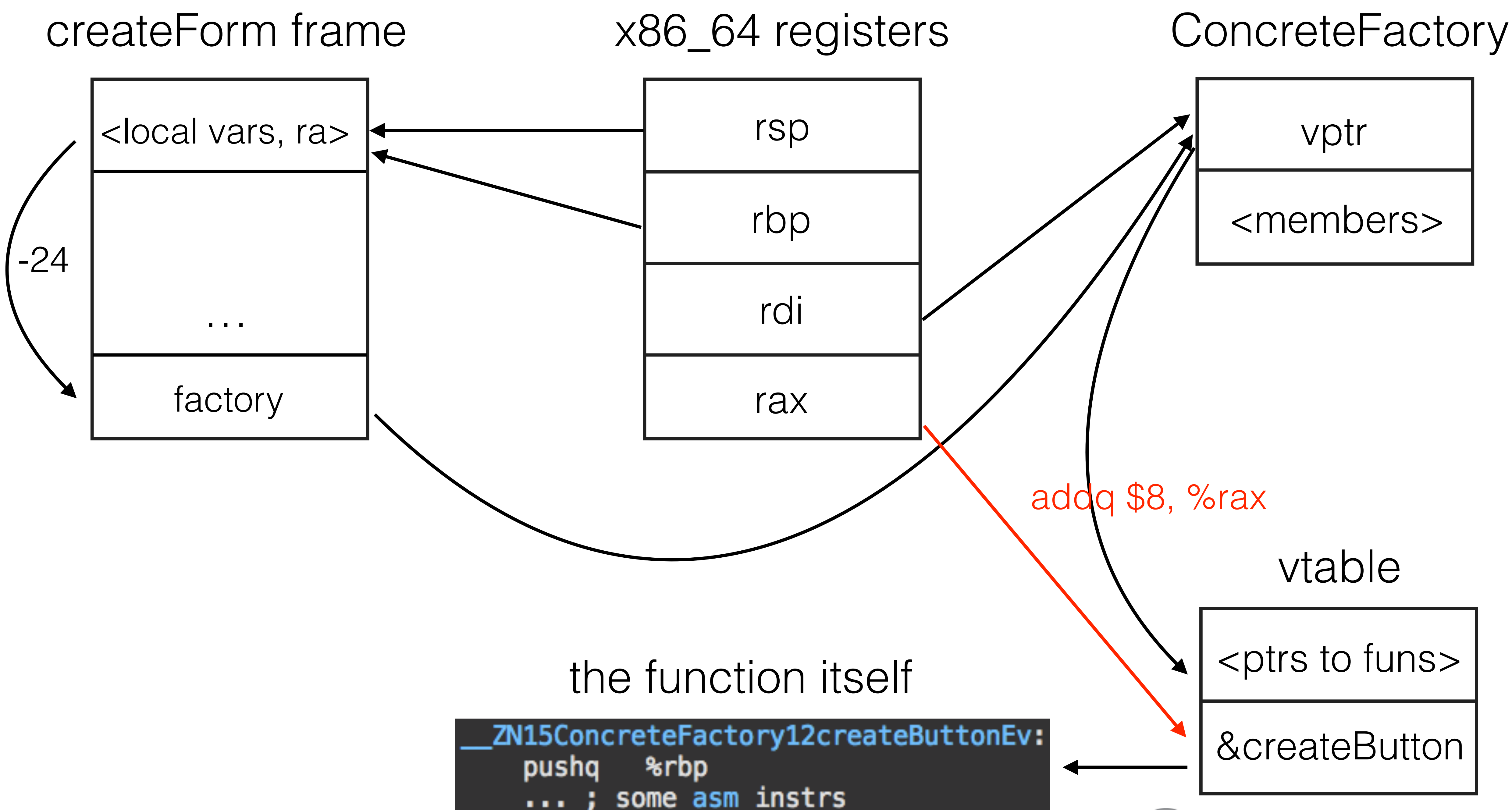
Dynamic polymorphism



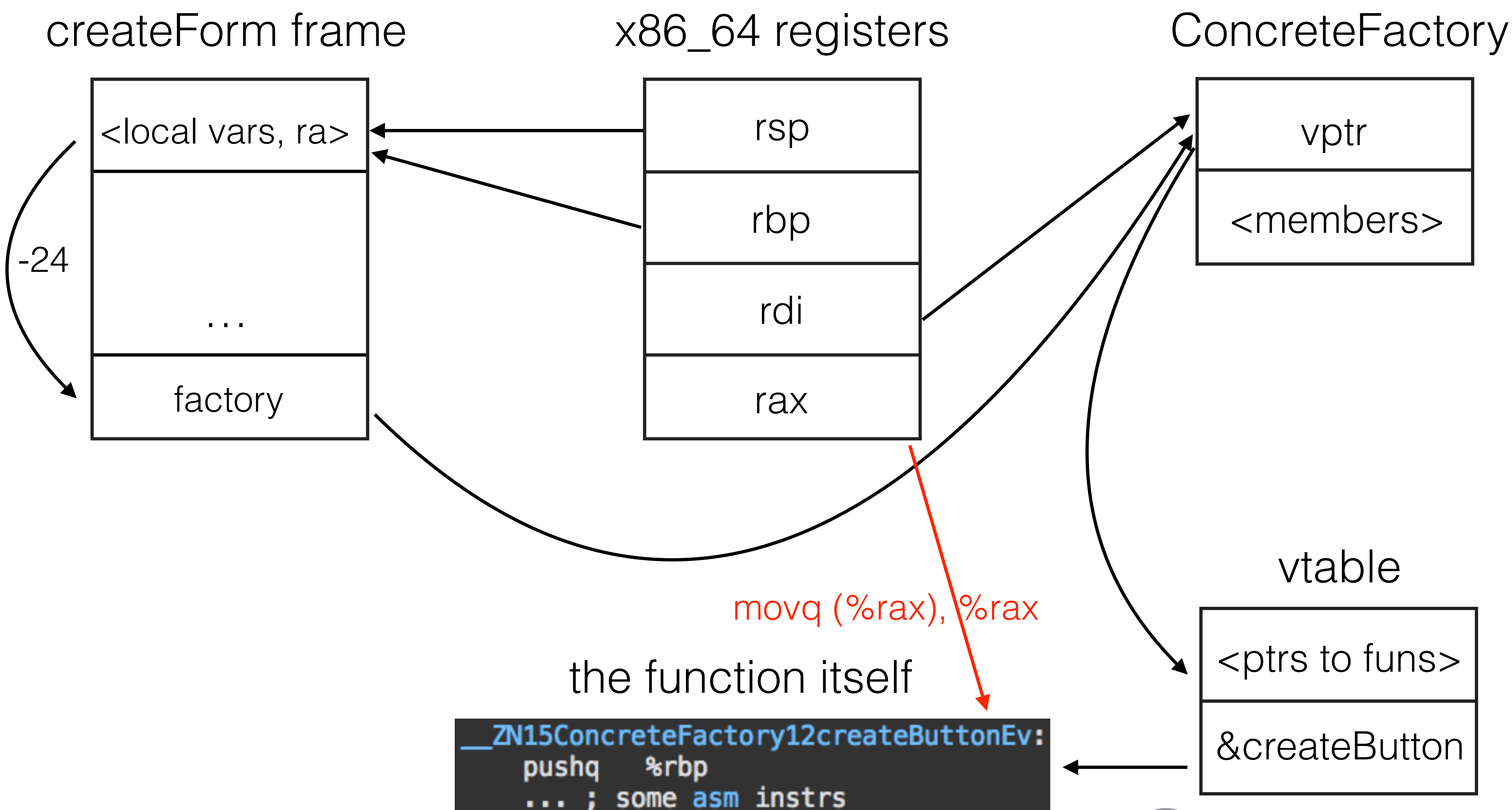
Dynamic polymorphism



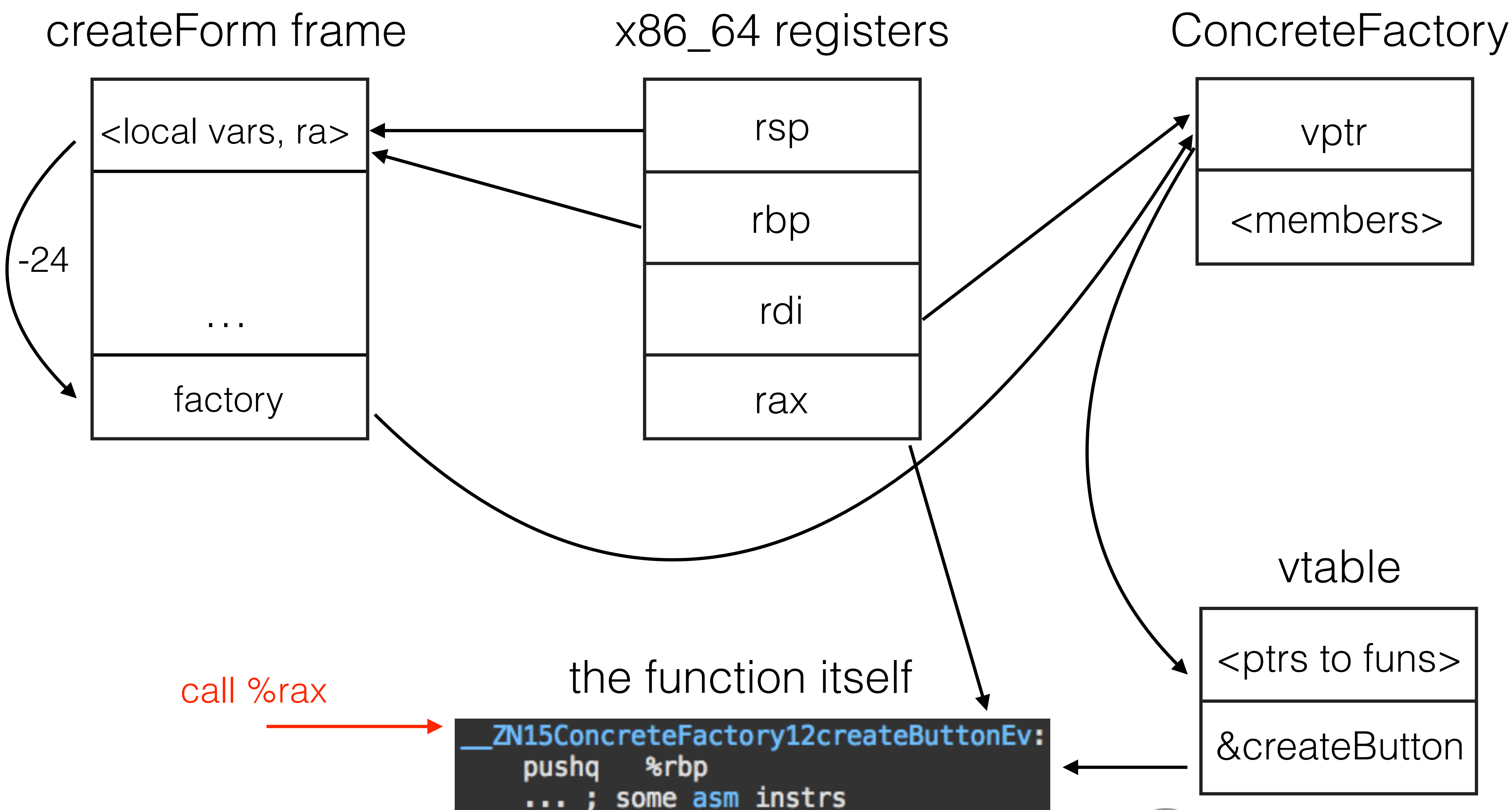
Dynamic polymorphism



Dynamic polymorphism



Dynamic polymorphism



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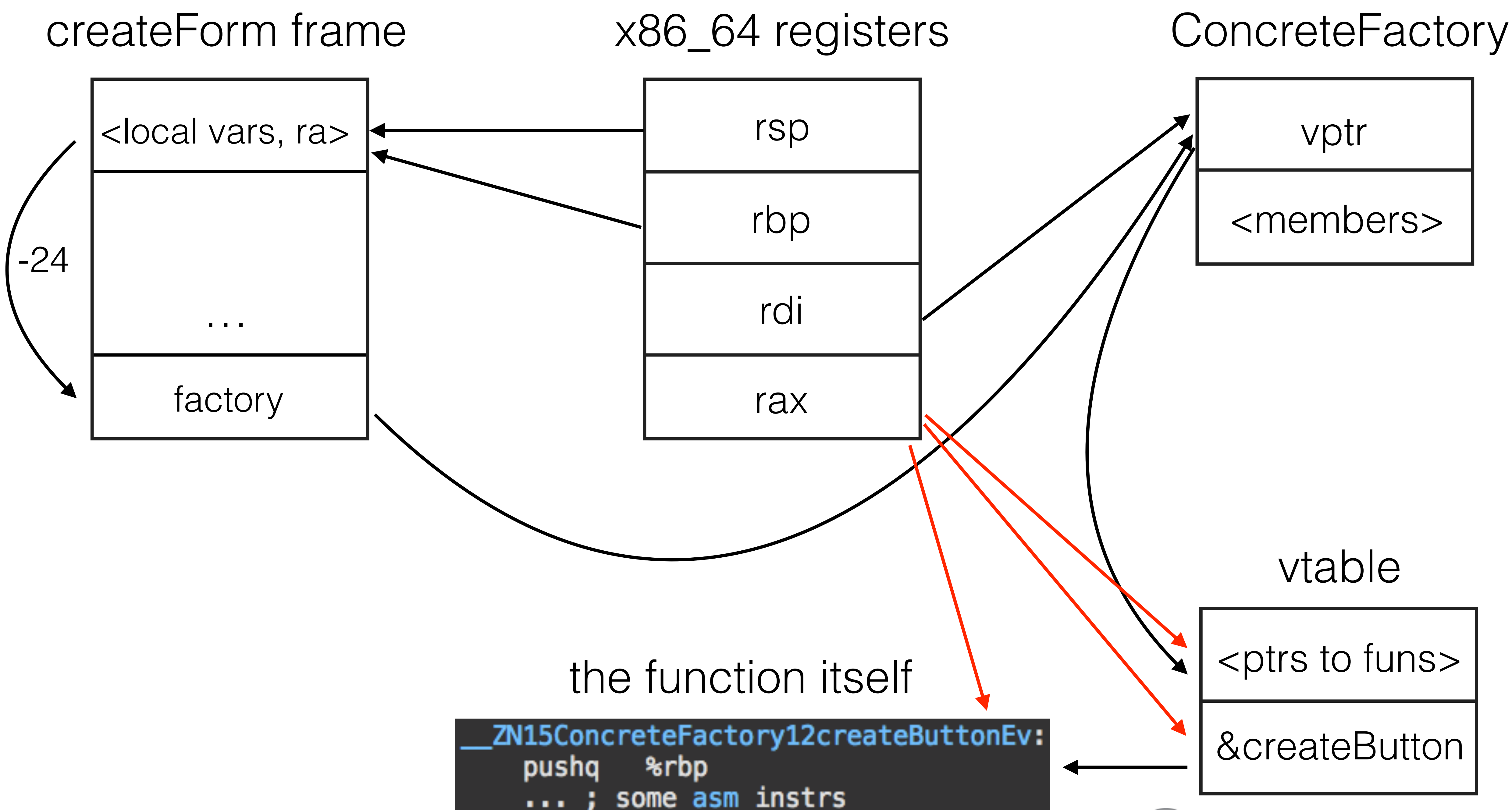
Dynamic polymorphism overhead



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C++ templates — solution?

```
template <class Factory>
void createForm(Factory& factory)
{
    auto button = factory.createButton();
}
```

C++ templates — solution?

```cpp
template <class Factory>
void createForm(Factory& factory)
{
    auto button = factory.createButton();
}

template void createForm(ConcreteFactory&);
```

```asm
__Z10createFormI15ConcreteFactoryEvRT_:
LFB2819:
    pushq   %rbp
LCFI27:
    movq    %rsp, %rbp
LCFI28:
    subq    $48, %rsp
    movq    %rdi, -40(%rbp)
    leaq    -16(%rbp), %rax
    movq    -40(%rbp), %rdx
    movq    %rdx, %rsi
    movq    %rax, %rdi
    call    __ZN15ConcreteFactory12createButtonEv
```

C++ static interface. CRTP

```
template <class Impl>
struct Factory
{
    std::unique_ptr<AbstractButton> createButton()
    {
        return static_cast<Impl*>(this)->createButton();
    }
};
```

C++ static interface. CRTP

```cpp
template <class Impl>
struct Factory
{
    std::unique_ptr<AbstractButton> createButton()
    {
        return static_cast<Impl*>(this)->createButton();
    }
};

struct ConcreteFactory: Factory<ConcreteFactory>
{
    std::unique_ptr<AbstractButton> createButton()
    {
        return std::make_unique<ConcreteButton>();
    }
};
```

C++ static interface. Usage

```
template <class Impl>
void createForm(Factory<Impl>& fact)
{
    auto button = fact.createButton();
}

template void createForm(Factory<ConcreteFactory>&);
```

```
__Z10createFormI15ConcreteFactoryEvR7FactoryIT_E:
LFB2820:
    pushq   %rbp
LCFI27:
    movq    %rsp, %rbp
LCFI28:
    subq    $48, %rsp
    movq    %rdi, -40(%rbp)
    leaq    -16(%rbp), %rax
    movq    -40(%rbp), %rdx
    movq    %rdx, %rsi
    movq    %rax, %rdi
    call    __ZN15ConcreteFactory12createButtonEv
```

CRTP problems

- looks like a hack;
- no possibility to get nested types from Impl;
- Impl is incomplete at point of instantiation.

Concepts — solution?

```
template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> std::unique_ptr<AbstractButton>;
    };
```

Concepts — solution?

```
template <class T>
concept bool factory = requires (T t)
   {
      {t.createButton()} -> std::unique_ptr<AbstractButton>;
   };

template <class T>
   requires factory<T>
void createForm(T& fact)
{
   auto button = fact.createButton();
}
```

Concepts — solution?

```
template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> std::unique_ptr<AbstractButton>;
    };

template <factory T>
void createForm(T& fact)
{
    auto button = fact.createButton();
}
```

Concepts — solution?

```
template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> std::unique_ptr<AbstractButton>;
    };

factory{T}
void createForm(T& fact)
{
    auto button = fact.createButton();
}
```

Concepts — solution?

```
template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> std::unique_ptr<AbstractButton>;
    };

void createForm(factory& fact)
{
    auto button = fact.createButton();
}
```

Defining concepts

```
template <class T>
concept bool variable_concept = constraint-expression;


template <class T>
concept bool function_concept()
{
    return constraint-expression;
}
```

Defining concepts. Type traits

```
template <class T>
concept bool integral = std::is_integral<T>::value;
```

Defining concepts. Type traits

```
template <class T>
concept bool integral = std::is_integral<T>()();
```

Defining concepts. Type traits

```
// from library fundamentals TS
namespace std::experimental
{
    template <class T>
    constexpr bool is_integral_v = is_integral<T>::value;
}


namespace stde = std::experimental;

template <class T>
concept bool integral = stde::is_integral_v<V>;
```


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Concepts. Iterator example

Table 112 — Relations among iterator categories

Random Access	$\rightarrow$ **Bidirectional**	$\rightarrow$ **Forward**	$\rightarrow$ **Input**
			$\rightarrow$ **Output**

Concepts. Iterator example

A type `X` satisfies the `Iterator` requirements if:

- `X` satisfies the `CopyConstructible`, `CopyAssignable`, and `Destructible` requirements (17.6.3.1) and lvalues of type `X` are swappable (17.6.3.2), and
- the expressions in Table 113 are valid and have the indicated semantics.

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition
`*r`	unspecified		pre: `r` is dereferenceable.
`++r`	`X&`		

```
template <class T>
concept bool iterator = ...;
```

Concepts. Iterator example

```
template <class T>
concept bool swappable = requires (T t)
    {
        {std::swap(t, t)} -> void;
    }
    or requires (T t)
    {
        // for ADL
        {swap(t, t)} -> void;
    };
```

Concepts. Iterator example

```
template <class T>
concept bool iterator = stde::is_copy_constructible_v<T>
    and stde::is_copy_assignable_v<T>
    and stde::is_destructible_v<T>
    and swappable<T>
    and requires (T r)
    {
        *r;
        {++r} -> T&;
    };
```

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition
`*r`	unspecified		pre: `r` is dereferenceable.
`++r`	`X&`		

Concepts. Input iterator

```
template <class T>
concept bool equality_comparable = requires (T t)
    {
        {t == t} -> bool;
    };

template <class T>
concept bool input_iterator = iterator<T>
    and equality_comparable<T>;
```

Concepts. Forward iterator

A class or pointer type `X` satisfies the requirements of a forward iterator if

- `X` satisfies the requirements of an input iterator (24.2.3),
- X satisfies the `DefaultConstructible` requirements (17.6.3.1),
- if `X` is a mutable iterator, `reference` is a reference to `T`; if `X` is a const iterator, `reference` is a reference to `const T`,
- the expressions in Table 116 are valid and have the indicated semantics, and
- objects of type `X` offer the multi-pass guarantee, described below.

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition
`r++`	convertible to `const X&`	`{ X tmp = r; ++r; return tmp; }`	

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Concepts. Forward iterator

```
template <class T>
concept bool forward_iterator = input_iterator<T>
    and stde::is_default_constructible_v<T>
    and requires (T r)
    {
        {r++} -> const T&;
    };
```

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition

`r++`	convertible to `const X&`	`{ X tmp = r;`
		`++r;`
		`return tmp; }`	

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Concepts. Bidirectional iterator

```
template <class T>
concept bool bidirectional_iterator = forward_iterator<T>
    and requires (T r)
    {
        {--r} -> T&
        {r--} -> const T&;
    };
```

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition
`--r`	`X&`		pre: there exists `s` such that `r == ++s`. post: `r` is dereferenceable. `--(++r) == r`. `--r == --s` implies `r == s`. `&r == &--r`.

`r--`	convertible to `const X&`	`{ X tmp = r;`
		`--r;`
		`return tmp; }`	

Concepts. Random access iterator

Expression	Return type	Operational semantics	Assertion/note pre-/post-condition

`r += n`	`X&`	`{ difference_type m = n;`
		`if (m >= 0)`
		`while (m--)`
		`++r;`
		`else`
		`while (m++)`
		`--r;`
		`return r; }`	

`a + n` `n + a`	`X`	`{ X tmp = a;` `return tmp += n; }`	`a + n == n + a`.
`r -= n`	`X&`	`return r += -n;`	
`a - n`	`X`	`{ X tmp = a;` `return tmp -= n; }`	
`b - a`	`difference_-` `type`	`return n`	pre: there exists a value `n` of type `difference_type` such that `a + n == b`. `b == a + (b - a)`.
`a[n]`	convertible to `reference`	`*(a + n)`	
`a < b`	contextually convertible to `bool`	`b - a > 0`	`<` is a total ordering relation
`a > b`	contextually convertible to `bool`	`b < a`	`>` is a total ordering relation opposite to `<`.
`a >= b`	contextually convertible to `bool`	`!(a < b)`	
`a <= b`	contextually convertible to `bool`.	`!(a > b)`	

Concepts. Random access iterator

```
template <class T>
concept bool random_access_iterator = bidirectional_iterator<T>
    and requires (T it,
            typename std::iterator_traits<T>::difference_type n)
    {
        {it += n} -> T&;
        {it + n} -> T;
        {n + it} -> T;
        {it -= n} -> T&;
        {it - it} ->
            typename std::iterator_traits<T>::difference_type;
        {it[n]} ->
            typename std::iterator_traits<T>::reference;
        {it < it} -> bool;
        {it <= it} -> bool;
        {it > it} -> bool;
        {it >= it} -> bool;
    };
```

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Concepts. Iterators. Let's test!

```
static_assert(forward_iterator<
    std::forward_list<int>::iterator>);
```

Concepts. Iterators. Let's test!

```
static_assert(forward_iterator<
    std::forward_list<int>::iterator>);

static_assert(bidirectional_iterator<
    std::list<int>::iterator>);
static_assert(bidirectional_iterator<
    std::map<char, int>::iterator>);
```

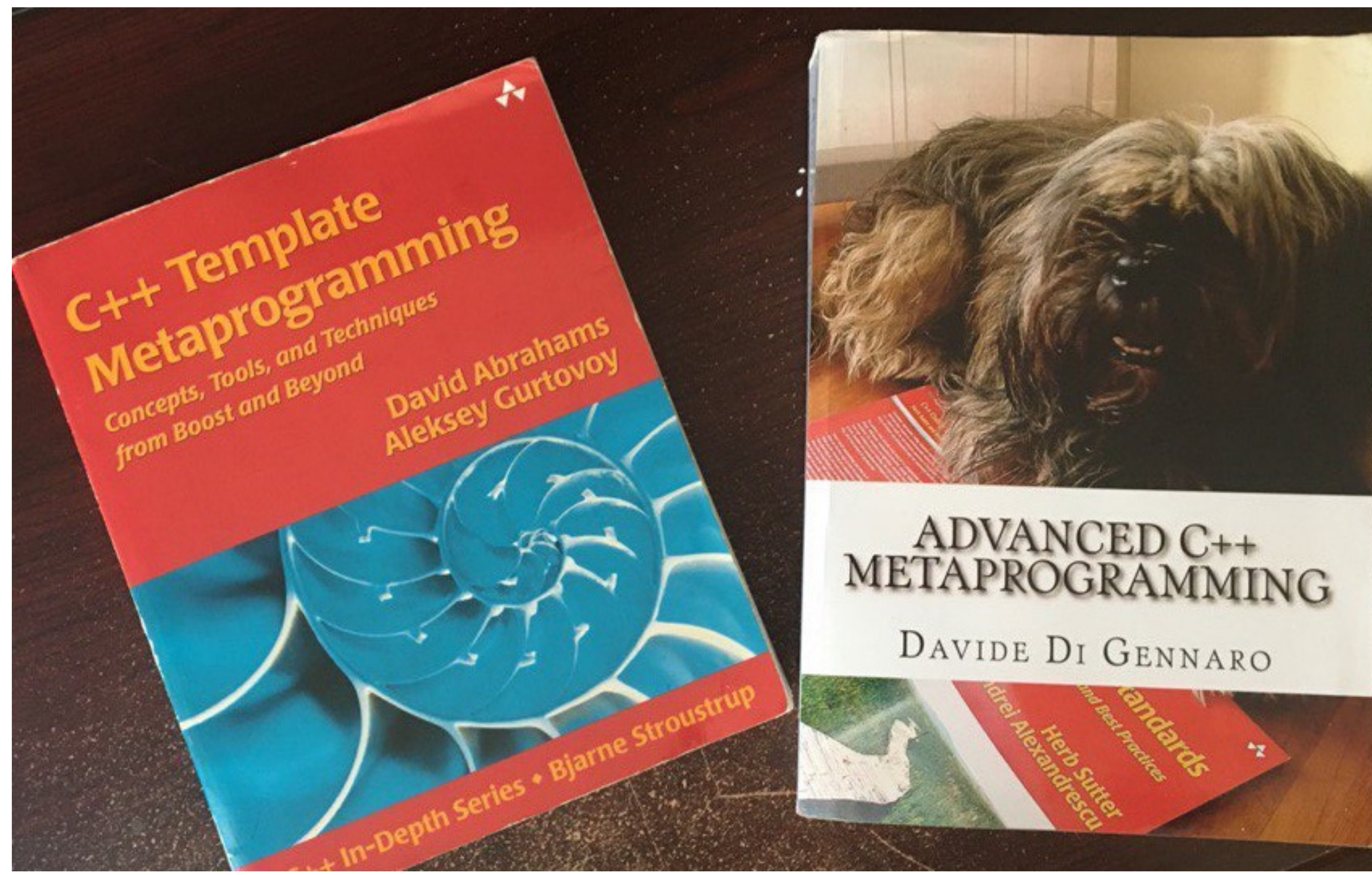
Concepts. Iterators. Let's test!

```
static_assert(forward_iterator<
    std::forward_list<int>::iterator>);

static_assert(bidirectional_iterator<
    std::list<int>::iterator>);
static_assert(bidirectional_iterator<
    std::map<char, int>::iterator>);

static_assert(random_access_iterator<int*>);
static_assert(random_access_iterator<
    std::vector<int>::iterator>);
static_assert(random_access_iterator<
    std::deque<int>::iterator>);
```

C++ generic programming and TMP



Without concepts: libc++

```
template <class _InputIterator>
    vector(_InputIterator __first,
        typename enable_if<
            __is_input_iterator<_InputIterator>::value &&
            !__is_forward_iterator<_InputIterator>::value &&
                is_constructible<
                    value_type,
                    typename iterator_traits<
                        _InputIterator>::reference>::value,
                _InputIterator>::type __last);
template <class _ForwardIterator>
    vector(_ForwardIterator __first,
        typename enable_if<
            __is_forward_iterator<_ForwardIterator>::value &&
            is_constructible<
                value_type,
                typename iterator_traits<
                    _ForwardIterator>::reference>::value,
            _ForwardIterator>::type __last);
```

With concepts: libc++

```
vector(input_iterator __first, input_iterator __last);
vector(forward_iterator __first, forward_iterator __last);
```

That's it!

The greediness of T&&

The greediness of T&&

```
// from Meyers's EMC++ Item 26
std::multiset<std::string> names;

void logAndAdd(const std::string& name)
{
    auto now = std::chrono::system_clock::now();

    log(now, "logAndAdd");
    names.emplace(name);
}
```

The greediness of T&&

```
// from Meyers's EMC++ Item 26
std::multiset<std::string> names;

void logAndAdd(const std::string& name)
{
    auto now = std::chrono::system_clock::now();

    log(now, "logAndAdd");
    names.emplace(name);
}

std::string petName("Darla");
logAndAdd(petName); // 1)
logAndAdd(std::string("Persephone")); // 2)
logAndAdd("Patty Dog"); // 3)
```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The greediness of T&&

```
// from Meyers’s EMC++ Item 26
std::multiset<std::string> names;

void logAndAdd(const std::string& name)
{
    auto now = std::chrono::system_clock::now();

    log(now, "logAndAdd");
    names.emplace(name);
}

std::string petName("Darla");
logAndAdd(petName); // 1) okay, just copying
logAndAdd(std::string("Persephone")); // 2) extra copy
logAndAdd("Patty Dog”); // 3) no need to copy or move
```

The greediness of T&&

```
// from Meyers's EMC++ Item 26
template <typename T>
void logAndAdd(T&& name)
{
    auto now = std::chrono::system_clock::now();

    log(now, "logAndAdd");
    names.emplace(std::forward<T>(name));
}


std::string petName("Darla");
logAndAdd(petName); // 1) okay, just copying
logAndAdd(std::string("Persephone")); // 2) moving!
logAndAdd("Patty Dog"); // 3) neither moving nor copying,
                        //    just creating inplace
```

The greediness of T&&

```
// from Meyers's EMC++ Item 26
std::string nameFromIdx(int idx);

void logAndAdd(int idx)
{
    auto now = std::chrono::system_clock::now();

    log(now, "logAndAdd");
    names.emplace(nameFromIdx(idx));
}

short nameIdx;
logAndAdd(nameIdx); // error!
```

The greediness of T&&

Meyers, “Effective Modern C++”,
Item 26:
Avoid overloading on universal references.

The greediness of T&&

Meyers, “Effective Modern C++”,
Item 26:
Avoid overloading on universal references.

...

The greediness of T&&

Meyers, “Effective Modern C++”,
Item 26:
Avoid overloading on universal references.

...

but not on constrained universal references!

Constrained T&&
as the best parameter type for efficiency and safety

```
void logAndAdd(int idx);

template <typename T>
void logAndAdd(T&& name)
{
    ...
    names.emplace(std::forward<T>(name));
}
```

Constrained T&&
as the best parameter type for efficiency and safety

```
void logAndAdd(int idx);

template <typename T, typename =
    std::enable_if_t<
        stde::is_convertible_v<
            T, std::string>>>
void logAndAdd(T&& name)
{
    ...
    names.emplace(std::forward<T>(name));
}
```

Constrained T&&
as the best parameter type for efficiency and safety

```
void logAndAdd(int idx);

template <typename T, typename =
    std::enable_if_t<
        stde::is_convertible_v<
            std::remove_reference_t<T>, std::string>>>
void logAndAdd(T&& name)
{
    ...
    names.emplace(std::forward<T>(name));
}
```

Constrained T&&
as the best parameter type for efficiency and safety

```
void logAndAdd(int idx);

template <typename T, typename =
    std::enable_if_t<
        stde::is_convertible_v<
            std::remove_reference_t<T>, std::string>>>
void logAndAdd(T&& name)
{
    ...
    names.emplace(std::forward<T>(name));
}


short nameIdx;
logAndAdd(nameIdx); // calls logAndAdd(int) just fine!
```

Constrained T&&
as the best parameter type for efficiency and safety

```
template <class From, class To>
concept bool convertible =
    stde::is_convertible_v<
        std::remove_reference_t<From>, To>;
```

Constrained T&&
as the best parameter type for efficiency and safety

```
template <class From, class To>
concept bool convertible =
    stde::is_convertible_v<
        std::remove_reference_t<From>, To>;


void logAndAdd(convertible<std::string>&& name)
{
    ...
    names.emplace(std::forward<decltype(name)>(name));
}


short nameIdx;
logAndAdd(nameIdx); // calls logAndAdd(int) just fine!
```

Constrained T&&
as the best parameter type for efficiency and safety

```
// from Meyers's EMC++ Item 26
class Person {
public:
    template <typename T>
    explicit Person(T&& n)  // perfect forwarding ctor
    : name(std::forward<T>(n)) {}

    explicit Person(int idx)
    : name(nameFromIdx(idx)) {}

private:
    std::string name;
};
```

Constrained T&&
as the best parameter type for efficiency and safety

```
// from Meyers's EMC++ Item 26
class Person {
public:
    template <typename T>
    explicit Person(T&& n)  // perfect forwarding ctor
    : name(std::forward<T>(n)) {}

    explicit Person(int idx)
    : name(nameFromIdx(idx)) {}

private:
    std::string name;
};

Person p("Nancy");
auto cloneOfP(p);  // WOW!
```

Constrained T&&
as the best parameter type for efficiency and safety

```
// from Meyers's EMC++ Item 26
class Person {
public:
    explicit Person(convertible<std::string>&& n)
    : name(std::forward<decltype(n)>(n)) {}

    explicit Person(int idx)
    : name(nameFromIdx(idx)) {}

private:
    std::string name;
};

Person p("Nancy");
auto cloneOfP(p);  // now works fine!
```

std::future<C++> example:

flat_map

C++17 example: boost::flat_map

```
namespace boost::container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class Allocator =
                  std::allocator<std::pair<Key, Value>>>
    class flat_map;
}
```

C++17 example: my flat_map

```
namespace mine::container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, Value>>>
    class flat_map;
}
```

C++17 example: my flat_map

```
namespace mine::container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, Value>>>
        requires default_constructible<Value>
    class flat_map;
}
```

C++17 example: my flat_map

```
namespace mine::container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, Value>>>
        requires default_constructible<Value>
              and random_access_iterator<
                  typename UnderlyingContainer::iterator>
    class flat_map;
}
```

C++17 example: my flat_map

```
namespace mine::container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, Value>>>
        requires default_constructible<Value>
            and random_access_iterator<
                typename UnderlyingContainer::iterator>
            and requires (Compare cmp, Key key)
            {
                {cmp(key, key)} -> bool;
            }
    class flat_map;
}
```


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flat_map: typedefs

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using key_type = Key;
    using mapped_type = Value;
    using underlying_type = UnderlyingContainer;

    using typename underlying_type::value_type;
    static_assert(stde::is_same_v<value_type,
            std::pair<key_type, mapped_type>>);

    using key_compare = Compare;
    using value_compare = struct {
        ...
    };

};
```

flat_map: typedefs

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using value_compare = struct {
        bool operator()(const value_type& left,
                        const value_type& right) const {
            return key_compare()(left.first, right.first);
        }
        bool operator()(const key_type& left,
                        const value_type& right) const {
            return key_compare()(left, right.first);
        }
        bool operator()(const value_type& left,
                        const key_type& right) const {
            return key_compare()(left.first, right);
        }};
};
```

flat_map: typedefs

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using typename underlying_type::size_type;
    using typename underlying_type::difference_type;
    using typename underlying_type::allocator_type;
    using typename underlying_type::reference;
    using typename underlying_type::const_reference;
    using typename underlying_type::pointer;
    using typename underlying_type::const_pointer;
    using typename underlying_type::iterator;
    using typename underlying_type::const_iterator;
    using typename underlying_type::reverse_iterator;
    using typename underlying_type::const_reverse_iterator;


};
```

flat_map: laconic wrapping

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using underlying_type::begin; // laconic wrapping
    using underlying_type::cbegin;
    using underlying_type::end;
    using underlying_type::cend;
    using underlying_type::rbegin;
    using underlying_type::crbegin;
    using underlying_type::rend;
    using underlying_type::crend;




};
```

flat_map: laconic wrapping

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using underlying_type::swap;
    using underlying_type::clear;
    using underlying_type::empty;
    using underlying_type::size;
    using underlying_type::max_size;
    using underlying_type::capacity;
    using underlying_type::reserve;
    using underlying_type::shrink_to_fit;



};
```

flat_map: ctors

```
template <...>
class flat_map final: private UnderlyingContainer
{
    flat_map() = default;

    template <class Iterator>
    flat_map(Iterator first, Iterator last):
        underlying_type{first, last}
    {
        std::sort(begin(), end());
    }

    flat_map(std::initializer_list<value_type> list):
        flat_map{list.begin(), list.end()}
    {
    }
};
```

flat_map: ctors

```
template <...>
class flat_map final: private UnderlyingContainer
{
    flat_map() = default;


    flat_map(input_iterator first, input_iterator last):
        underlying_type{first, last}
    {
        std::sort(begin(), end());
    }

    flat_map(std::initializer_list<value_type> list):
        flat_map{list.begin(), list.end()}
    {
    }
};
```

flat_map: ctors

```
template <...>
class flat_map final: private UnderlyingContainer
{
    flat_map() = default;


    flat_map(input_iterator first, input_iterator last):
        underlying_type{first, last}
    {
        stde::sort(stde::par, begin(), end());
    }

    flat_map(std::initializer_list<value_type> list):
        flat_map{list.begin(), list.end()}
    {
    }
};
```

flat_map: binary_search

```
namespace detail
{
    template <class Iterator, class Key, class Compare>
    Iterator binary_search(Iterator begin,
            Iterator end,
            const Key& key,
            const Compare& cmp)
    {
        auto it = std::lower_bound(begin, end, key, cmp);
        if (it == end || cmp(key, *it))
            return end;

        return it;
    }


}
```

flat_map: binary_search

```
namespace detail
{

    auto binary_search(forward_iterator begin,
            forward_iterator end,
            const auto& key,
            const auto& cmp)
    {
        auto it = std::lower_bound(begin, end, key, cmp);
        if (it == end || cmp(key, *it))
            return end;

        return it;
    }


}
```

flat_map: find

```
template <...>
class flat_map final: private UnderlyingContainer
{
    iterator find(const key_type& key)
    {
        return detail::binary_search(
            begin(), end(), key, value_compare{});
    }

    const_iterator find(const key_type& key) const
    {
        return detail::binary_search(
            cbegin(), cend(), key, value_compare{});
    }


};
```

flat_map: at

```
template <...>
class flat_map final: private UnderlyingContainer
{
    mapped_type& at(const key_type& key)
    {
        const auto it = find(key);
        if (it == end()) throw std::range_error("no key");

        return it->second;
    }

    const mapped_type& at(const key_type& key) const
    {
        // same as above
    }

};
```

flat_map: emplace

```
template <...>
class flat_map final: private UnderlyingContainer
{
    std::pair<iterator, bool> emplace(
            auto&& first, auto&&... args)
    {
        value_compare comp;
        const auto it = std::lower_bound(
            begin(), end(), first, comp);
        if (it == end() || comp(first, *it))
            return {underlying_type::emplace(it,
                       std::forward<decltype(first)>(first),
                       std::forward<decltype(args)>(args)...),
                    true};
        return {it, false};
    }
};
```

flat_map: insert

```
template <...>
class flat_map final: private UnderlyingContainer
{
    std::pair<iterator, bool> insert(const value_type& value)
    {
        return emplace(value);
    }









};
```


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flat_map: insert

```
template <...>
class flat_map final: private UnderlyingContainer
{
    std::pair<iterator, bool> insert(const value_type& value)
    {
        return emplace(value);
    }

    std::pair<iterator, bool> insert(value_type&& value)
    {
        return emplace(std::move(value));
    }



};
```


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flat_map: insert

```
template <...>
class flat_map final: private UnderlyingContainer
{
    std::pair<iterator, bool> insert(
        convertible<value_type>&& value)
    {
        return emplace(std::forward<decltype(value)>(value));
    }

    // no need to provide anything else!

};
```

flat_map: insert

```
template <...>
class flat_map final: private UnderlyingContainer
{
    void insert(input_iterator first,
                input_iterator last)
    {
        const auto count = std::distance(first, last);
        const auto room = capacity() - size();

        if (room < count)
            reserve(size() + count);

        for (; first != last; ++first)
            emplace(*first);
    }

};
```

flat_map: insert

```
template <...>
class flat_map final: private UnderlyingContainer
{
    void insert(std::initializer_list<value_type> list)
    {
        insert(list.begin(), list.end());
    }









};
```

flat_map: index operator

```
template <...>
class flat_map final: private UnderlyingContainer
{
    mapped_type& operator[](convertible<key_type>&& key)
    {
        return emplace(
                std::forward<decltype(key)>(key),
                mapped_type{}
            ).first->second;
    }




};
```

flat_map: erase

```
template <...>
class flat_map final: private UnderlyingContainer
{
    using underlying_type::erase;

    size_type erase(const key_type& key)
    {
        const auto it = find(key);
        if (it == end())
            return 0u;

        erase(it);
        return 1u;
    }


};
```

Modularizing flat_map. Interface

```
// flat_map.hpp
#include <...>



namespace container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, T>>>
    class flat_map
    {
        ...
    };
}
```

Modularizing flat_map. Interface

```
// flat_map.ixx
#include <...>

module container.flat_map;

export namespace container
{
    template <class Key, class Value,
              class Compare = std::less<Key>,
              class UnderlyingContainer =
                  std::vector<std::pair<Key, T>>>
    class flat_map
    {
        ...
    };
}
```


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Modularizing flat_map. Consuming

```
// main.cpp
import std.io;
import container.flat_map;

int main()
{
    container::flat_map<std::string, int> map =
        {{"second", 2}, {"first", 1}, {"third", 3}};

    for (const auto& p: map)
        std::cout << p.first << ": " << p.second << std::endl;

    return 0;
}
```

Some more slides…

Static polymorphism with concepts. Improving

```
template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> std::unique_ptr<AbstractButton>;
    };

void createForm(factory& fact)
{
    auto button = fact.createButton();
}
```

Static polymorphism with concepts. Improving

```
struct AbstractButton
{
    virtual void onClick(std::function<void ()>) = 0;
    virtual void onMove (std::function<void ()>) = 0;
};
```

Static polymorphism with concepts. Improving

```
namespace detail // or std? or whatever
{
    constexpr auto empty = [](auto...){};
}

template <class T>
concept bool button = requires (T t)
    {
        t.onClick(detail::empty);
        t.onMove(detail::empty);
    };
```

Static polymorphism with concepts. Improving

```
template <class T>
concept bool button = ...;

template <class T>
concept bool factory = requires (T t)
    {
        {t.createButton()} -> button;
    };
```

Static polymorphism with concepts. Improving

```
class TButton
{
   void onClick(...);
   void onMove(...);
};
```

```
class QPushButton
{
   void onClick(...);
   void onMove(...);
};
```

Static polymorphism with concepts. Improving

```
class TButton
{
    void onClick(...);
    void onMove(...);
};
```

```
class VCLFactory
{
    TButton createButton()
    {
        return TButton{};
    }
};
```

```
class QPushButton
{
    void onClick(...);
    void onMove(...);
};
```

```
class QtFactory
{
    QPushButton createButton()
    {
        return QPushButton{};
    }
};
```

Static polymorphism with concepts. Using

```
void createForm(factory& fact)
{
    auto button = fact.createButton();
    button.onClick([]{ /* pum pum pum */ });
}

int main()
{
    QtFactory factory;
    createForm(factory);

    QApplication::run();
}
```

Thank you for your attention!