Better Code: Runtime Polymorphism

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Better Code

- Regular Types
  - Goal: No Incomplete Types
- Algorithms
  - Goal: No Raw Loops
- Data Structures
  - Goal: No Incidental Data Structures
- Runtime Polymorphism
  - Goal: No Inheritance
- Concurrency
  - Goal: No Raw Synchronization Primitives
- …

Better Code

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Goal: No inheritance

What is inheritance?

What is inheritance?

Inheritance is a mechanism to implement runtime-polymorphism where one class is derived from another class, but overriding all or part of the implementation.

Disclaimer

In the following code, the proper use of header files, inline functions, and namespaces are ignored for clarity

client | library

cout | guidelines | defects

```
int main()
{
    cout << "Hello World!" << endl;
}
```

client | library

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cout

Hello World!

client | library

cout | guidelines | defects

```
using object_t = int;

void draw(const object_t& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
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```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

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    draw(document, cout, 0);
}
```

cout

```
<document>
 0
 1
 2
 3
</document>
```

client | library

```
int main()
{
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    draw(document, cout, 0);
}
```

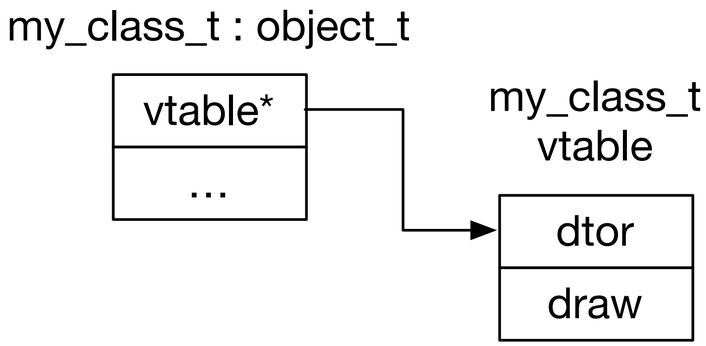
guidelines

- Write all code as a library.
  - Reuse increases your productivity.
  - Writing unit tests is simplified.

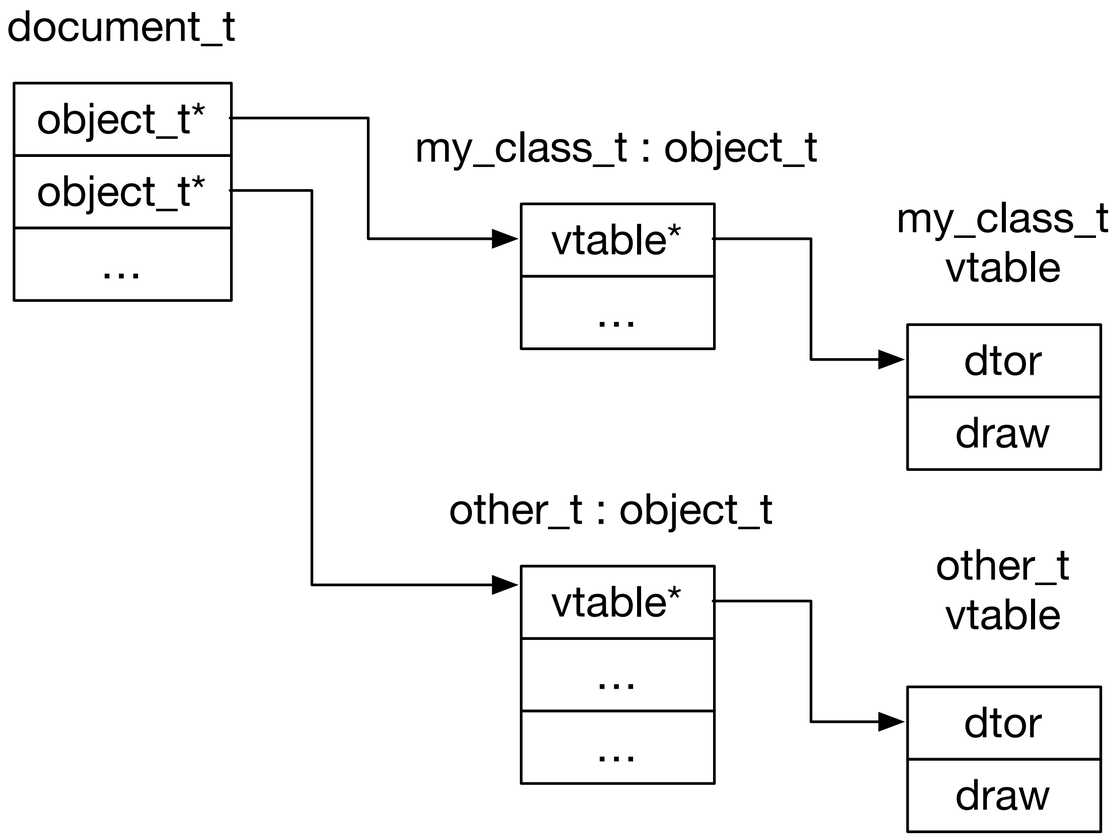
Runtime Polymorphism

- What happens if we want the document to hold any drawable object?

Runtime Polymorphism



Runtime Polymorphism



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```
class object_t {
  public:
    virtual ~object_t() { }
    virtual void draw(ostream&, size_t) const = 0;
};

using document_t = vector<shared_ptr<object_t>>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) e->draw(out, position + 2);
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```
class my_class_t final : public object_t
{
  public:
    void draw(ostream& out, size_t position) const override
    { out << string(position, ' ') << "my_class_t" << endl; }
    /* ... */
};


int main()
{
    document_t document;

    document.emplace_back(new my_class_t());

    draw(document, cout, 0);
}
```

client | library

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class my_class_t final : public object_t
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cout

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 my_class_t
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```

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defects

- An instance of my_class_t will be allocated first
- Then the document will grow to make room
- If growing the document throws an exception, the memory from my_class_t is leaked

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class my_class_t final : public object_t
{
  public:
    void draw(ostream& out, size_t position) const override
    { out << string(position, ' ') << "my_class_t" << endl; }
    /* ... */
};


int main()
{
    document_t document;

    document.emplace_back(make_shared<my_class_t>());

    draw(document, cout, 0);
}
```

defects

- An instance of my_class_t will be allocated first
- Then the document will grow to make room
- If growing the document throws an exception, the memory from my_class_t is leaked

Deep problem #1

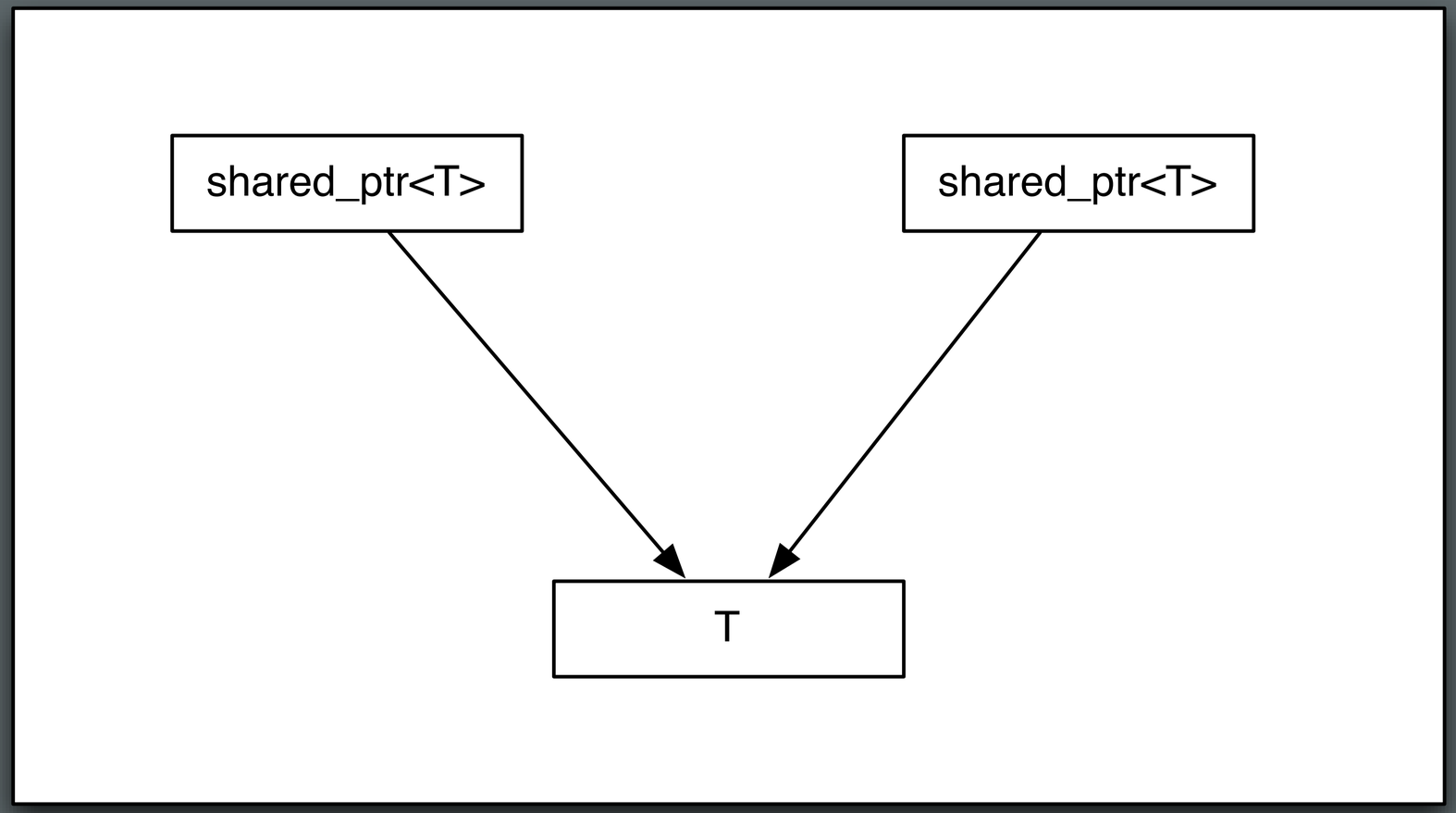
- Changed semantics of copy, assignment, and equality of my document
  - leads to *incidental data-structures*
  - thread safety concerns

Semantics & Syntax

- We define an operation in terms of the operation's semantics:

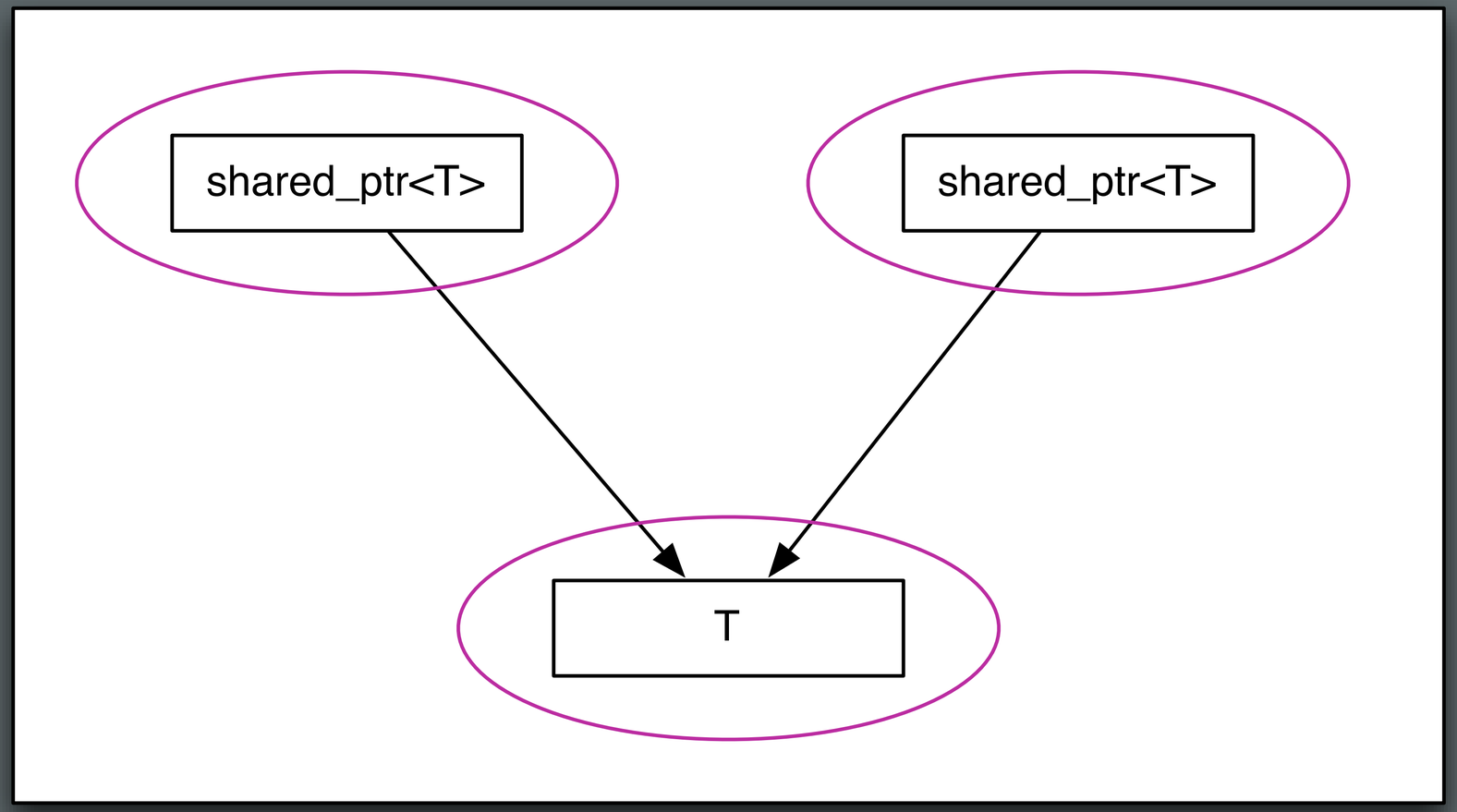
"*Assignment* is a procedure taking two objects of the same type that makes the first object equal to the second without modifying the second." – *Elements of Programming*, Section 1.5

Semantics & Syntax



Adobe

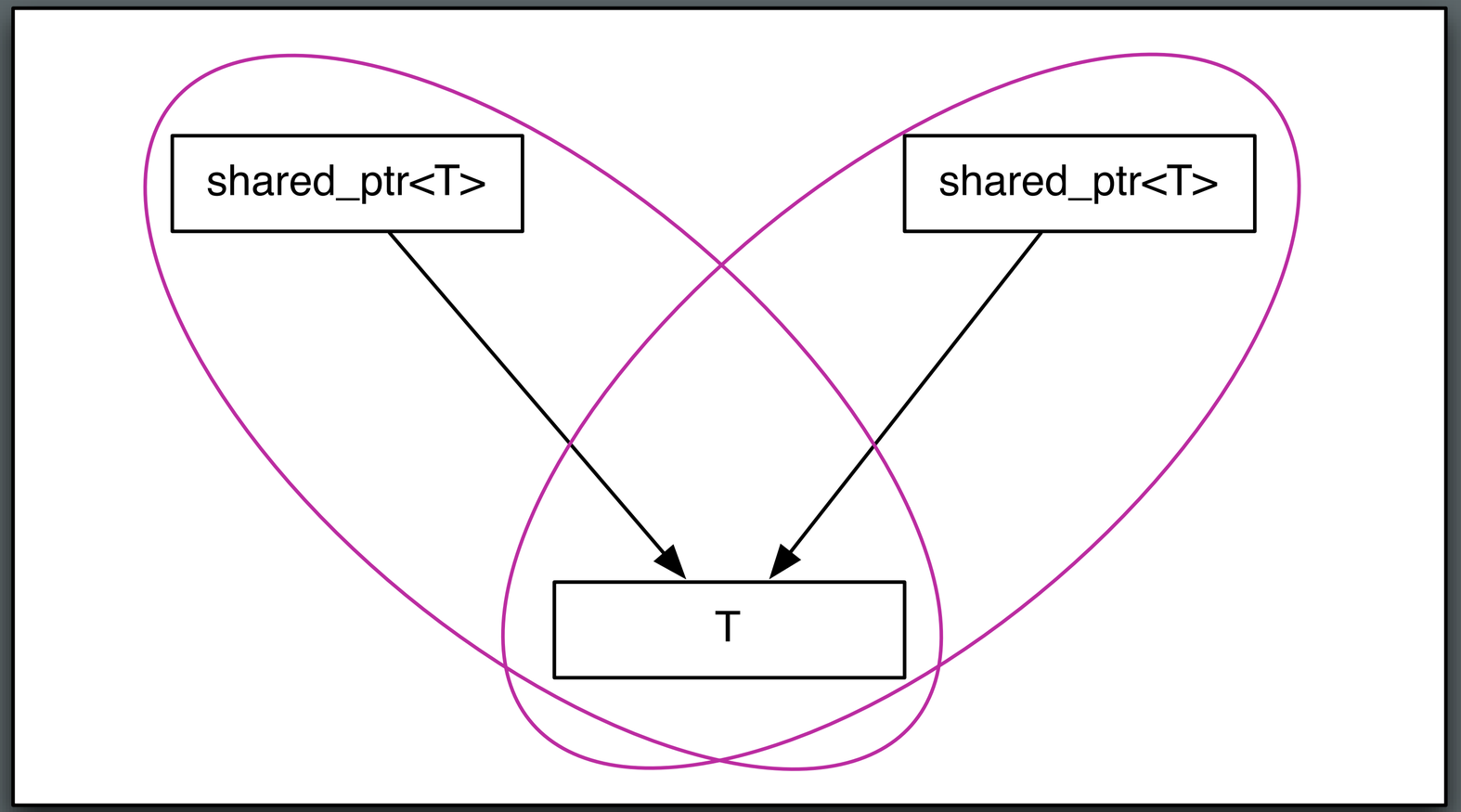
Semantics & Syntax



Semantics & Syntax

- Considered as individual types, assignment and copy hold their regular semantic meanings
  - However, this fails to account for the relationships (the arrows) which form an incidental data-structure. You cannot operate on T through one of the shared pointers without considering the effect on the other shared pointer

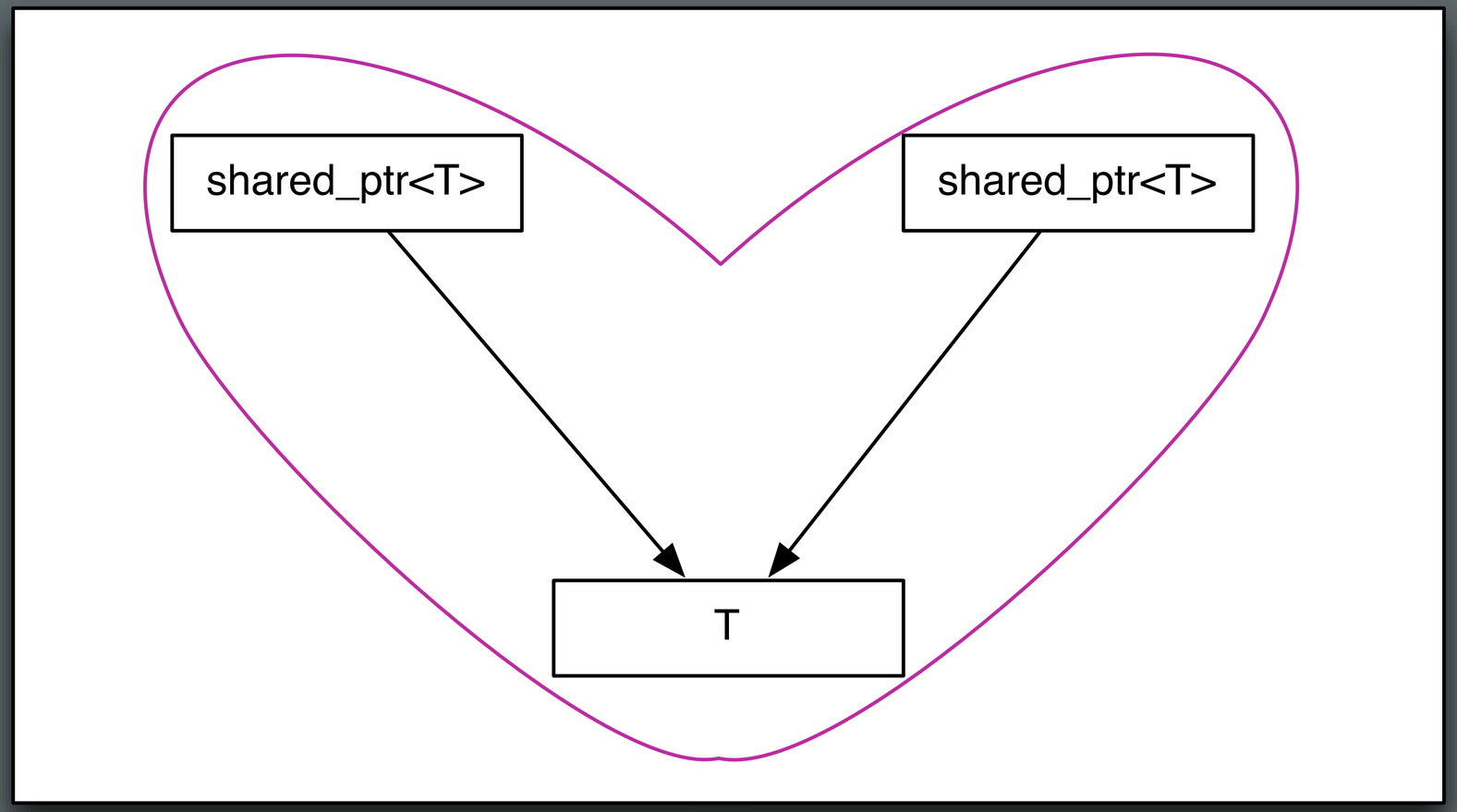
Semantics & Syntax



Semantics & Syntax

- If we extend our notion of object type to include the directly related part then we have intersecting objects which will interfere with each other

Semantics & Syntax



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A shared pointer is as good as a global variable

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- C++ has defined semantics for operations on built-in types, including assignment, copy, equality, address-of
  - Using the same operator names to provide the same semantics on user types enables code reuse

Regular Types

"There is a set of procedures whose inclusion in the computational basis of a type lets us place objects in data structures and use algorithms to copy objects from one data structure to another. We call types having such a basis *regular*, since their use guarantees regularity of behavior and, therefore, interoperability." – *Elements of Programming, Section 1.5*

Semantics & Syntax

- Regular types where the regular operations are implemented with the standard names are said to have *value semantics*

- When objects are referred to indirectly, through a shared reference or pointer, the objects are said to have *reference semantics*

Deep problem #2

- Inefficient
  - calls to draw() on my_class_t are often indirect through virtual calls, including the destructor
  - my_class_t is *always* heap allocated
  - access to my class_t must be synchronized

Deep problem #3

- Polymorphism is intrusive
  - Document can no longer hold a drawable integer

“Polymorphic Types”

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- There are no polymorphic types, only a *polymorphic use* of similar types

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Inheritance is the base class of Evil

client | library

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```
using object_t = int;

void draw(const object_t& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
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```
void draw(const int& x, ostream& out, size_t position)
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class object_t {
  public:
    object_t(const int& x) : self_(x)
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { draw(x.self_, out, position); }

  private:
    int self_;
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using document_t = vector<object_t>;

void draw(const d                tream& out, size_t position)
{
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guidelines

- The compiler will supply member-wise copy and assignment operators.
- Let the compiler do the work where appropriate.

client | library

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int main()
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    document.emplace_back(0);
    document.emplace_back(1);
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    draw(document, cout, 0);
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client | library

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guidelines

- Write classes that behave like *regular* objects to increase reuse.

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```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

    unique_ptr<int_model_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
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guidelines

- Do your own memory management - don't create garbage for your client to clean-up.

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  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_
    };
```

guidelines

- The semantics of copy are to create a new object which is equal to, and logically disjoint from, the original.
- Copy constructor must copy the object. The compiler is free to elide copies so if the copy constructor does something else the code is incorrect.

- When a type manages *remote parts* it is necessary to supply a copy constructor.
  - If you can, use an existing class (such as a vector) to manage remote parts.

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

    unique_ptr<int_model_t> self_;
};
```

cout | guidelines | defects

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { }
    object_t& operator=(const object_t& x)
    { object_t tmp(x); self_ = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

    unique_ptr<int_model_t> self_;
};
```

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { }
    object_t& operator=(const object_t& x)
    { object_t tmp(x); self_ = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(da                              on); }
```

guidelines

- Assignment is consistent with copy. Generally:
  `T x; x = y;` is equivalent to `T x = y;`
- Assignment satisfying the *strong exception guarantee* is a nice property.
  - Either complete successfully or throw an exception, leaving the object unchanged.
- Assignment (like all other operations) must satisfy the basic exception guarantee.
- Don't optimize for rare cases which impact common cases.
  - Don't test for self-assignment to avoid the copy.

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

client | library

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

cout

```
<document>
 0
 1
 2
 3
</document>
```

client | library

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

guidelines

- The Private Implementation (Pimpl), or Handle-Body, idom is good for separating the implementation and reducing compile times.

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { }
    object_t& operator=(const object_t& x)
    { object_t tmp(x); *this = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

cout | guidelines | defects

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { }

    object_t& operator=(const object_t& x)
    { object_t tmp(x); *this = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

cout | guidelines | defects

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t& operator=(const object_t& x)
    { object_t tmp(x); *this = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

cout | guidelines | defects

client | library

cout | guidelines | defects

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = func();
}
```

client | library

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = func();
}
```

cout

```
ctor
```

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

}
```

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = 0;

    x = func();
}
```

client | library

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = 0;

    func();
}
```

cout

```
ctor
ctor
copy
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t& operator=(const object_t& x)
    { object_t tmp(x); self_ = move(tmp.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(da                              on); }
```

guidelines

- Pass *sink* arguments by value and swap or *move* into place.

- A sink argument is any argument consumed or returned by the function.
  - The argument to assignment is a sink argument.

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = 0;

    x = func();
}
```

client | library

```
object_t func()
{
    object_t result = 5;
    return result;
}

int main()
{
    /*
        Quiz: What will this print?
    */

    object_t x = 0;

    x = func();
}
```

cout

```
ctor
ctor
```

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

```
int main()
{
    document_t document;
    document.reserve(5);

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    reverse(document.begin(), document.end());

    draw(document, cout, 0);
}
```

client | library

```
int main()
{
    document_t document;
    document.reserve(5);

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);
```

cout

```
ctor
ctor
ctor
ctor
copy
copy
copy
copy
copy
copy
copy
<document>
 3
 2
 1
 0
</document>
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }

    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&& x) noexcept : self_(move(x.self_)) { }
    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }

    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;
    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;
    object_t& operator=(object_t x) noexcept
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw(ostream& out, size_t position) const
        { draw(data_, out, position); }
```

guidelines

- Provide a move constructor and move assignment to avoid copies and get fast permutations
  - Prior to C++11, provide a swap() function.
- Use "= default" when possible
- Include the expected exception specification to catch mistakes

```
int main()
{
    document_t document;
    document.reserve(5);

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    reverse(document.begin(), document.end());

    draw(document, cout, 0);
}
```

client | library

```
int main()
{
    document_t document;
    document.reserve(5);

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    reverse(document.begin(), document.end());

    draw(document, cout, 0);
}
```

cout

```
ctor
ctor
ctor
ctor
<document>
 3
 2
 1
 0
</document>
```

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

int main()
{
    /*
        Quiz: What will this print?
    */

    some_t x = { 0 };

    x = func();
}
```

client | library

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

int main()
{
    /*
        Quiz: What will this print?
    */

    some_t x = { 0 };

    [illegible]()
}
```

cout

```
ctor
ctor
copy
```

client | library

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

int main()
{
    /*
        Quiz: What will this print?
    */

    some_t x = { 0 };

    x = func();
}
```

guidelines

- 12.8.23 - "A defaulted copy/move assignment operator for class X is defined as deleted if X has:

...

— for the move assignment operator, a non-static data member or direct base class with a type that does not have a **move assignment operator** and is not trivially copyable..."

- Core Issue 1402

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;
    object_t& operator=(object_t x)
    { self_ = move(x.self_); return *this; }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;
```

```
    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { object_t tmp(x); *this = move(tmp); return *this; }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

client | library

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { object_t tmp(x); *this = move(tmp); return *this; }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_mo
        int_model                    : data_(x) { }
```

guidelines

- Pass *sink* arguments by value and swap or *move* into place.

- A sink argument is any argument consumed or returned by the function.
  - The argument to assignment is a sink argument.
  - *However, because of a language defect, you must write a move assignment operator.*

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)

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

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

int main()
{
    /*
        Quiz: What will this print?
    */

    some_t x = { 0 };

    x = func();
}
```

client | library

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

int main()
{
    /*
        Quiz: What will this print?
    */

    some_t x = { 0 };

    func()
}
```

cout

```
ctor
ctor
```

Keypoint

- Returning objects from functions, passing read-only arguments, and passing rvalues as sink arguments do not require copying
  - Understanding this can greatly improve the efficiency of your application

```
class object_t {
  public:
    object_t(const int& x) : self_(make_unique<int_model_t>(x))
    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

client | library

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class object_t {
  public:
    object_t(const int& x) : self (make_unique<int_model_t>(x))
    { }

    object_t(const object_t& x) : self (make_unique<int_model_t>(*x.self_))
    { }

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class object_t {
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    object_t(int x) : self_(make_unique<int_model_t>(move(x)))
    { }

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    { }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
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    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct int_model_t {
        int_model_t(int x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
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public:
  object_t(string x) : self_(make_unique<string_model_t>(move(x)))
  { }
  object_t(int x) : self_(make_unique<int_model_t>(move(x)))
  { }

  object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
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  struct string_model_t {
      string_model_t(string x) : data_(move(x)) { }
      void draw_(ostream& out, size_t position) const
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private:
  struct concept_t {
      virtual ~concept_t() = default;
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  struct string_model_t final : concept_t {
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  { x.self_->draw_(out, position); }

private:
  struct concept_t {
      virtual ~concept_t() = default;
      virtual void draw_(ostream&, size_t) const = 0;
  };
  struct string_model_t final : concept_t {
      string_model_t(string x) : data_(move(x)) { }
      void draw_(ostream& out, size_t position) const override
      { draw(data_, out, position); }

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      string_model_t(string x) : data_(move(x)) { }
      void draw_(ostream& out, size_t position) const override
      { draw(data_, out, position); }
```

```
  { }
  object_t(int x) : self_(make_unique<int_model_t>(move(x)))
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  object_t(object_t&&) noexcept = default;

  object_t& operator=(const object_t& x)
  { return *this = object_t(x); }
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```

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      int data_;
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 unique_ptr<concept_t> self_;
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  struct string_model_t final : concept_t {
      string_model_t(string x) : data_(move(x)) { }
      unique_ptr<concept_t> copy_() const override
      { return make_unique<string_model_t>(*this); }
      void draw_(ostream& out, size_t position) const override
      { draw(data_, out, position); }

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      void draw_(ostream& out, size_t position) const override
      { draw(data_, out, position); }
```

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(1);
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

client | library

```
int main()
{
    document_t document;

    document.emplace_back(0);

    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

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```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(string("Hello!"));
    document.emplace_back(2);
    document.emplace_back(3);

    draw(document, cout, 0);
}
```

client | library

```
int main()
{
    document_t document;

    document.emplace_back(0);
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cout

```
<document>
 0
 Hello!
 2
 3
</document>
```

client | library

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int main()
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```

guidelines

- Don't allow polymorphism to complicate the client code
  - Polymorphism is an implementation detail

```
void draw(const string& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

void draw(const int& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

class object_t {
  public:
    object_t(string x) : self_(make_unique<string_model_t>(move(x)))
    { }
    object_t(int x) : self_(make_unique<int_model_t>(move(x)))
    { }

    object_t(const object_t& x) : self_(x.self_->copy_())
    { }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
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  private:
```

client | library

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  private:
    struct concept_t {
        virtual ~concept_t() = default;
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```

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```
template <typename T>
void draw(const T& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    object_t(const object_t& x) : self_(x.self_->copy_())
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  };
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  object_t& operator=(object_t&&) noexcept = default;

  friend void draw(const object_t& x, ostream& out, size_t position)
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```

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client | library

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      string data_;
  };
  struct int_model_t final : concept_t {
```

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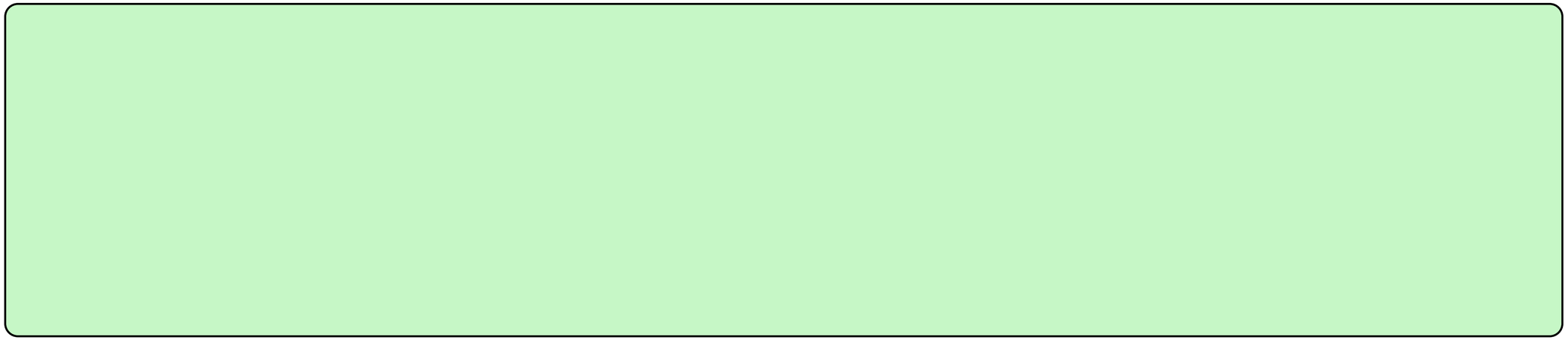

```
    unique_ptr<concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
```

```
  private:
    struct concept_t {
        virtual ~concept_t() = default;
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    };
    template <typename T>
    struct model final : concept_t {
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    out << string(position, ' ') << "<document>" << endl;
```

client | library

```
int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(string("Hello!"));
    document.emplace_back(2);

    draw(document, cout, 0);
}
```

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```
class my_class_t {
    /* ... */
};

void draw(const my_class_t&, ostream& out, size_t position)
{ out << string(position, ' ') << "my_class_t" << endl; }

int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(string("Hello!"));
    document.emplace_back(2);
    document.emplace_back(my_class_t());

    draw(document, cout, 0);
}
```

client | library

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    draw(document, cout, 0);
}
```

cout

```
<document>
 0
 Hello!
 2
 my_class_t
</document>
```

client | library

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```

guidelines

- The runtime-concept idiom allows polymorphism when needed without inheritance.
  - Client isn't burdened with inheritance, factories, class registration, and memory management.
  - Penalty of runtime polymorphism is only payed when needed.
  - Polymorphic types are used like any other types, including built-in types.

```
class my_class_t {
    /* ... */
};

void draw(const my_class_t&, ostream& out, size_t position)
{ out << string(position, ' ') << "my_class_t" << endl; }

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    document.emplace_back(my_class_t());

    draw(document, cout, 0);
}
```

client | library

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```

cout

```
<document>
 0
 Hello!
 <document>
  0
  Hello!
 </document>
 my_class_t
</document>
```

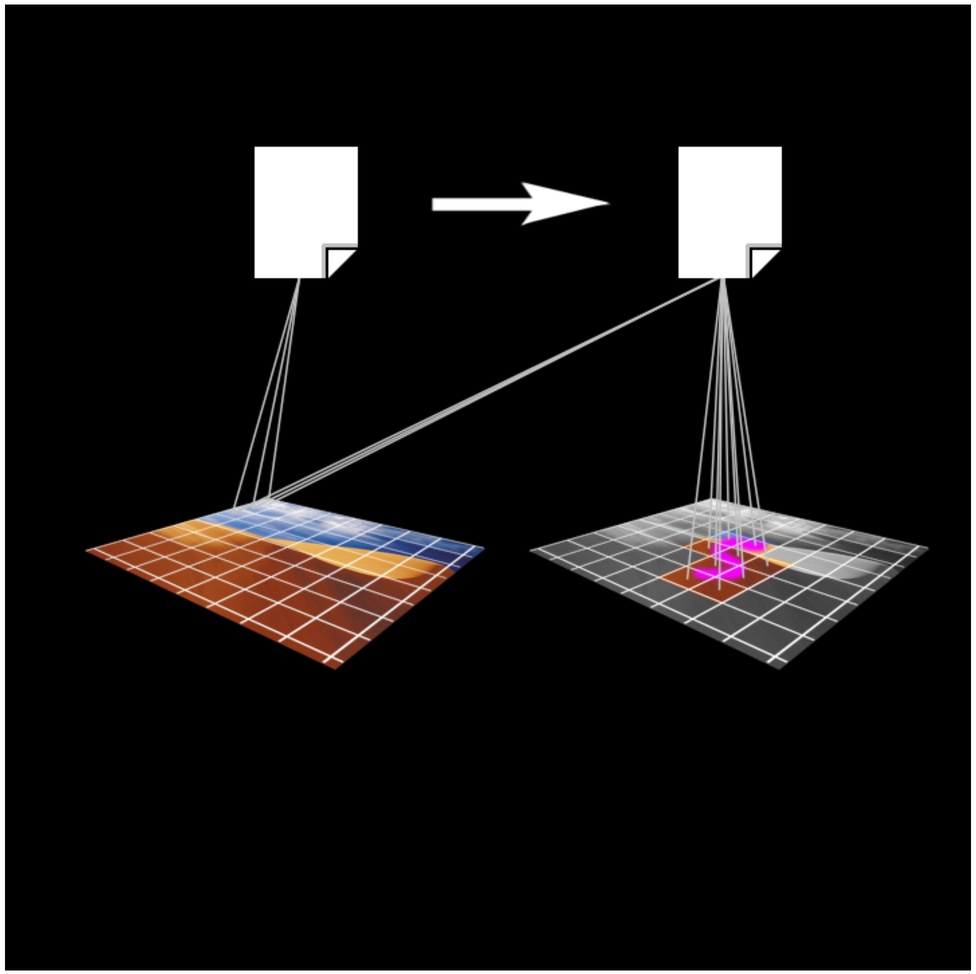
Polymorphic Use

- Shifting polymorphism from *type* to *use* allows for greater reuse and fewer dependencies
- Using regular semantics for the common basis operations, copy, assignment, and move helps to reduce shared objects
- Regular types promote interoperability of software components, increases productivity as well as quality, security, and performance
- There is no performance penalty to using value semantics, and often times there are performance benefits from a decreased use of the heap

Demo

Photoshop History

Photoshop History



```
        { return make_unique<model>(*this); }
         void draw_(ostream& out, size_t position) const override
         { draw(data_, out, position); }

         T data_;
    };

   unique_ptr<concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
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```

client | library

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```
using history_t = vector<document_t>;

void commit(history_t& x) { assert(x.size()); x.push_back(x.back()); }
void undo(history_t& x) { assert(x.size()); x.pop_back(); }
document_t& current(history_t& x) { assert(x.size()); return x.back(); }
```

```
        model(T x) : data_(move(x)) { }
        unique_ptr<concept_t> copy_() const override
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    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;
```

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```
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        unique_ptr<concept_t> copy_() const override
        { return make_unique<model>(*this); }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

  unique_ptr<concept_t> self_;
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using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
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    out << string(position, ' ') << "<document>" << endl;
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void draw(const document_t& x, ostream& out, size_t position)
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```

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```
    { x.self_->draw_(out, position); }

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```
    { return *this = object_t(x); }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
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  object_t(object_t&&) noexcept = default;

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```
  object_t(T x) : self_(make_unique<model<T>>(move(x)))
  { }

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class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    object_t(const object_t& x) : self_(x.self_->copy_())
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
    object_t& operator=(object_t&&) noexcept = default;

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        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
```

```
class my_class_t {
    /* ... */
};

void draw(const my_class_t&, ostream& out, size_t position)
{ out << string(position, ' ') << "my_class_t" << endl; }

int main()
{
    document_t document;

    document.emplace_back(0);
    document.emplace_back(string("Hello!"));
    document.emplace_back(document);
    document.emplace_back(my_class_t());

    draw(document, cout, 0);
}
```

```
    /* ... */
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void draw(const my_class_t&, ostream& out, size_t position)
{ out << string(position, ' ') << "my_class_t" << endl; }

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    draw(document, cout, 0);
}
```

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```
int main()
{

}
```

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```
int main()
{
    history_t h(1);

    current(h).emplace_back(0);
    current(h).emplace_back(string("Hello!"));

    draw(current(h), cout, 0);
    cout << "------------------------" << endl;

    commit(h);

    current(h)[0] = 42.5;
    current(h)[1] = string("World");
    current(h).emplace_back(current(h));
    current(h).emplace_back(my_class_t());

    draw(current(h), cout, 0);
    cout << "------------------------" << endl;

    undo(h);

    draw(current(h), cout, 0);
}
```

```
int main()
{
    history_t h(1);

    current(h).emplace_back(0);
    current(h).emplace_back(string("Hello!"));

    draw(current(h), cout, 0);
    cout << "-------------------------" << endl;

    commit(h);

    current(h)[0] = 42.5;
    current(h)[1] = string("World");
    current(h).emplace_back(current(h));
    current(h).emplace_back(my_class_t());

    draw(current(h), cout, 0);
    cout << "-------------------------" << endl;

    undo(h);

    draw(current(h), cout, 0);
}
```

client library

cout

```
<document>
 0
 Hello!
</document>
------------------------
copy
copy
copy
copy
<document>
 42.5
 World
 <document>
  42.5
  World
 </document>
 my_class_t
</document>
------------------------
<document>
 0
 Hello!
</document>
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    object_t(const object_t& x) : self_(x.self_->copy_())
    { cout << "copy" << endl; }
    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
    { return *this = object_t(x); }
    object_t& operator=(object_t&&) noexcept = default;

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual unique_ptr<concept_t> copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual unique_ptr<concept_t> copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        unique_ptr<concept_t> copy_() const override
        { return make_unique<model>(*this); }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual unique_ptr<concept_t> copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        unique_ptr<concept_t> copy_() const override
        { return make_unique<model>(*this); }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

    unique_ptr<concept_t> self_;
};
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

};
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

    shared_ptr<concept_t> self_;
};
```

client | library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

};
```

cout | guidelines | defects

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

    shared_ptr<const concept_t> self_;
};
```

client | library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }
```

guidelines

- A shared pointer to an immutable (const) object has value semantics.
  - This is why passing arguments by const & works.
- Observation: Mutable polymorphic objects are the exception.
- Copy-on-write can be obtained using shared_ptr::unique().

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_unique<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};
```

client | library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};
```

cout | guidelines | defects

```
int main()
{
    history_t h(1);

    current(h).emplace_back(0);
    current(h).emplace_back(string("Hello!"));

    draw(current(h), cout, 0);
    cout << "-------------------------" << endl;

    commit(h);

    current(h)[0] = 42.5;
    current(h)[1] = string("World");
    current(h).emplace_back(current(h));
    current(h).emplace_back(my_class_t());

    draw(current(h), cout, 0);
    cout << "-------------------------" << endl;

    undo(h);

    draw(current(h), cout, 0);
}
```

client

library

cout

```
<document>
 0
 Hello!
</document>
-----------------------
<document>
 42.5
 World
 <document>
  42.5
  World
 </document>
 my_class_t
</document>
-----------------------
<document>
 0
 Hello!
</document>
```

```
int main()
{
    history_t h(1);

    current(h).emplace_back(0);
    current(h).emplace_back(string("Hello!"));

    draw(current(h), cout, 0);
    cout << "-------------------------" << endl;

    commit(h);

    current(h)[0] = 42.5;
```

```
    current(h)[1] = string("World");
    current(h).emplace_back(current(h));
    current(h).emplace_back(my_class_t());
```

```
int main()
{
    history_t h(1);

    current(h).emplace_back(0);
    current(h).emplace_back(string("Hello!"));

    draw(current(h), cout, 0);
    cout << "------------------------" << endl;

    commit(h);

    current(h)[0] = 42.5;

    auto saving = async([document = current(h)]() {
        this_thread::sleep_for(chrono::seconds(3));
        cout << "-------- 'save' --------" << endl;
        draw(document, cout, 0);
     });

    current(h)[1] = string("World");
    current(h).emplace_back(current(h));
    current(h).emplace_back(my_class_t());
```

cout

library

```
<document>
 0
 Hello!
</document>
------------------------
<document>
 42.5
 World
 <document>
  42.5
  World
 </document>
 my_class_t
</document>
------------------------
<document>
 0
 Hello!
</document>
-------- 'save' --------
<document>
 42.5
 Hello!
</document>
```

Compared To Inheritance Based Design

- More flexible
  - Non-intrusive design doesn't require class wrappers
- More efficient
  - Polymorphism is only paid for when needed
- Less error prone
  - Client doesn't do any heap allocation, worry about object ownership or lifetimes
  - Exception safe
- Thread safe

```
template <typename T>
void draw(const T& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
```

```
void draw(const T& x, ostream& out, size_t position)
{ out << string(position, ' ') << x << endl; }

class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };
```

client | library

```
{ out << string(position, ' ') << x << endl; }

class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };
```

cout | guidelines | defects

client | library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
```

cout | guidelines | defects

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
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        model(T x) : data_(move(x)) { }
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        { draw(data_, out, position); }

        T data_;
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```

client | library

```
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    { }

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    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
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    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};
```

cout | guidelines | defects

```
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;
```

client | library

```
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;
```

cout | guidelines | defects

```
    { }

    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
```

```
    friend void draw(const object_t& x, ostream& out, size_t position)
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
```

```
    friend void draw(const object_t& x, ostream& out, size_t position)
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  private:
    struct concept_t {
        virtual ~concept_t() = default;
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    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
```

```
    { x.self_->draw_(out, position); }

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
```

```
  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
```

```
  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
```

```
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
```

```
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;
```

client | library

```
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;
```

cout | guidelines | defects

```
    };
    template <typename T>
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

        T data_;
    };

   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
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using history_t = vector<document_t>;

void commit(history_t& x) { assert(x.size()); x.push_back(x.back()); }
```

```
    template <typename T>
    struct model final : concept_t {
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using history_t = vector<document_t>;

void commit(history_t& x) { assert(x.size()); x.push_back(x.back()); }
void undo(history_t& x) { assert(x.size()); x.pop_back(); }
```

client | library

```
    struct model final : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const override
        { draw(data_, out, position); }

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void draw(const document_t& x, ostream& out, size_t position)
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    for (const auto& e: x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;

void commit(history_t& x) { assert(x.size()); x.push_back(x.back()); }
void undo(history_t& x) { assert(x.size()); x.pop_back(); }
document_t& current(history_t& x) { assert(x.size()); return x.back(); }
```

cout | guidelines | defects

Concluding Remarks

- As we increasingly move to heavily threaded systems using futures, reactive programming, and task queues, value semantics becomes critical to avoid locking and to reason about code

- It is my hope that the language (and libraries) will evolve to make creating polymorphic types with value semantics easier

- Thanks to Alex Stepanov, Howard Hinnant, and Dave Abrahams

- http://sean-parent.stlab.cc/papers-and-presentations

- Stepanov, Alexander and Paul McJones. *Elements of Programming.* Addison-Wesley Professional, 2009.


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