Abstract

We propose the addition of two new class templates to the C++ Standard Library: `indirect<T>` and `polymorphic<T>`.

These class templates have value semantics and compose well with other standard library types (such as vector) allowing the compiler to correctly generate special member functions.

The class template `indirect` confers value-like semantics on a free-store-allocated object. An `indirect` may hold an object of a class `T`. Copying the `indirect` will copy the object `T`. When a parent object contains a member of type `indirect<T>` and is accessed through a const access path, `constness` will propagate from the parent object to the instance of `T` owned by the `indirect` member.

The class template `polymorphic` confers value-like semantics on a free-store-allocated object. A `polymorphic<T>` may hold an object of a class publicly derived from `T`. Copying the `polymorphic<T>` will copy the object of the derived type. When a parent object contains a member of type `polymorphic<T>` and is accessed through a const access path, `constness` will propagate from the parent object to the instance of `T` owned by the `polymorphic` member.

This proposal is a fusion of two earlier individual proposals, P1950 and P0201. The design of the two proposed class templates is sufficiently similar that they should not be considered in isolation.

Motivation

The standard library has no vocabulary type for a free-store-allocated object with value semantics. When designing a composite class, we may need an object to be stored indirectly to support incomplete types, reduce object size or support open-set polymorphism.

We propose the addition of two new class templates to the standard library to represent indirectly stored values: `indirect` and `polymorphic`. Both class templates
represent free-store-allocated objects with value-like semantics. `polymorphic<T>` can own any object of a type publicly derived from `T`, allowing composite classes to contain polymorphic components. We require the addition of two classes to avoid the cost of virtual dispatch (calling the copy constructor of a potentially derived-type object through type erasure) when copying of polymorphic objects is not needed.

**Design requirements**

We review the fundamental design requirements of `indirect` and `polymorphic` that make them suitable for composite class design.

**Special member functions**

Both class templates are suitable for use as members of composite classes where the compiler will generate special member functions. This means that the class templates should provide the special member functions where they are supported by the owned object type `T`.

- `indirect<T, Alloc>` and `polymorphic<T, Alloc>` are default constructible in cases where `T` is default constructible.
- `indirect<T, Alloc>` is copy constructible where `T` is copy constructible and assignable.
- `polymorphic<T, Alloc>` is unconditionally copy constructible and assignable.
- `indirect<T, Alloc>` and `polymorphic<T, Alloc>` are unconditionally move constructible and assignable.
- `indirect<T, Alloc>` and `polymorphic<T, Alloc>` destroy the owned object in their destructors.

**Deep copies**

Copies of `indirect<T>` and `polymorphic<T>` should own copies of the owned object created with the copy constructor of the owned object. In the case of `polymorphic<T>`, this means that the copy should own a copy of a potentially derived type object created with the copy constructor of the derived type object.

Note: Including a `polymorphic` component in a composite class means that virtual dispatch will be used (through type erasure) in copying the `polymorphic` member. Where a composite class contains a polymorphic member from a known set of types, prefer `std::variant` or `indirect<std::variant>` if indirect storage is required.
**const propagation**

When composite objects contain `pointer`, `unique_ptr` or `shared_ptr` members they allow non-const access to their respective pointees when accessed through a const access path. This prevents the compiler from eliminating a source of const-correctness bugs and makes it difficult to reason about the const-correctness of a composite object.

Accessors of unique and shared pointers do not have const and non-const overloads:

```cpp
t* unique_ptr<T>::operator->() const;
t& unique_ptr<T>::operator*() const;
```

```cpp
t* shared_ptr<T>::operator->() const;
t& shared_ptr<T>::operator*() const;
```

When a parent object contains a member of type `indirect<T>` or `polymorphic<T>`, access to the owned object (of type `T`) through a const access path should be `const` qualified.

```cpp
struct A {
  enum class Constness { CONST, NON_CONST };
  Constness foo() { return Constness::NON_CONST; }
  Constness foo() const { return Constness::CONST; }
};

class Composite {
  indirect<A> a_;

  Constness foo() { return a_.foo(); }
  Constness foo() const { return a_.foo(); }
};

int main() {
  Composite c;
  assert(c.foo() == A::Constness::NON_CONST);
  const Composite& cc = c;
  assert(cc.foo() == A::Constness::CONST);
}
```

**Value semantics**

Both `indirect` and `polymorphic` are value types whose owned object is free-store-allocated (or some other memory resource controlled by the specified allocator).

When a value type is copied it gives rise to two independent objects that can be modified separately.
The owned object is part of the logical state of indirect and polymorphic. Operations on a const-qualified object do not make changes to the object’s logical state nor to the logical state of other object.

indirect<T> and polymorphic<T> are default constructible in cases where T is default constructible. Moving a value type onto the free store should not add or remove the ability to be default constructed.

Pairwise-comparison operators, which are defined only for indirect, compare the owned objects where the owned objects can be compared: where T is ordered, indirect<T> is also ordered.

The hash operation, which is defined only for indirect, hashes the owned object where the owned object can be hashed.

We discuss why only indirect is comparable and hashable in an appendix.

Unobservable null state and interaction with std::optional

Both indirect and polymorphic have a null state that is used to implement move. The null state is not intended to be observable to the user. There is no operator bool or has_value member function. Accessing the value of an indirect or polymorphic after it has been moved from is erroneous behaviour.

We provide a valueless_after_move member function that returns true if an object is in a valueless state to allow explicit checks for the valueless state in cases where it cannot be verified statically.

Without a null state, moving indirect or polymorphic would require allocation and moving from the owned object. This would be expensive and would require the owned object to be moveable. The existence of a null state allows move to be implemented cheaply without requiring the owned object to be moveable.

Where a nullable indirect or polymorphic is required, using std::optional is recommended. This may become common practice, since indirect and polymorphic can replace smart pointers in composite classes, where they are currently used to (mis)represent component objects. Putting T onto the free store should not make it nullable. Nullability must be explicitly opted into by using std::optional<indirect<T>> or std::optional<polymorphic<T>>.

std::optional<> is specialized for indirect<> and polymorphic<> so they incur no additional overhead.

Access to a std::optional<indirect<T>> or std::optional<polymorphic<T>> can be done with double indirection, (**v), or with a single arrow operator to access a member, v->some_member.

Note: As the null state of indirect and polymorphic is not observable, and access to a moved-from object is erroneous, std::optional can be specialized by implementers to exchange pointers on move construction and assignment.
Design for polymorphic types

A type PolymorphicInterface used as a base class with polymorphic does not need a virtual destructor. The same mechanism that is used to call the copy constructor of a potentially derived-type object will be used to call the destructor.

To allow compiler-generation of special member functions of an abstract interface type PolymorphicInterface in conjunction with polymorphic, PolymorphicInterface needs at least a non-virtual protected destructor and a protected copy constructor. PolymorphicInterface does not need to be assignable, move constructible or move assignable for polymorphic<PolymorphicInterface> to be assignable, move constructible or move assignable.

```cpp
class PolymorphicInterface {
    protected:
        PolymorphicInterface(const PolymorphicInterface&) = default;
    -PolymorphicInterface() = default;
    public:
        // virtual functions
};
```

For an interface type with a public virtual destructor, users would potentially pay the cost of virtual dispatch twice when deleting polymorphic<I> objects containing derived-type objects.

All derived types owned by a polymorphic must be publicly copy constructible.

Prior work

This proposal continues the work started in [P0201] and [P1950].

Previous work on a cloned pointer type [N3339] met with opposition because of the mixing of value and pointer semantics. We feel that the unambiguous value semantics of indirect and polymorphic as described in this proposal address these concerns.

Impact on the standard

This proposal is a pure library extension. It requires additions to be made to the standard library header <memory>.

Technical specifications

X.Y Class template indirect [indirect]

X.Y.1 Class template indirect general [indirect.general] An indirect value is an object that manages the lifetime of an owned object. An indirect
value object is *valueless* if it has no owned object. An indirect value may only become valueless after it has been moved from.

In every specialization `indirect<T, Allocator>`, the type `allocator_traits<Allocator>::value_type` shall be the same type as `T`. Every object of type `indirect<T, Allocator>` uses an object of type `Allocator` to allocate and free storage for the owned object as needed. The owned object shall be constructed using the function `allocator_traits<Allocator>::rebind_traits<U>::construct` and destroyed using the function `allocator_traits<Allocator_type>::rebind_traits<U>::destroy`, where `U` is either `allocator_type::value_type` or an internal type used by the indirect value.

The template parameter `T` of `indirect` must be a non-union class type.

The template parameter `T` of `indirect` may be an incomplete type.

**X.Y.2 Class template indirect synopsis [indirect.syn]**

```cpp
template <class T, class Allocator = std::allocator<T>>
class indirect {
  T* p_; // exposition only
  Allocator allocator_; // exposition only
public:
  using value_type = T;
  using allocator_type = Allocator;
  using pointer = typename allocator_traits<Allocator>::pointer;
  using const_pointer = typename allocator_traits<Allocator>::const_pointer;

  constexpr indirect();

  template <class... Ts>
  explicit constexpr indirect(Ts&&... ts);

  template <class... Ts>
  constexpr indirect(
    std::allocator_arg_t, const Allocator& alloc, Ts&&... ts);

  constexpr indirect(const indirect& other);

  constexpr indirect(const indirect& other) noexcept;

  constexpr indirect(std::allocator_arg_t, const Allocator& alloc,
    const indirect& other);

  constexpr indirect(indirect&& other) noexcept;

  constexpr indirect(std::allocator_arg_t, const Allocator& alloc,
    indirect&& other) noexcept;
};
```
constexpr ~indirect();
constexpr indirect& operator=(const indirect& other);
constexpr indirect& operator=(indirect&& other) noexcept (see below);
constexpr const T& operator*() const noexcept;
constexpr T& operator*() noexcept;
constexpr const_pointer operator->() const noexcept;
constexpr pointer operator->() noexcept;
constexpr bool valueless_after_move() const noexcept;
constexpr allocator_type get_allocator() const noexcept;
constexpr void swap(indirect& other) noexcept (see below);
friend constexpr void swap(indirect& lhs, indirect& rhs) noexcept (see below);

template <class U, class AA>
friend constexpr bool operator==(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

template <class U, class AA>
friend constexpr bool operator!=(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

template <class U, class AA>
friend constexpr auto operator<=>(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

template <class U>
friend constexpr bool operator==(const indirect<T, A>& lhs, const U& rhs);

template <class U>
friend constexpr bool operator==(const U& lhs, const indirect<T, A>& rhs);

template <class U>
friend constexpr bool operator!=(const U& lhs, const indirect<T, A>& rhs);

template <class U>
friend constexpr bool operator!=(const indirect<T, A>& lhs, const U& rhs);
template <class U>
friend constexpr auto operator<=>(const indirect<T, A>& lhs, const U& rhs);

template <class U>
friend constexpr auto operator<=>(const U& lhs, const indirect<T, A>& rhs);

};

template <class T, class Alloc>
struct hash<indirect<T, Alloc>>;

X.Y.3 Constructors [indirect ctor]

constexpr indirect()

• Mandates: is_default_constructible_v<T> is true.
• Effects: Constructs an indirect owning a default-constructed T.
• Postconditions: *this is not valueless.

explicit constexpr indirect(Ts&&... ts);

• Constraints: is_constructible_v<T, Ts...> is true.
• Effects: Constructs an indirect owning an instance of T created with the arguments Ts.
• Postconditions: *this is not valueless.

template <class... Ts>
constexpr indirect(std::allocator_arg_t, const Allocator& alloc, Ts&&... ts);

• Constraints: is_constructible_v<T, Ts...> is true.
• Preconditions: Allocator meets the Cpp17Allocator requirements.
• Effects: Equivalent to the preceding constructor except that the allocator is initialized with alloc.
• Postconditions: *this is not valueless.

constexpr indirect(const indirect& other);

• Mandates: is_copy_constructible_v<T> is true.
• Preconditions: other is not valueless.
• Effects: Constructs an indirect owning an instance of T created with the copy constructor of the object owned by other.
• Postconditions: *this is not valueless.

constexpr indirect(std::allocator_arg_t, const Allocator& alloc, const indirect& other);
• **Mandates:** `is_copy_constructible_v<T>` is true.

• **Preconditions:** `other` is not valueless and `Allocator` meets the `Cpp17Allocator` requirements.

• **Effects:** Equivalent to the preceding constructor except that the allocator is initialized with `alloc`.

• **Postconditions:** `*this` is not valueless.

```cpp
constexpr indirect(indirect&& other) noexcept;
```

• **Preconditions:** `other` is not valueless.

• **Effects:** Constructs an `indirect` owning the object owned by `other`.

• **Postconditions:** `other` is valueless.

• **Remarks:** This constructor does not require that `is_move_constructible_v<T>` is true.

```cpp
constexpr indirect(std::allocator_arg_t, const Allocator& alloc,
                  indirect&& other) noexcept;
```

• **Preconditions:** `other` is not valueless and `Allocator` meets the `Cpp17Allocator` requirements.

• **Effects:** Equivalent to the preceding constructors except that the allocator is initialized with `alloc`.

• **Postconditions:** `other` is valueless.

• **Remarks:** This constructor does not require that `is_move_constructible_v<T>` is true.

X.Y.4 Destructor [indirect.dtor]

```cpp
constexpr ~indirect();
```

• **Effects:** If `*this` is not valueless, destroys the owned object.

X.Y.5 Assignment [indirect.assign]

```cpp
constexpr indirect& operator=(const indirect& other);
```

• **Mandates:** `is_copy_constructible_v<T>` is true.

• **Preconditions:** `other` is not valueless.

• **Effects:** If `*this` is not valueless and `std::is_copy_assignable_v<T>` is true, copy assigns owned object in `*this` from the owned object in `other`. Otherwise if `*this` is not valueless and `std::is_copy_assignable_v<T>` is false, destroys the owned object, then constructs a new owned object using the copy constructor of the object owned by `other`. Otherwise if
• **this** is valueless, constructs an owned object using the copy constructor of the object owned by other.

  - **Postconditions**: **this** is not valueless.

```cpp
constexpr indirect& operator=(indirect&& other) noexcept(
  allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
  allocator_traits<Allocator>::is_always_equal::value);
```

  - **Preconditions**: other is not valueless.
  
  - **Effects**: If **this** is not valueless, destroys the owned object, then takes ownership of the object owned by other.
  
  - **Postconditions**: **this** is not valueless. other is valueless.

**X.Y.6 Observers** [indirect.observers]

```cpp
constexpr const T& operator*() const noexcept;
constexpr T& operator*() noexcept;
```

  - **Preconditions**: **this** is not valueless.
  
  - **Effects**: Returns a reference to the owned object.
  
  - **Remarks**: These functions are constexpr functions.

```cpp
constexpr const_pointer operator->() const noexcept;
constexpr pointer operator->() noexcept;
```

  - **Preconditions**: **this** is not valueless.
  
  - **Effects**: Returns a pointer to the owned object.
  
  - **Remarks**: These functions are constexpr functions.

```cpp
constexpr bool valueless_after_move() const noexcept;
```

  - **Returns**: true if **this** is valueless, otherwise false.

```cpp
constexpr allocator_type get_allocator() const noexcept;
```

  - **Returns**: A copy of the Allocator object used to construct the owned object.

**X.Y.7 Swap** [indirect.swap]

```cpp
constexpr void swap(indirect& other) noexcept(
  allocator_traits<Allocator>::propagate_on_container_swap::value ||
  allocator_traits<Allocator>::is_always_equal::value);
```

  - **Preconditions**: **this** is not valueless, other is not valueless.
  
  - **Effects**: Swaps the objects owned by **this** and other.
  
  - **Remarks**: Does not call swap on the owned objects directly.
constexpr void swap(indirect& lhs, indirect& rhs) noexcept(
    allocator_traits<Allocator>::propagate_on_container_swap::value ||
    allocator_traits<Allocator>::is_always_equal::value);

• Preconditions: lhs is not valueless, rhs is not valueless.
• Effects: Swaps the objects owned by lhs and rhs.
• Remarks: Does not call swap on the owned objects directly.

X.Y.8 Relational operators [indirect.rel]

template <class U, class AA>
constexpr bool operator==(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

• Preconditions: lhs is not valueless, rhs is not valueless.
• Effects: Returns *lhs == *rhs.
• Remarks: Specializations of this function template for which *lhs ==
  *rhs is a core constant expression are constexpr functions.

template <class U, class AA>
constexpr bool operator!=(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

• Preconditions: lhs is not valueless, rhs is not valueless.
• Effects: Returns *lhs != *rhs.
• Remarks: Specializations of this function template for which *lhs !=
  *rhs is a core constant expression, are constexpr functions.

template <class U, class AA>
constexpr auto operator<=>(const indirect<T, A>& lhs, const indirect<U, AA>& rhs);

• Preconditions: lhs is not valueless, rhs is not valueless.
• Effects: Returns *lhs <=> *rhs.
• Remarks: Specializations of this function template for which *lhs <=>
  *rhs is a core constant expression, are constexpr functions.

X.Y.9 Comparison with T [indirect.comp.with.t]

template <class T, class A, class U>
constexpr bool operator==(const indirect<T, A>& lhs, const U& rhs);

• Preconditions: lhs is not valueless.
• Effects: Returns *lhs == rhs.
• Remarks: Specializations of this function template for which *lhs ==
  *rhs is a core constant expression, are constexpr functions.
template <class T, class A, class U>
constexpr bool operator==(const U& lhs, const indirect<T, A>& rhs);

• **Preconditions:** rhs is not valueless.
• **Effects:** Returns \( \text{lhs} == \text{rhs} \).
• **Remarks:** Specializations of this function template for which \( \text{lhs} == \text{rhs} \) is a core constant expression, are constexpr functions.

template <class T, class A, class U>
constexpr bool operator!=(const indirect<T, A>& lhs, const U& rhs)

• **Preconditions:** lhs is not valueless.
• **Effects:** Returns \( \text{lhs} != \text{rhs} \).
• **Remarks:** Specializations of this function template for which \( \text{lhs} != \text{rhs} \) is a core constant expression, are constexpr functions.

template <class T, class A, class U>
constexpr bool operator!=(const U&lhs, const indirect<T, A>& rhs);

• **Preconditions:** rhs is not valueless.
• **Effects:** Returns \( \text{lhs} != \text{rhs} \).
• **Remarks:** Specializations of this function template for which \( \text{lhs} != \text{rhs} \) is a core constant expression, are constexpr functions.

template <class T, class A, class U>
constexpr auto operator<=>(const indirect<T, A>& lhs, const U& rhs);

• **Preconditions:** lhs is not valueless.
• **Effects:** Returns \( \text{lhs} \leftrightarrow \text{rhs} \).
• **Remarks:** Specializations of this function template for which \( \text{lhs} \leftrightarrow \text{rhs} \) is a core constant expression, are constexpr functions.

template <class T, class A, class U>
constexpr auto operator<=>(const U& lhs, const indirect<T, A>& rhs);

• **Preconditions:** rhs is not valueless.
• **Effects:** Returns \( \text{lhs} \leftrightarrow \text{rhs} \).
• **Remarks:** Specializations of this function template for which \( \text{lhs} \leftrightarrow \text{rhs} \) is a core constant expression, are constexpr functions.

• **Preconditions:** Alloc meets the `Cpp17Allocator` requirements.

X.Y.10 Hash support [indirect.hash]

template <class T, class Alloc>
struct std::hash<indirect<T, Alloc>>;

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• **Preconditions:** i is not valueless.

The specialization `hash<indirect<T, Alloc>>` is enabled ([unord.hash]) if and only if `hash<remove_const_t<T>>` is enabled. When enabled for an object i of type `indirect<T, Alloc>`, then `hash<indirect<T, Alloc>>()`(i) evaluates to the same value as `hash<remove_const_t<T>>()`(*i). The member functions are not guaranteed to be noexcept.

**X.Y.12 Optional support [indirect.optional]**

```cpp
template <class T, class Alloc> class std::optional<indirect<T, Alloc>>;
```

The specialization `std::optional<indirect<T, Alloc>>` guarantees `sizeof(std::optional<indirect<T, Alloc>>) == sizeof(indirect<T, Alloc>>)`.

```cpp
// [optional.observe], observers
costexpr const indirect<T, Alloc>& operator->() const noexcept;
constexpr indirect<T, Alloc>& operator->() noexcept;
```

• **Preconditions:** `*this` contains a value. The contained indirect value is not valueless.

• **Returns:** val.

• **Remarks:** These functions are constexpr. The specialization `std::optional<indirect<T, Alloc>>` provides `operator->` that returns a reference to the contained `indirect`.

Otherwise, the interface of the specialization is as defined in [optional].

**X.Y.13 Formatter support [indirect.fmt]**

```cpp
// [indirect.fmt]
template <class T, class Alloc, class charT>
struct std::formatter<indirect<T, Alloc>, charT> : std::formatter<T, charT> {
    template<class ParseContext>
    constexpr typename ParseContext::iterator parse(ParseContext& ctx);

    template<class FormatContext>
    typename FormatContext::iterator format(
        indirect<T, Alloc> const& value, FormatContext& ctx) const;
};
```

Specialization of `std::formatter<indirect<T, Alloc>, charT>` when the underlying T supports specialisation of `std::formatter<T, charT>`.

• **Preconditions:** value is not valueless. The specialization `formatter<T, charT>` meets the `Formatter` requirements.
Feature-test Macro [indirect.predefined.ft]

Add a new feature-test macro:

#define __cpp_lib_indirect 2023XXL

X.Z Class template polymorphic [polymorphic]

X.Z.1 Class template polymorphic general [polymorphic.general] A polymorphic value is an object that manages the lifetime of an owned object. A polymorphic value object may own objects of different types at different points in its lifetime. A polymorphic value object is valueless if it has no owned object. A polymorphic value may only become valueless after it has been moved from.

In every specialization polymorphic<T, Allocator>, the type allocator_traits<Allocator>::value_type shall be the same type as T. Every object of type polymorphic<T, Allocator> uses an object of type Allocator to allocate and free storage for the owned object as needed. The owned object shall be constructed using the function allocator_traits<Allocator>::rebind_traits<U>::construct and destroyed using the function allocator_traits<Allocator>::rebind_traits<U>::destroy, where U is either allocator_type::value_type or an internal type used by the polymorphic value.

The template parameter T of polymorphic must be a non-union class type.

The template parameter T of polymorphic may be an incomplete type.

X.Z.2 Class template polymorphic synopsis [polymorphic.syn]

template <class T, class Allocator = std::allocator<T>>
class polymorphic {
    control_block* control_block_; // exposition only
    Allocator allocator_; // exposition only
public:
    using value_type = T;
    using allocator_type = Allocator;
    using pointer = typename allocator_traits<Allocator>::pointer;
    using const_pointer = typename allocator_traits<Allocator>::const_pointer;
}

constexpr polymorphic();

template <class U, class... Ts>
explicit constexpr polymorphic(std::in_place_type_t<U>, Ts&&... ts);

template <class U, class... Ts>
constexpr polymorphic(std::allocator_arg_t, const Allocator& alloc,
    std::in_place_type_t<U>, Ts&&... ts);

constexpr polymorphic(const polymorphic& other);
constexpr polymorphic(std::allocator_arg_t, const Allocator& alloc, const polymorphic& other);
constexpr polymorphic& operator=(const polymorphic& other);
constexpr polymorphic& operator=(polymorphic&& other) noexcept (see below);
constexpr const T& operator*() const noexcept;
constexpr T& operator*() noexcept;
constexpr const_pointer operator->() const noexcept;
constexpr pointer operator->() noexcept;
constexpr bool valueless_after_move() const noexcept;
constexpr allocator_type get_allocator() const noexcept;
friend constexpr void swap(polymorphic& other) noexcept (see below);

X.Z.3 Constructors [polymorphic_ctor]

constexpr polymorphic()
  • Mandates: is_default_constructible_v<T> is true, is_copy_constructible_v<T> is true.
  • Effects: Constructs a polymorphic owning a default-constructed T.
  • Postconditions: *this is not valueless.

template <class U, class... Ts>
explicit constexpr polymorphic(std::in_place_type_t<U>, Ts&&... ts);
  • Constraints: is_base_of_v<T, U> is true, is_constructible_v<U, Ts...> is true, is_copy_constructible_v<U> is true.
 Effects: Constructs a polymorphic owning an instance of U created with the arguments Ts.

 Postconditions: *this is not valueless.

template <class U, class... Ts>
constexpr polymorphic(std::allocator_arg_t, const Allocator& alloc, std::in_place_type_t<U>, Ts&&... ts);

 Constraints: is_base_of_v<T, U> is true, is_constructible_v<U, Ts...> is true, is_copy_constructible_v<U> is true.

 Preconditions: Allocator meets the Cpp17Allocator requirements.

 Effects: Equivalent to the preceding constructor except that the allocator is initialized with alloc.

 Postconditions: *this is not valueless.

constexpr polymorphic(const polymorphic& other);

 Preconditions: other is not valueless.

 Effects: Constructs a polymorphic owning an instance of T created with the copy constructor of the object owned by other.

 Postconditions: *this is not valueless.

constexpr polymorphic(std::allocator_arg_t, const Allocator& alloc, const polymorphic& other);

 Preconditions: other is not valueless and Allocator meets the Cpp17Allocator requirements.

 Effects: Equivalent to the preceding constructor except that the allocator is initialized with alloc.

 Postconditions: *this is not valueless.

constexpr polymorphic(polymorphic&& other) noexcept;

 Preconditions: other is not valueless.

 Effects: Constructs a polymorphic that takes ownership of the object owned by other.

 Postconditions: other is valueless.

 Remarks: This constructor does not require that is_move_constructible_v<T> is true.

constexpr polymorphic(std::allocator_arg_t, const Allocator& alloc, polymorphic&& other) noexcept;

 Preconditions: other is not valueless and Allocator meets the Cpp17Allocator requirements.
• **Effects**: Equivalent to the preceding constructor except that the allocator is initialized with alloc.

• **Postconditions**: other is valueless.

• **Remarks**: This constructor does not require that `is_move_constructible_v<T>` is true.

X.Z.4 Destructor [polymorphic.dtor]

```cpp
constexpr polymorphic();
```

• **Effects**: If *this is not valueless, destroys the owned object.

X.Z.5 Assignment [polymorphic.assign]

```cpp
constexpr polymorphic& operator=(const polymorphic& other);
```

• **Preconditions**: other is not valueless.

• **Effects**: If *this is not valueless, destroys the owned object, then constructs an owned object using the (possibly derived-type) copy constructor of the object owned by other.

• **Postconditions**: *this is not valueless.

```cpp
constexpr polymorphic& operator=(polymorphic&& other) noexcept(
  allocator_traits<Allocator>::propagate_on_container_move_assignment::value ||
  allocator_traits<Allocator>::is_always_equal::value);
```

• **Preconditions**: other is not valueless.

• **Effects**: If *this is not valueless, destroys the owned object, then takes ownership of the object owned by other.

• **Postconditions**: *this is not valueless. other is valueless.

X.Z.6 Observers [polymorphic.observers]

```cpp
constexpr const T& operator*() const noexcept;
constexpr T& operator*() noexcept;
```

• **Preconditions**: *this is not valueless.

• **Effects**: Returns a reference to the owned object.

• **Remarks**: These functions are constexpr functions.

```cpp
constexpr const_pointer operator->() const noexcept;
constexpr pointer operator->() noexcept;
```

• **Preconditions**: *this is not valueless.

• **Effects**: Returns a pointer to the owned object.
• **Remarks:** These functions are constexpr functions.

```cpp
constexpr bool valueless_after_move() const noexcept;
```

• **Returns:** true if *this is valueless, otherwise false.

```cpp
constexpr allocator_type get_allocator() const noexcept;
```

• **Returns:** A copy of the Allocator object used to construct the owned object.

### X.Z.7 Swap [polymorphic.swap]

```cpp
constexpr void swap(polymorphic& other) noexcept(
    allocator_traits<Allocator>::propagate_on_container_swap::value ||
    allocator_traits<Allocator>::is_always_equal::value);
```

• **Preconditions:** *this is not valueless, other is not valueless.

• **Effects:** Swaps the objects owned by *this and other.

• **Remarks:** Does not call swap on the owned objects directly.

```cpp
constexpr void swap(polymorphic& lhs, polymorphic& rhs) noexcept(
    allocator_traits<Allocator>::propagate_on_container_swap::value ||
    allocator_traits<Allocator>::is_always_equal::value);
```

• **Preconditions:** lhs is not valueless, rhs is not valueless.

• **Effects:** Swaps the objects owned by lhs and rhs.

### X.Z.8 Optional support [polymorphic.optional]

```cpp
template <class T, class Alloc>
class std::optional<polymorphic<T, Alloc>>;
```

The specialization `std::optional<polymorphic<T, Alloc>>` guarantees `sizeof(std::optional<polymorphic<T, Alloc>>) == sizeof(polymorphic<T, Alloc>>).`

// [optional.observe], observers

```cpp
constexpr const polymorphic<T, Alloc>& operator->() const noexcept;
constexpr polymorphic<T, Alloc>& operator->() noexcept;
```

• **Preconditions:** *this is not valueless. The contained polymorphic value is not valueless.

• **Returns:** val.

• **Remarks:** These functions are constexpr. The specialization `std::optional<polymorphic<T, Alloc>>` provides operator-> that returns a reference to the contained polymorphic.

Otherwise, the interface of the specialization is as defined in [optional].
Feature-test Macro [polymorphic.predefined.ft]
Add a new feature-test macro:

```c
#define __cpp_lib_polymorphic 2023XXL
```

Reference implementation

A C++20 reference implementation of this proposal is available on GitHub at [https://www.github.com/jbcoe/value_types].

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References


A Free-Store-Allocated Value Type for C++, J. B. Coe, A. Peacock 2022 [https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2022/p1950r2.html]

A C++20 reference implementation is available on GitHub [https://www.github.com/jbcoe/value_types]

Appendix A: Detailed design decisions

We discuss some of the decisions that were made in the design of indirect and polymorphic. Where there are multiple options, we discuss the advantages and disadvantages of each.

Two class templates, not one

It is conceivable that a single class template could be used as a vocabulary type for an indirect value type supporting polymorphism. However, implementing this would impose efficiency costs on the copy constructor when the owned object is the same type as the template type. When the owned object is a derived type, the copy constructor uses type erasure to perform dynamic dispatch and call the derived type copy constructor. The overhead of indirection and a virtual
function call is not tolerable where the owned object type and template type match.

One potential solution would be to use a `std::variant` to store the owned type or the control block used to manage the owned type. This would allow the copy constructor to be implemented efficiently when the owned type and template type match. This would increase the object size beyond that of a single pointer as the discriminant must be stored.

For the sake of minimal size and efficiency, we opted to use two class templates.

**Copiers, deleters, pointer constructors, and allocator support**

The older types `indirect_value` and `polymorphic_value` had constructors that take a pointer, copier, and deleter. The copier and deleter could be used to specify how the object should be copied and deleted. The existence of a pointer constructor introduces undesirable properties into the design of `polymorphic_value`, such as allowing the possibility of object slicing on copy when the dynamic and static types of a derived-type pointer do not match.

We decided to remove the copier, delete, and pointer constructor in favour of adding allocator support. A pointer constructor and support for custom copiers and deleters are not core to the design of either class template; both could be added in a later revision of the standard if required.

We have been advised that allocator support must be a part of the initial implementation and cannot be added retrospectively. As `indirect` and `polymorphic` are intended to be used alongside other C++ standard library types, such as `std::map` and `std::vector`, it is important that they have allocator support in contexts where allocators are used.

**Pointer-like helper functions**

Earlier revisions of `polymorphic_value` had helper functions to get access to the underlying pointer. These were removed under the advice of the Library Evolution Working Group as they were not core to the design of the class template, nor were they consistent with value-type semantics.

Pointer-like accessors like `dynamic_pointer_cast` and `static_pointer_cast`, which are provided for `std::shared_ptr`, could be added in a later revision of the standard if required.

**Comparisons and hashing**

We support comparisons and hashing for `indirect` but not `polymorphic`. This is because comparing and hashing polymorphic types is not a uniquely solved problem, though it could be implemented by adding suitable member functions to the base class. Rather than impose the signatures of these member functions on
users of `polymorphic`, we decided to leave hashing and comparison unsupported but implementable by users.

For `indirect`, in the case where the owned object `T` is hashable or comparable, `indirect<T>` is hashable or comparable by forwarding the hash or comparison to the owned object.

**Implicit conversions**

We decided that there should be no implicit conversion of a value `T` to an `indirect<T>` or `polymorphic<T>`. An implicit conversion would require using the free store and memory allocation, which is best made explicit by the user.

```cpp
Rectangle r(w, h);
polymorphic<Shape> s = r; // error
```

To transform a value into `indirect` or `polymorphic`, the user must use the appropriate constructor.

```cpp
Rectangle r(w, h);
polymorphic<Shape> s(std::in_place_type<Rectangle>, r);
assert(dynamic_cast<Rectangle*>(&*s) != nullptr);
```

**Explicit conversions**

The older class template `polymorphic_value` had explicit conversions, allowing construction of a `polymorphic_value<T>` from a `polymorphic_value<U>`, where `T` was a base class of `U`.

```cpp
polymorphic_value<Quadrilateral> q(std::in_place_type<Rectangle>, w, h);
polymorphic_value<Shape> s = q;
assert(dynamic_cast<Rectangle*>(&*s) != nullptr);
```

Similar code cannot be written with `polymorphic` as it does not allow conversions between derived types:

```cpp
polymorphic<Quadrilateral> q(std::in_place_type<Rectangle>, w, h);
polymorphic<Shape> s = q; // error
```

This is a deliberate design decision. `polymorphic` is intended to be used for ownership of member data in composite classes where compiler-generated special member functions will be used.

There is no motivating use case for explicit conversion between derived types outside of tests.

A converting constructor could be added in a future version of the C++ standard.

**Small Buffer Optimisation**

It is possible to implement `polymorphic` with a small buffer optimisation, similar to that used in `std::function`. This would allow `polymorphic` to store small
objects without allocating memory. Like `std::function`, the size of the small buffer is left to be specified by the implementation.

The authors are sceptical of the value of a small buffer optimisation for objects from a type hierarchy. If the buffer is too small, all instances of `polymorphic` will be larger than needed. This is because they will allocate heap in addition to having the memory from the (empty) buffer as part of the object size. If the buffer is too big, `polymorphic` objects will be larger than necessary, potentially introducing the need for `indirect<polymorphic<T>>`.

We could add a non-type template argument to `polymorphic` to specify the size of the small buffer:

```cpp
template <typename T, typename Alloc, size_t BufferSize>
class polymorphic;
```

However, we opt not to do this to maintain consistency with other standard library types. Both `std::function` and `std::string` leave the buffer size as an implementation detail. Including an additional template argument in a later revision of the standard would be a breaking change. With usage experience, implementers will be able to determine if a small buffer optimisation is worthwhile, and what the optimal buffer size might be.

A small buffer optimisation makes little sense for `indirect` as the sensible size of the buffer would be dictated by the size of the stored object. This removes support for incomplete types and locates storage for the object locally, defeating the purpose of `indirect`.

### Appendix B: Before and after examples

We include some minimal, illustrative examples of how `indirect` and `polymorphic` can be used to simplify composite class design.

#### Using `indirect` for binary compatibility using the PIMPL idiom

Without `indirect`, we use `std::unique_ptr` to manage the lifetime of the implementation object. All const-qualified methods of the composite will need to be manually checked to ensure that they are not calling non-const qualified methods of component objects.

**Before, without using `indirect`**

```cpp
// Class.h

class Class {
  class Impl;
  std::unique_ptr<Impl> impl_;

public:
  Class();
}
```

After, using `indirect`:

```cpp
class Class {
  indirect<Impl> impl;

public:
  Class();
}
```
~Class();
Class(const Class&);
Class& operator=(const Class&);
Class(Class&&) noexcept;
Class& operator=(Class&&) noexcept;

void do_something();
};

// Class.cpp

class Impl {
public:
  void do_something();
};

Class::Class() : impl_(std::make_unique<Impl>()) {}

Class::~Class() = default;

Class::Class(const Class& other) : impl_(std::make_unique<Impl>(*other.impl_)) {}

Class& Class::operator=(const Class& other) {
  if (this != &other) {
    Class tmp(other);
    using std::swap;
    swap(*this, tmp);
  }
  return *this;
}

Class(Class&&) noexcept = default;
Class& operator=(Class&&) noexcept = default;

void Class::do_something() {
  impl_->do_something();
}

After, using indirect

// Class.h

class Class {
  indirect<class Impl> impl_
  public:
    Class();

Using polymorphic for a composite class

Without polymorphic, we use `std::unique_ptr` to manage the lifetime of component objects. All const-qualified methods of the composite will need to be manually checked to ensure that they are not calling non-const qualified methods of component objects.

Before, without using polymorphic

```cpp
class Canvas;

class Shape {
public:
    virtual ~Shape() = default;
    virtual std::unique_ptr<Shape> clone() = 0;
    virtual void draw(Canvas&) const = 0;
};

class Picture {
    std::vector<std::unique_ptr<Shape>> shapes_;
public:
Picture(const std::vector<std::unique_ptr<Shape>>& shapes) {
    shapes_.reserve(shapes.size());
    for (auto& shape : shapes) {
        shapes_.push_back(shape->clone());
    }
}

Picture(const Picture& other) {
    shapes_.reserve(other.shapes_.size());
    for (auto& shape : other.shapes_) {
        shapes_.push_back(shape->clone());
    }
}

Picture& operator=(const Picture& other) {
    if (this != &other) {
        Picture tmp(other);
        using std::swap;
        swap(*this, tmp);
    }
    return *this;
}

void draw(Canvas& canvas) const;
};

After, using polymorphic
class Canvas;

class Shape {
    protected:
    ~Shape() = default;

    public:
    virtual void draw(Canvas&) const = 0;
};

class Picture {
    std::vector<polymorphic<Shape>> shapes_

    public:
    Picture(const std::vector<polymorphic<Shape>>& shapes) : shapes_(shapes) {}
// Picture(const Picture& other) = default;

// Picture& operator=(const Picture& other) = default;

void draw(Canvas& canvas) const;
};