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
- …

Goal: No 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

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

```
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;
}
```

client | library

```
int main()
{
    document_t document;

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

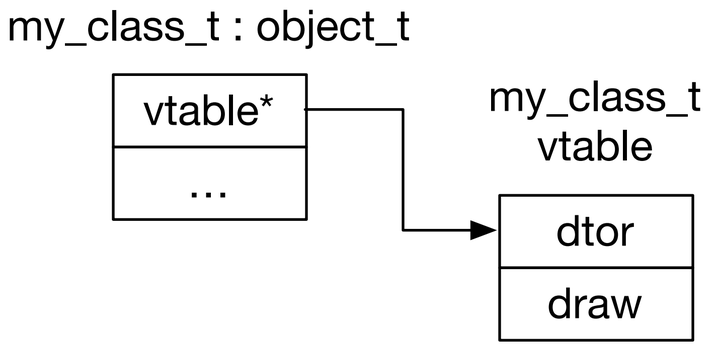
    draw(document, cout, 0);
}
```

cout | guidelines | defects

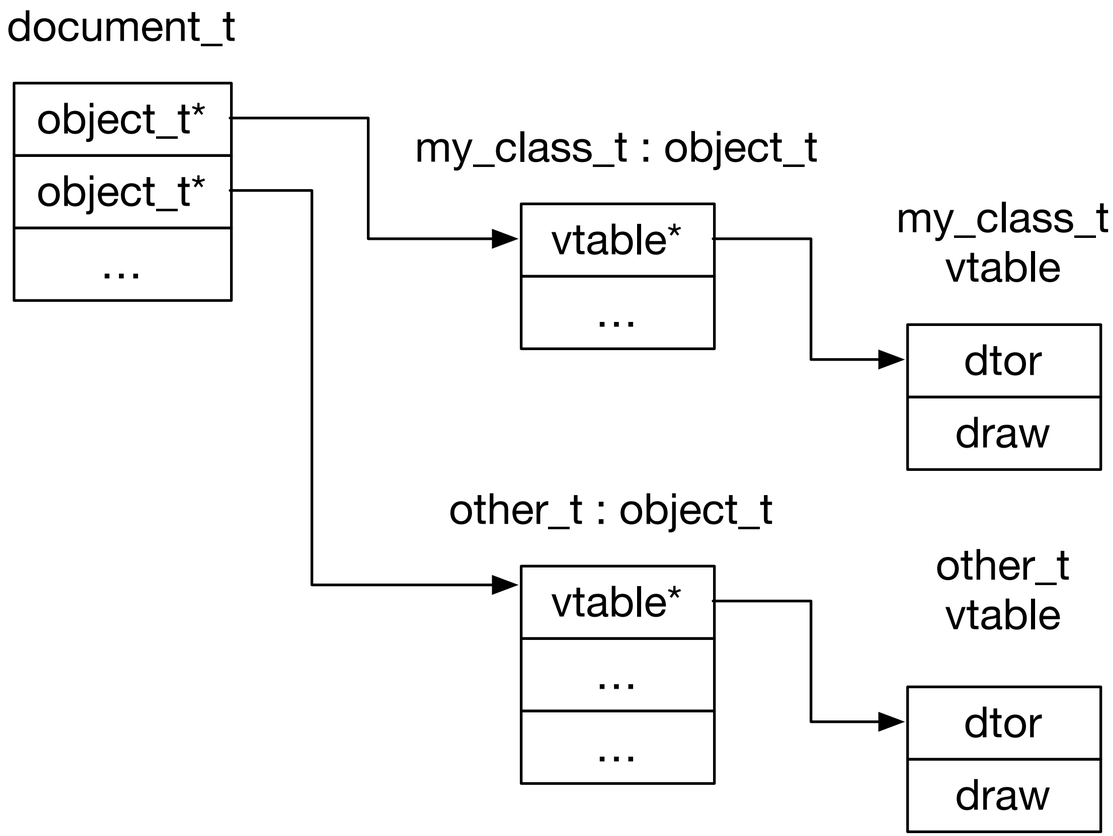
Runtime Polymorphism

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

Runtime Polymorphism



Runtime Polymorphism



```
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);
    out << string(position, ' ') << "</document>" << endl;
}
```

```
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);
}
```

Deep problem #1

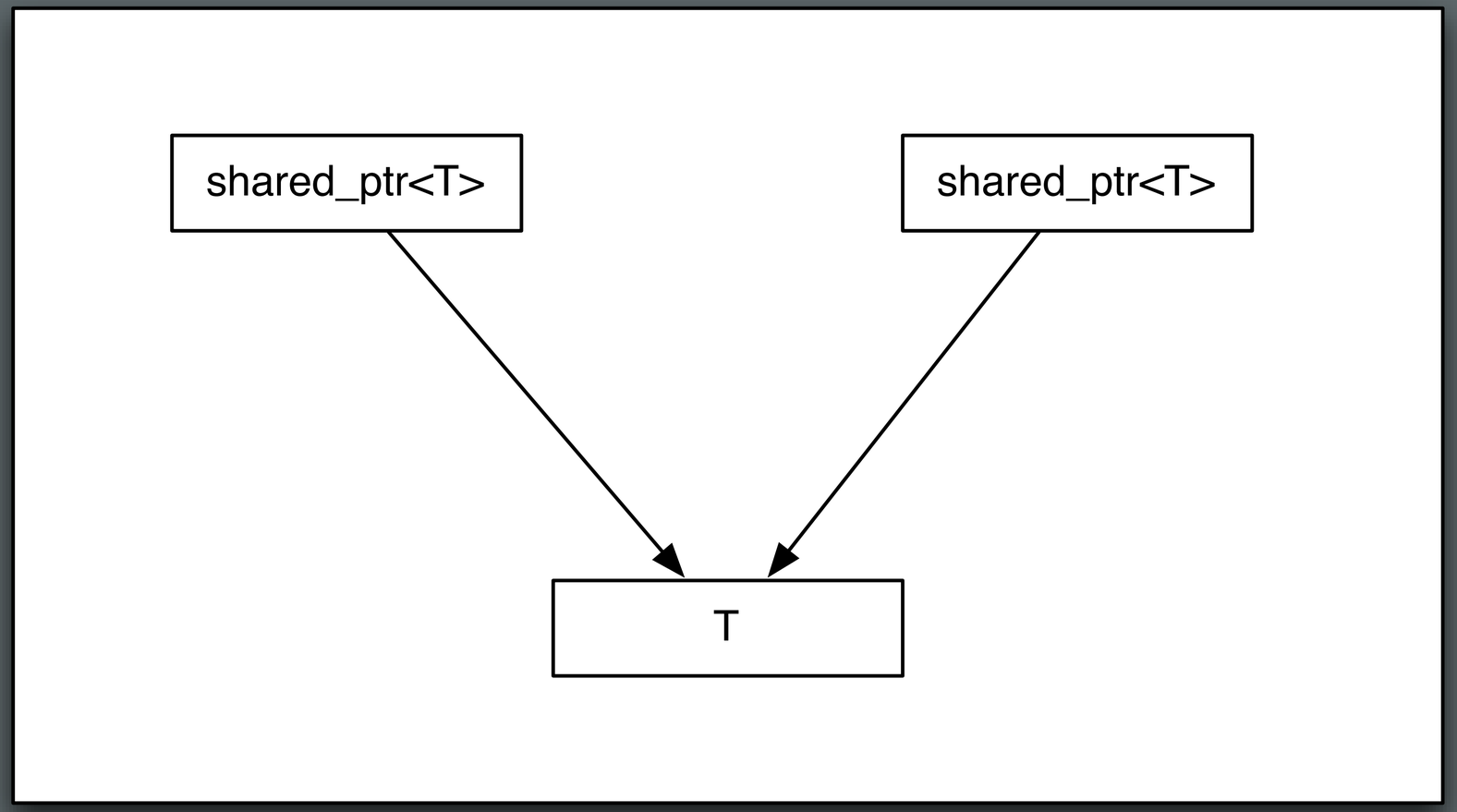
- Changed semantics of copy, assignment, and equality of my document
  - leads to *incidental data-structures*
  - thread safety concerns

Semantics & Syntax

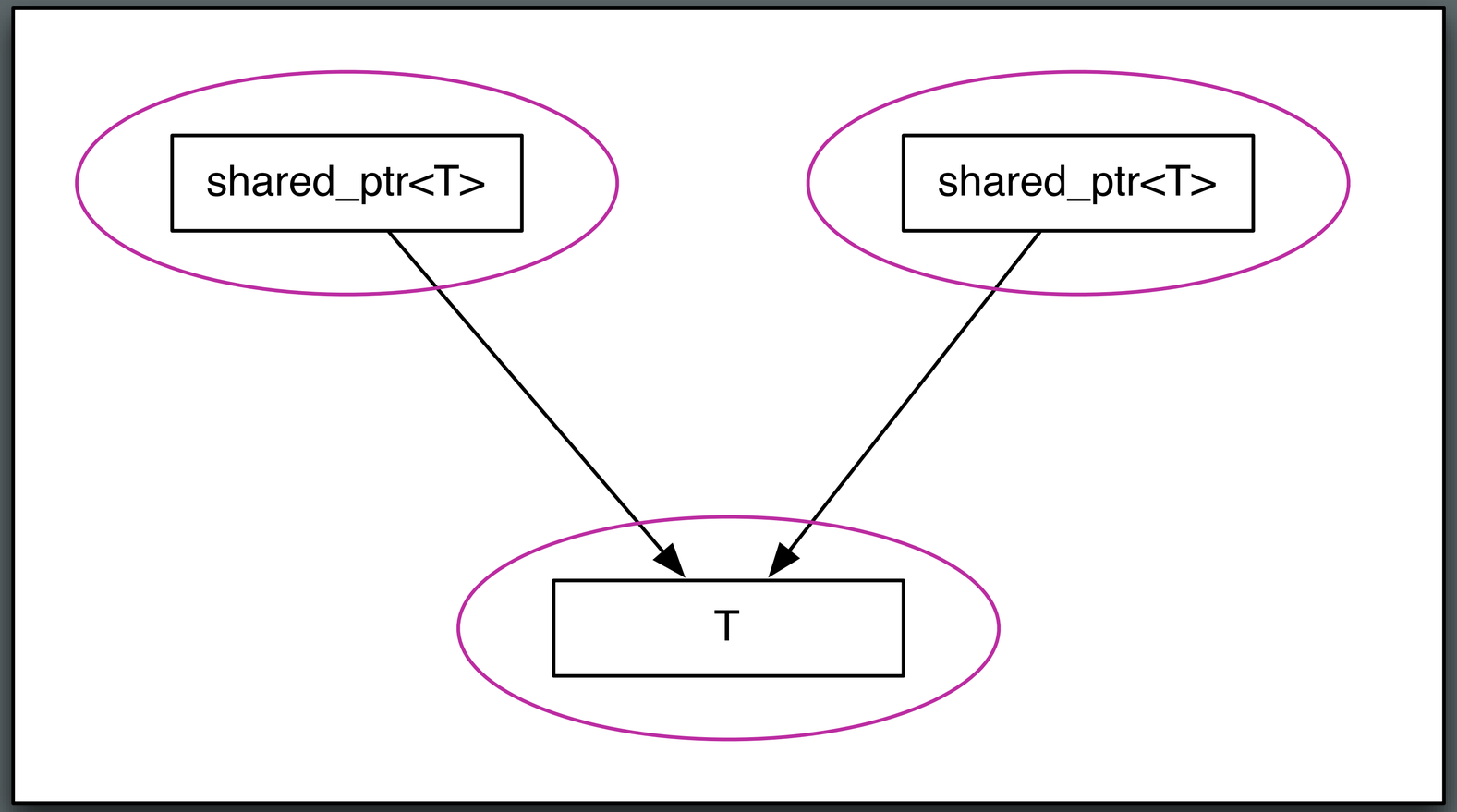
- We define an operation in terms of the operation's semantics:

"*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



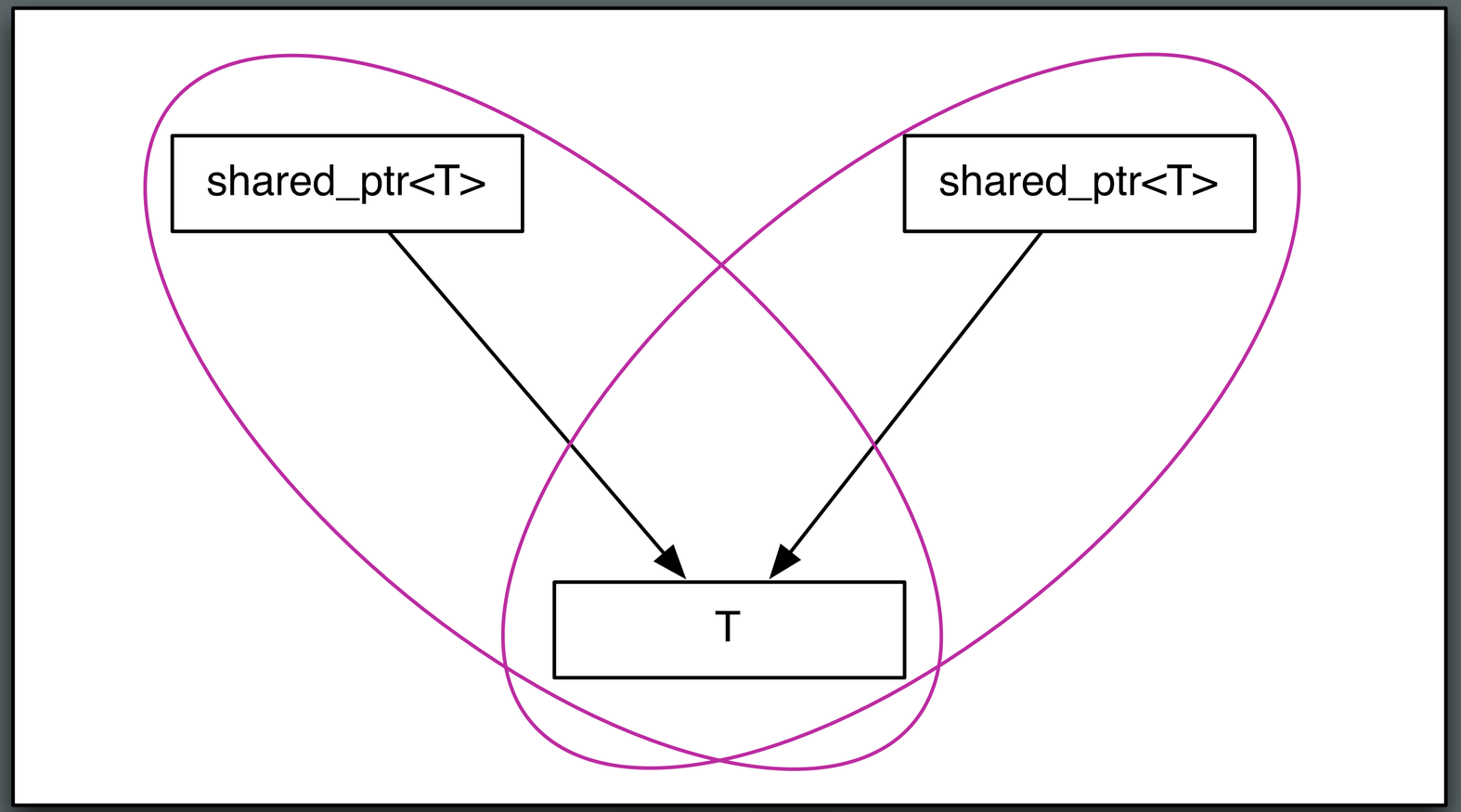
Semantics & Syntax



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

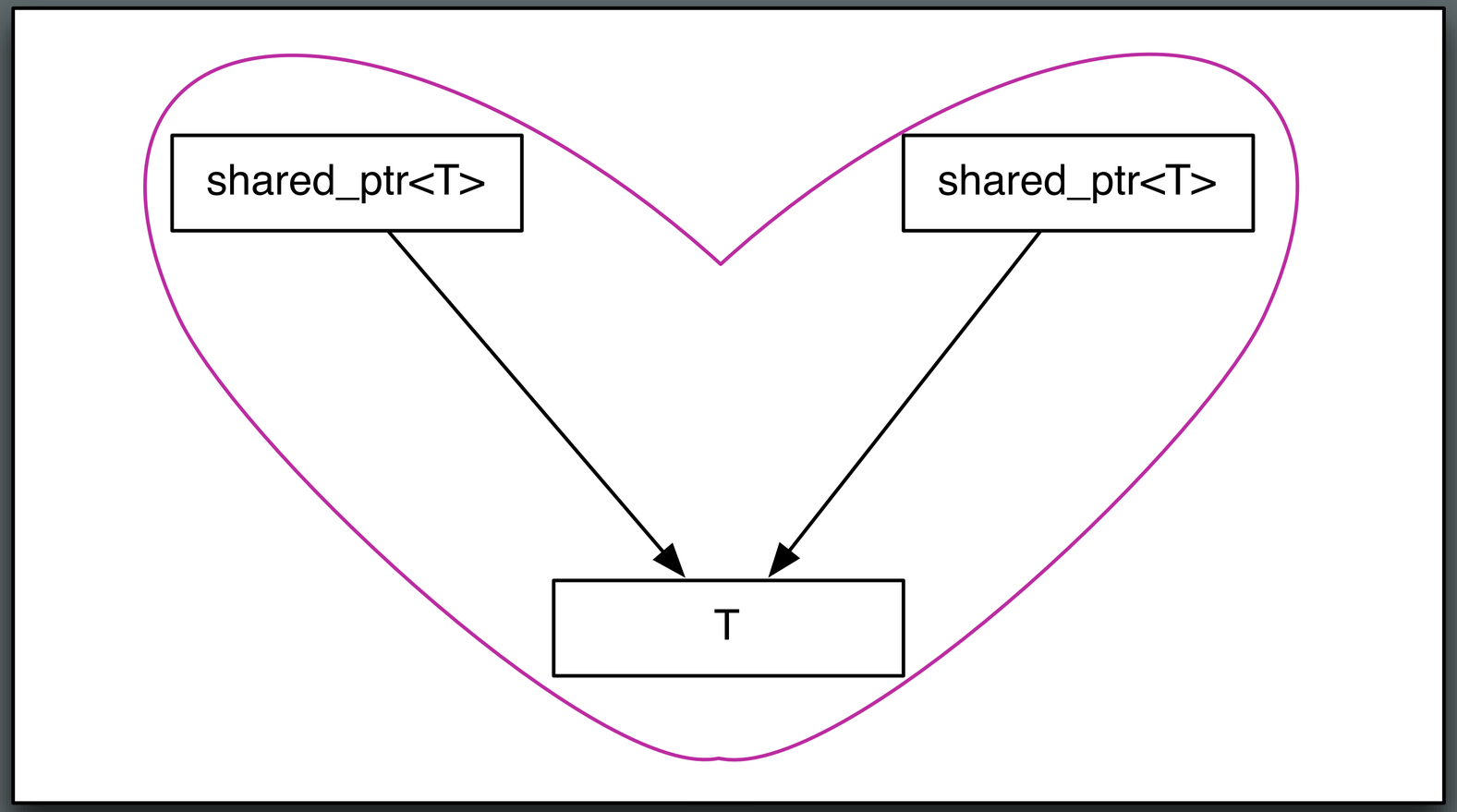
Semantics & Syntax



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



Semantics & Syntax

- When we consider the whole, the standard syntax for copy and assignment no longer have their regular semantics.
  - This structure is still copyable and assignable but these operations must be done through other means

- The shared structure also breaks our ability to reason locally about the code

A shared pointer is as good as a global variable

Semantics & Syntax

- Choosing the same syntax for the same semantics enables code reuse and avoids combinatoric interfaces
  - If a type has a proper set of basis operations then it can be adapted to any alternative set of basis operations regardless of syntax

- 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”

- The requirement of a polymorphic type, by definition, comes from it's use
- There are no polymorphic types, only a *polymorphic use* of similar types

“Polymorphic Types”

- By using inheritance to capture polymorphic use, we shift the burden of use to the type implementation, tightly coupling components
- Inheritance implies variable size, which implies heap allocation
- Heap allocation forces a further burden to manage the object lifetime
- Indirection, heap allocation, and virtualization, impacts performance
- Object lifetime management leads to garbage collection or reference counting
- This encourages *shared* ownership and the proliferation of *incidental data-structures*
- Shared ownership leads to synchronization issues, breaks local reasoning, and further impacts performance

Inheritance is the base class of Evil

```
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;
}
```

```
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;
}
```

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

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_;
};
```

```
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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    out << string(position, ' ') << "</document>" << endl;
}
```

```
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);
}
```

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

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_;
};

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;
}
```

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

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_;
};

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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    out << string(position, ' ') << "</document>" << endl;
}
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    object_t(const int& x) : self_(x)
    { }

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

```
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)
{
    out << string(position, ' ') << "<document>" << endl;
```

```
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:
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        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>;
```

```
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_;
};
```

```
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

```
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); 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); 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

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

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

    object_t x = func();
}
```

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

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

    object_t x = 0;

    x = func();
}
```

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

        int data_;
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   unique_ptr<int_model_t> self_;
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cout | guidelines | defects

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

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

    object_t x = 0;

    x = func();
}
```

```
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);
}
```

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

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

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

    some_t x = { 0 };

    x = func();
}
```

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

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    { 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_;
    };
```

```
struct some_t {
    object_t member_;
};

some_t func() { return { 5 }; }

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

    some_t x = { 0 };

    x = func();
}
```

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

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

    object_t(const object_t& x) : self_(make_unique<int_model_t>(*x.self_))
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client | library

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cout | guidelines | defects

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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);
}
```

```
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);
}
```

```
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)
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```
template <typename T>
void draw(const T& x, ostream& out, size_t position)
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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); }

      string data_;
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  struct int_model_t final : concept_t {
      int_model_t(int x) : data_(move(x)) { }
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      void draw_(ostream& out, size_t position) const override
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  friend void draw(const object_t& x, ostream& out, size_t position)
  { x.self_->draw_(out, position); }

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using document_t = vector<object_t>;

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

```
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);
}
```

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

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

int main()
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    document.emplace_back(string("Hello!"));
    document.emplace_back(document);
    document.emplace_back(my_class_t());

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

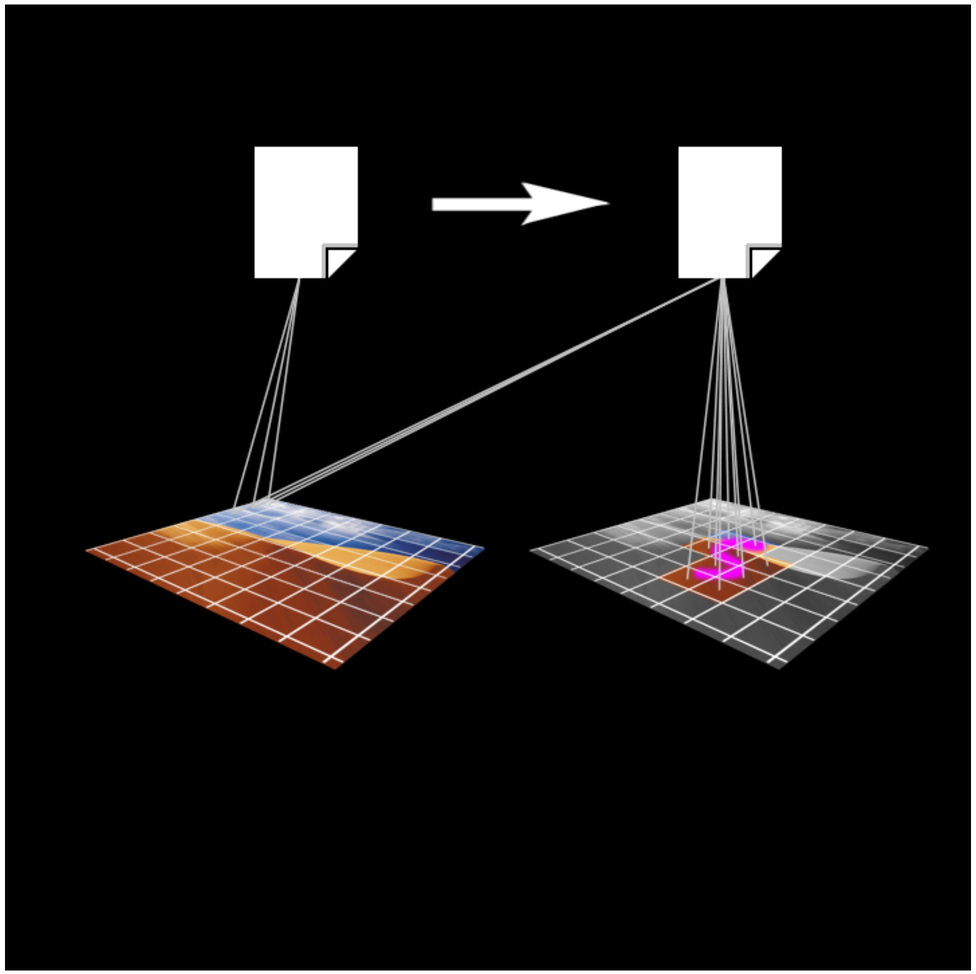
Polymorphic Use

- 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);
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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)) { }
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client | library

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        virtual void draw_(ostream&, size_t) const = 0;
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client | library

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  { 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_;
```

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```
  object_t(const object_t& x) : self_(x.self_->copy_())
  { }
  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); }

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      virtual unique_ptr<concept_t> copy_() const = 0;
      virtual void draw_(ostream&, size_t) const = 0;
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      void draw_(ostream& out, size_t position) const override
      { draw(data_, out, position); }
```

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```
  object_t(const object_t& x) : self_(x.self_->copy_())
  { }
  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); }

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

```
  { }

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

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

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```
  object_t(T x) : self_(make_unique<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)
  { object_t tmp(x); *this = move(tmp); return *this; }
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  friend void draw(const object_t& x, ostream& out, size_t position)
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      virtual ~concept_t() = default;
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  };
  template <typename T>
  struct model final : concept_t {
      model(T x) : data_(move(x)) { }
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      { return make_unique<model>(*this); }
```

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

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

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

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  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
```

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

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

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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_())
    { }
    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;

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    { 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 {
```

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

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

    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)
    { 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 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 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);
}
```

```
    /* ... */
};

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);
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    draw(document, cout, 0);
}
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```
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void draw(const my_class_t&, ostream& out, size_t position)
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int main()
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}
```

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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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```

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

int main()
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    document_t document;

    document.emplace_back(0);
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    draw(document, cout, 0);
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```

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

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```

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    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);
}
```

```
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;
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    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);
}
```

```
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)
    { 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 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;
    };
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    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_;
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    struct concept_t {
        virtual ~concept_t() = default;
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    };
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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_;
    };

    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_;
    };

    shared_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_;
    };

    shared_ptr<const 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;
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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_;
};
```

```
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_;
};
```

```
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;

    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());
```

```
------- '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;
    };
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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_;
```

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```
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;
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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_;
    };
```

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

        T data_;
    };
```

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```
class object_t {
  public:
    template <typename T>
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    { }

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

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    struct concept_t {
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        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)
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        { draw(data_, out, position); }

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

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  public:
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document_t& current(history_t& x) { assert(x.size()); return x.back(); }
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Concluding Remarks

- As we increasingly move to heavily threaded systems using promises, 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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