Value Semantics and Concept Based Polymorphism

Sean Parent | Principal Scientist

Outline of Talk

- Defining Value Semantics
- “Polymorphic Types”
- Demo of Photoshop History
- Implement History

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 (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

Polymorphism

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

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

client library

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


int main()
{
    document_t document;

    document.emplace_back(new my_class_t());

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

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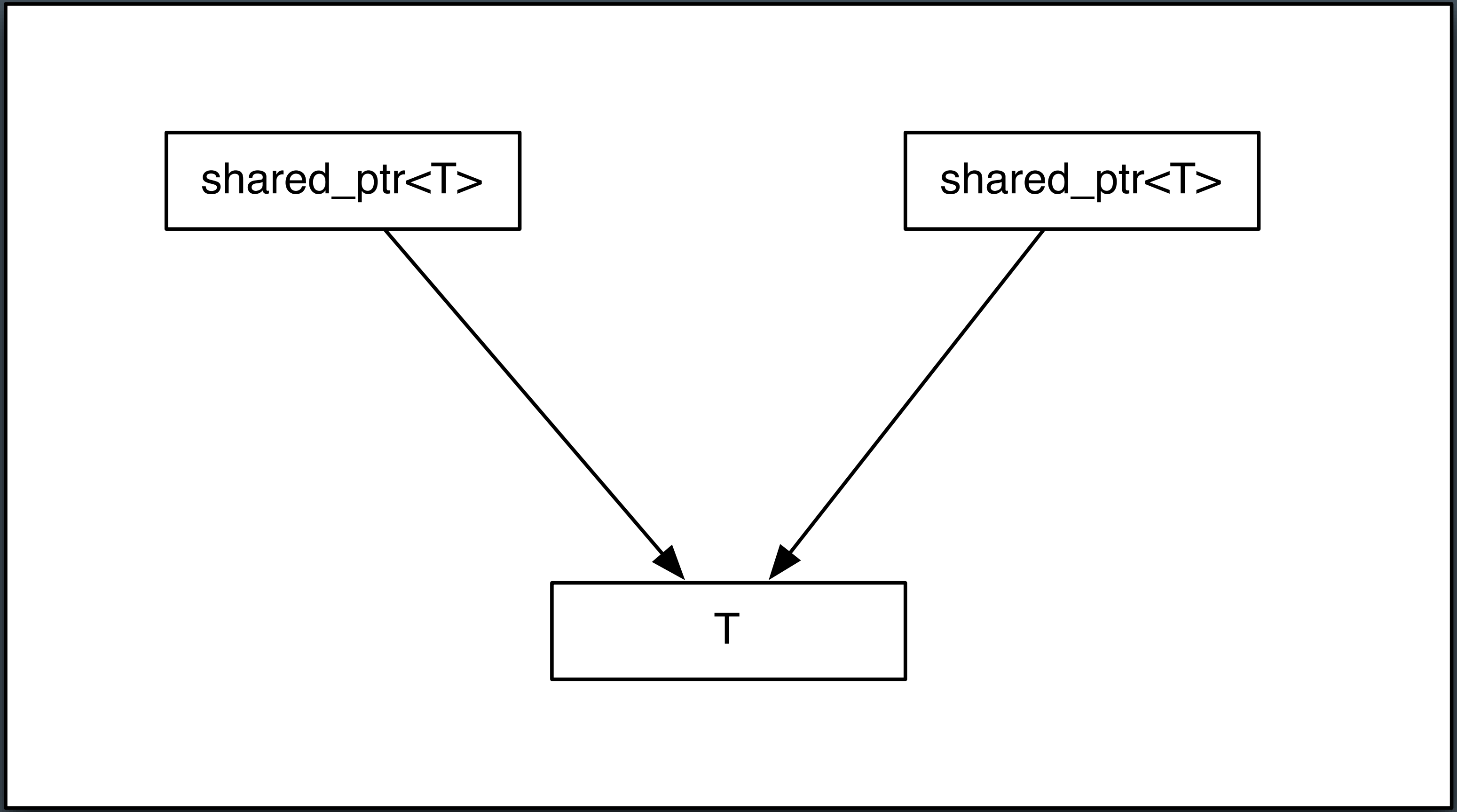
Deep problem #1

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

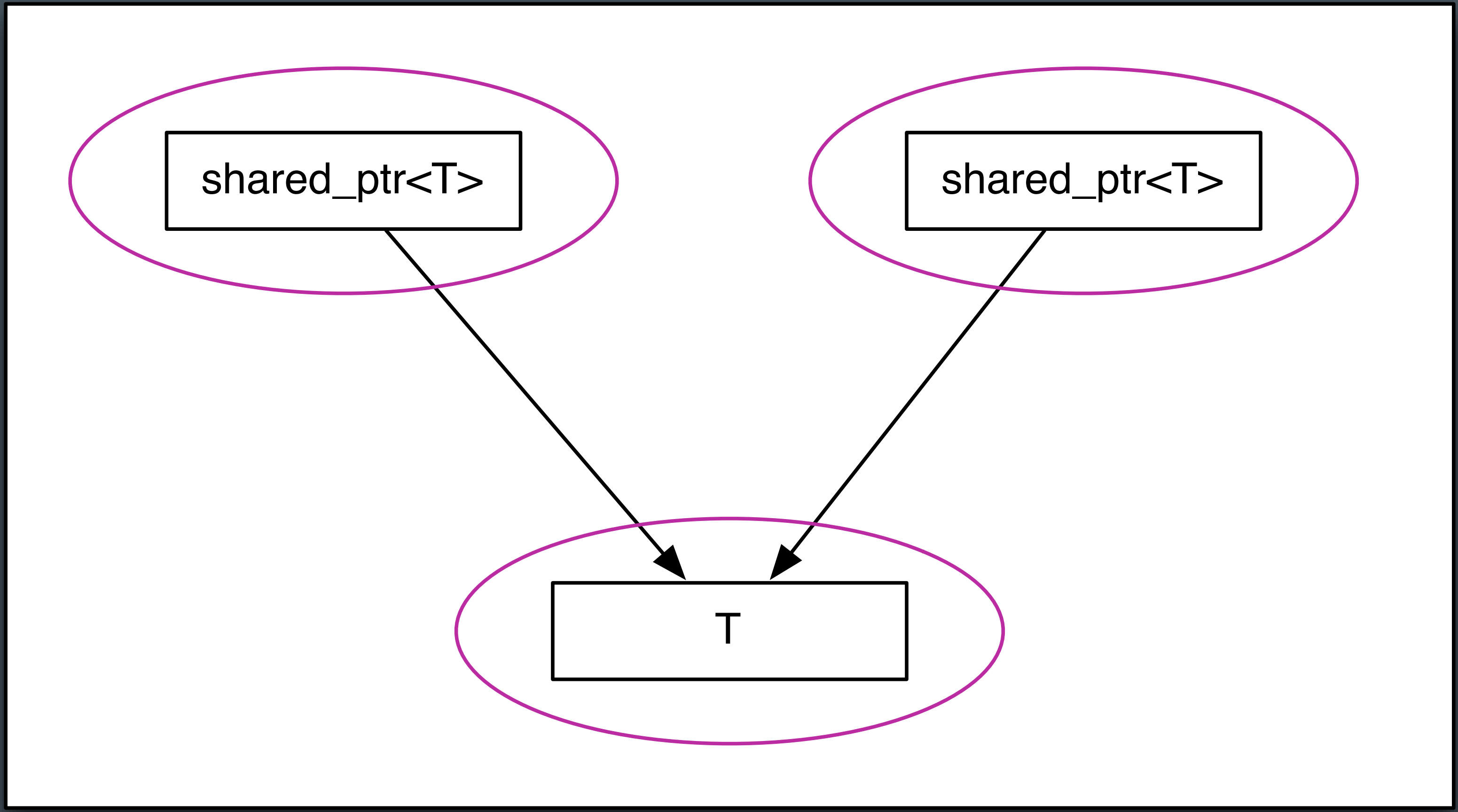
Semantics & Syntax

- 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."

Semantics & Syntax



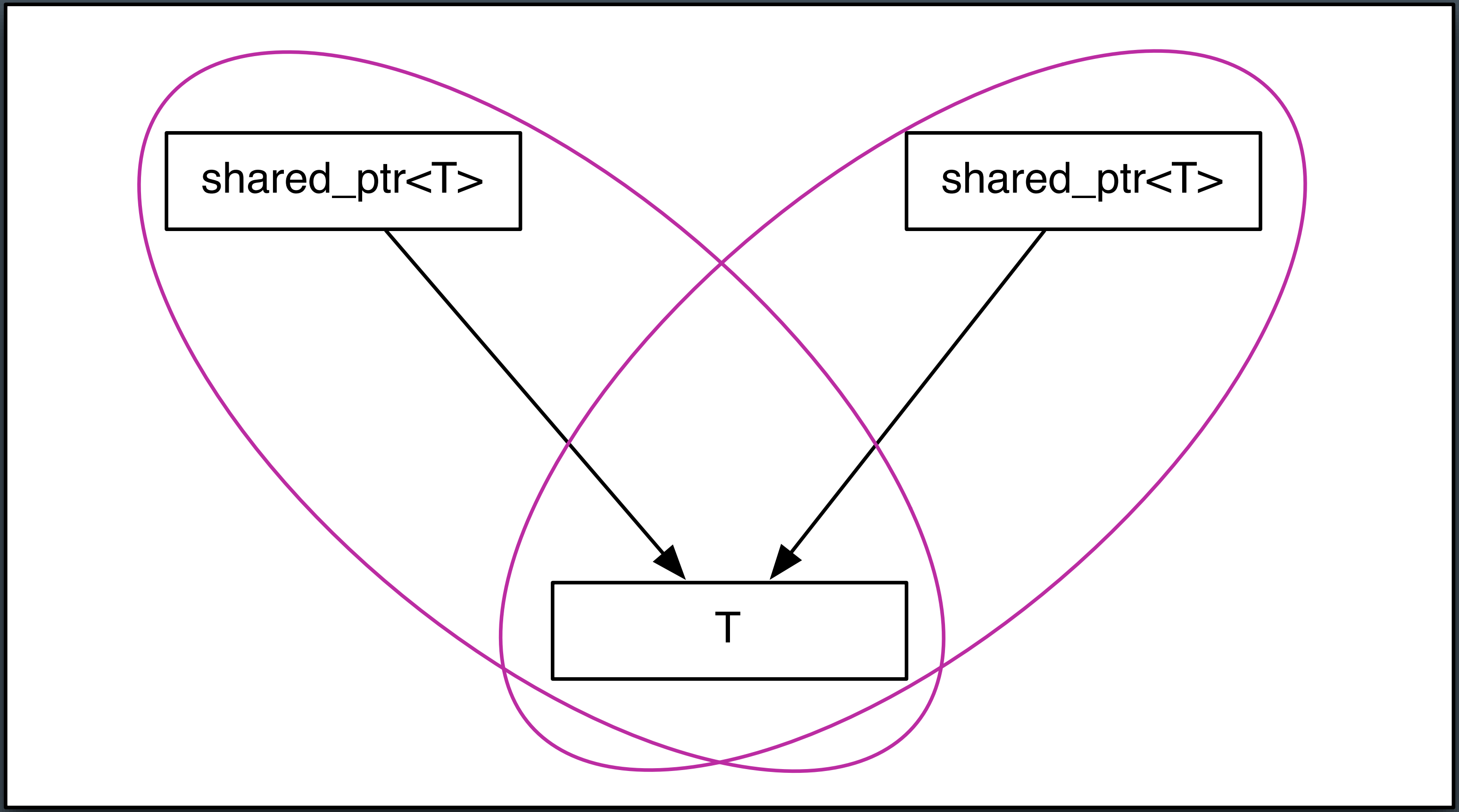
Semantics & Syntax



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

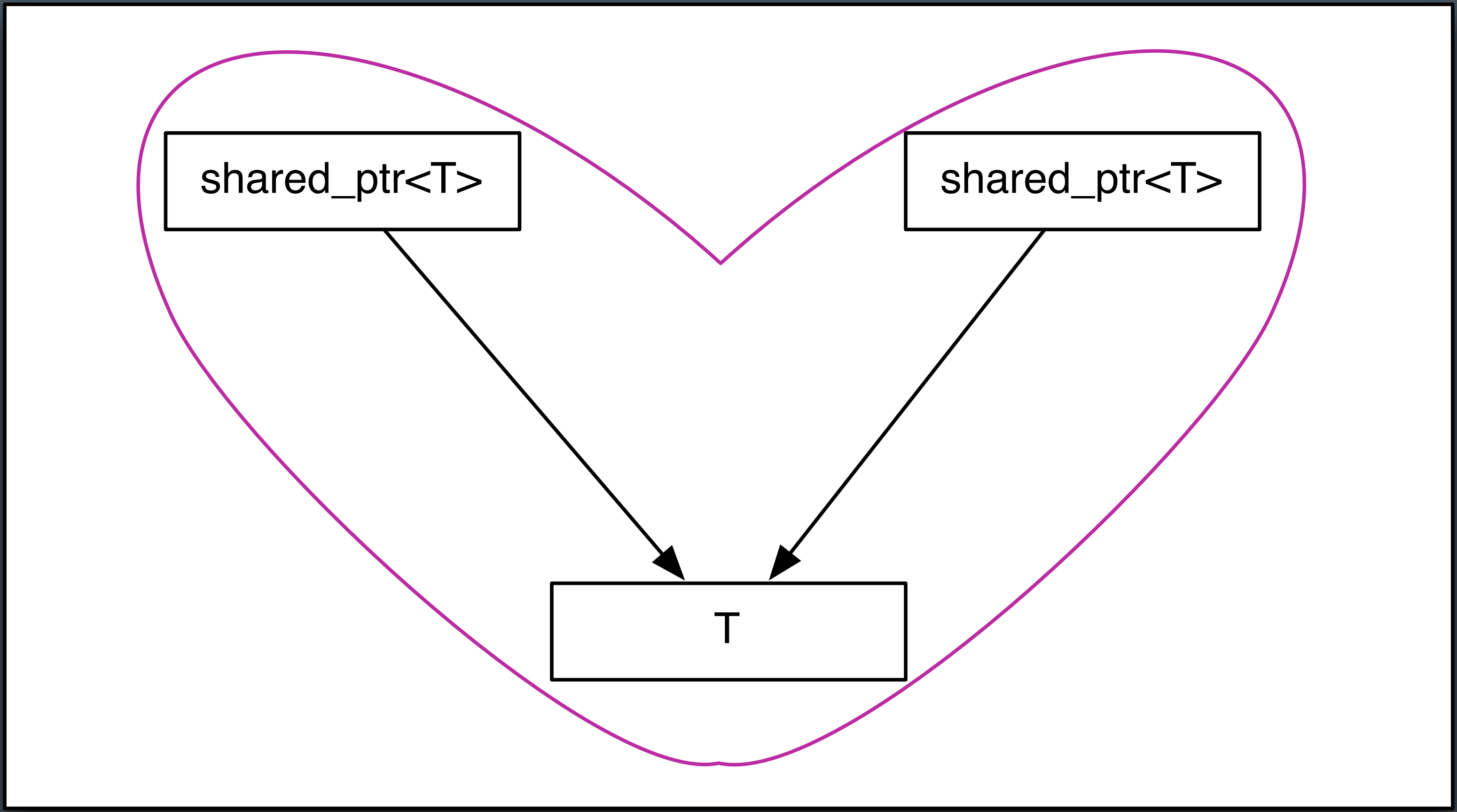
Semantics & Syntax



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*

Semantics & Syntax

- The shared structure also breaks our ability to reason locally about the code
  - A shared pointer is as good as a global variable

Deep problem #2

- Inefficient
  - calls to draw() on my_class_t are *always* virtual as is 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, 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 (auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
```

client library

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using object_t = int;

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cout guidelines defects

client | library

```
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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```
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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```
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  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); }

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}
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client library

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

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client library

```
class object_t {
  public:
    object_t(const int& x) : self_(new 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;
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client library

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class object_t {
  public:
    object_t(const int& x) : self_(new int_model_t(x))
    { }

    object_t(const object_t& x) : self_(new 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
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using document_t = vector<object_t>;
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  public:
    object_t(const int& x) : self_(new int_model_t(x))
    { }

    object_t(const object_t& x) : self_(new 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_;
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};
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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

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class object_t {
  public:
    object_t(const int& x) : self_(new int_model_t(x))
    { }

    object_t(const object_t& x) : self_(new 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)
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        void draw_(ostream& out, size_t position) const
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        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

client library

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

    object_t(const object_t& x) : self_(new 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();
}
```

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 guidelines defects

client library

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

    object_t(const object_t& x) : self_(new 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_;
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client library

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class object_t {
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    { cout << "ctor" << endl; }

    object_t(const object_t& x) : self_(new 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:
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cout guidelines defects

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

    object_t x = 0;

    x = func();
}
```

cout guidelines defects

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 guidelines defects

client library

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

    object_t(const object_t& x) : self_(new 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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cout guidelines defects

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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); }

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    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();
}
```

client library

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

    object_t(const object_t& x) : self_(new 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:
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        void draw_(ostream& out, size_t position) const
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    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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```
struct some_t {
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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

client library

```
class object_t {
  public:
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    { cout << "ctor" << endl; }

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        void draw_(ostream& out, size_t position) const
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cout guidelines defects

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cout guidelines defects

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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
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        int data_;
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class object_t {
  public:
    object_t(const int& x) : self_(new int_model_t(x))
    { }

    object_t(const object_t& x) : self_(new int_model_t(*x.self_))
    { }
    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)
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client library

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  public:
    object_t(string x) : self_(new string_model_t(move(x)))
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cout guidelines defects

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cout guidelines defects

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cout guidelines defects

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cout guidelines defects

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cout guidelines defects

client library

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cout guidelines defects

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client library

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

      int data_;
```

cout guidelines defects

```
  { 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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  struct concept_t {
      virtual ~concept_t() = default;
      virtual void draw_(ostream&, size_t) const = 0;
  };
  struct string_model_t : concept_t {
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client library

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cout guidelines defects

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cout guidelines defects

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

client library

```
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);
}
```

cout guidelines defects

client library

```
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_(new string_model_t(move(x)))
    { }
    object_t(int x) : self_(new 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)
    { 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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cout guidelines defects

client library

```
template <typename T>
void draw(const T& x, ostream& out, size_t position)
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cout guidelines defects

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cout guidelines defects

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        string data_;
    };
    struct int_model_t : concept_t {
        int_model_t(int x) : data_(move(x)) { }
        concept_t* copy_() const { return new int_model_t(*this); }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        int data_;
    };
```

```
private:
  struct concept_t {
      virtual ~concept_t() = default;
      virtual concept_t* copy_() const = 0;
      virtual void draw_(ostream&, size_t) const = 0;
  };
  struct string_model_t : concept_t {
      string_model_t(string x) : data_(move(x)) { }
      concept_t* copy_() const { return new string_model_t(*this); }
      void draw_(ostream& out, size_t position) const
      { draw(data_, out, position); }

      string data_;
  };
  struct int_model_t : concept_t {
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 unique_ptr<concept_t> self_;
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    template <typename T>
    struct model : concept_t {
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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;
    for (auto& e : x) draw(e, out, position + 2);
```

cout guidelines defects

```
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

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

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

cout guidelines defects

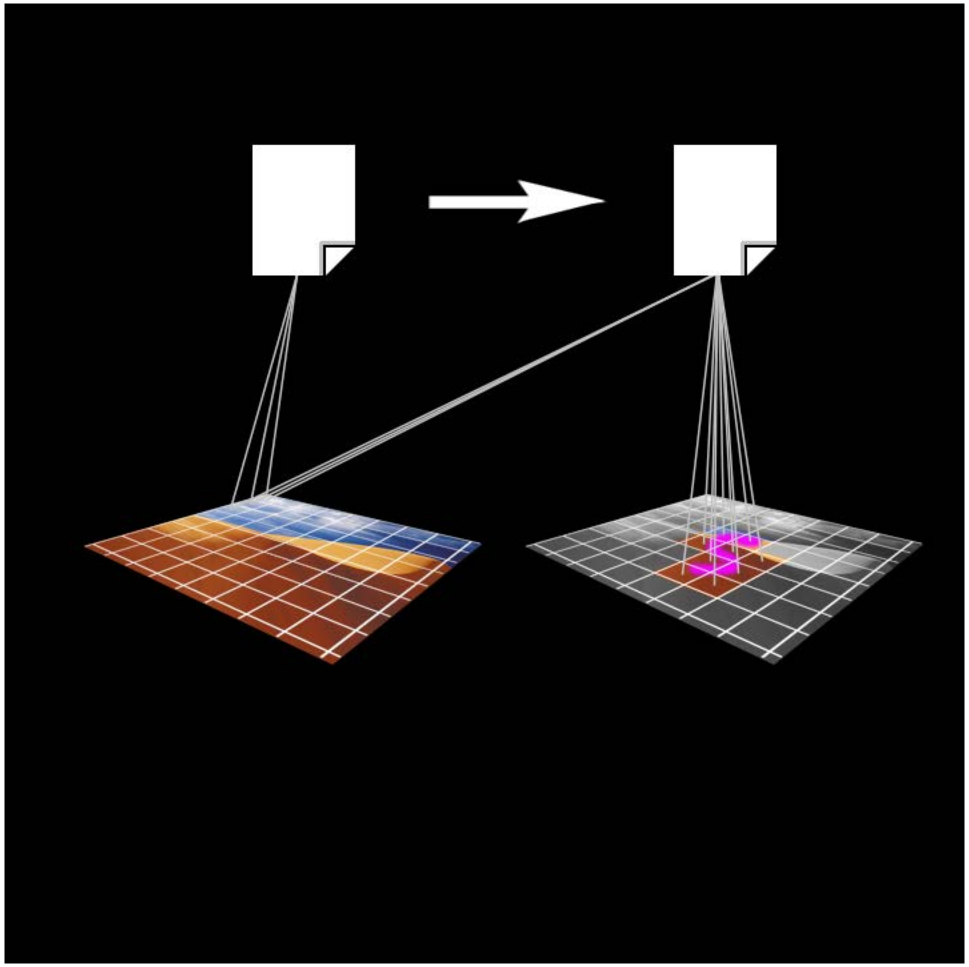
Polymorphic Use

- 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 regular semantics, and often times there are performance benefits from a decreased use of the heap

Demo

Photoshop History

Photoshop History



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        concept_t* copy_() const { return new model(*this); }
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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;
    for (auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
```

client library

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        concept_t* copy_() const { return new model(*this); }
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    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

client library

```
        model(T x) : data_(move(x)) { }
        concept_t* copy_() const { return new model(*this); }
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cout guidelines defects

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    out << string(position, ' ') << "<document>" << endl;
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client library

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cout guidelines defects

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    object_t(object_t&&) noexcept = default;

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

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

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

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

```
public:
  template <typename T>
  object_t(T x) : self_(new 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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  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 concept_t* copy_() const = 0;
      virtual void draw_(ostream&, size_t) const = 0;
  };
  template <typename T>
  struct model : concept_t {
      model(T x) : data_(move(x)) { }
```

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

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    object_t(object_t&&) noexcept = default;

    object_t& operator=(const object_t& x)
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    { x.self_->draw_(out, position); }

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

client library

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class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new model<T>(move(x)))
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        virtual concept_t* copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model : concept_t {
```

cout guidelines defects

client library

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class object_t {
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    { }

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

cout guidelines defects

```
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);
    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; }

int main()
{
    document_t document;

    document.emplace_back(0);
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    document.emplace_back(my_class_t());

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

```
void draw(const my_class_t&, ostream& out, size_t position)
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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);
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```

client library

```
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!"));
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    document.emplace_back(my_class_t());

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

cout guidelines defects

```
{ 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);
}
```

client library

```
{ 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);
}
```

cout guidelines defects

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

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

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

    undo(h);

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

client library

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

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

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

    undo(h);

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

cout guidelines defects

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new 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 concept_t* copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model : concept_t {
```

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new 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 concept_t* copy_() const = 0;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model : concept_t {
        model(T x) : data_(move(x)) { }
        concept_t* copy_() const { return new model(*this); }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        T data_;
    };
```

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

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

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

        T data_;
    };
```

client library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new 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 : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        T data_;
    };

    unique_ptr<concept_t> self_;
};
```

cout guidelines defects

client library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new 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 : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        T data_;
    };

    shared_ptr<concept_t> self_;
};
```

cout guidelines defects

client library

```
class object_t {
  public:
    template <typename T>
    object_t(T x) : self_(new 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 : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { 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_(new 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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    };
    template <typename T>
    struct model : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { 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 : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { draw(data_, out, position); }

        T data_;
    };

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

cout guidelines defects

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

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

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

    undo(h);

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

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

        T data_;
```

client library

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

        T data_;
    };
```

cout guidelines defects

```
{ 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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```
class object_t {
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        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { 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)))
    { }

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

        T data_;
    };

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};
```

cout guidelines defects

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

        T data_;
    };

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};
```

```
    template <typename T>
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
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        void draw_(ostream& out, size_t position) const
        { 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); }

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

client library

```
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    struct concept_t {
        virtual ~concept_t() = default;
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        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { 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;
```

cout guidelines defects

client library

```
    { 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 : concept_t {
        model(T x) : data_(move(x)) { }
        void draw_(ostream& out, size_t position) const
        { 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 (auto& e : x) draw(e, out, position + 2);
```

cout guidelines defects

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

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        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
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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(); }
```

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

Adobe