Inheritance Is The Base Class of Evil

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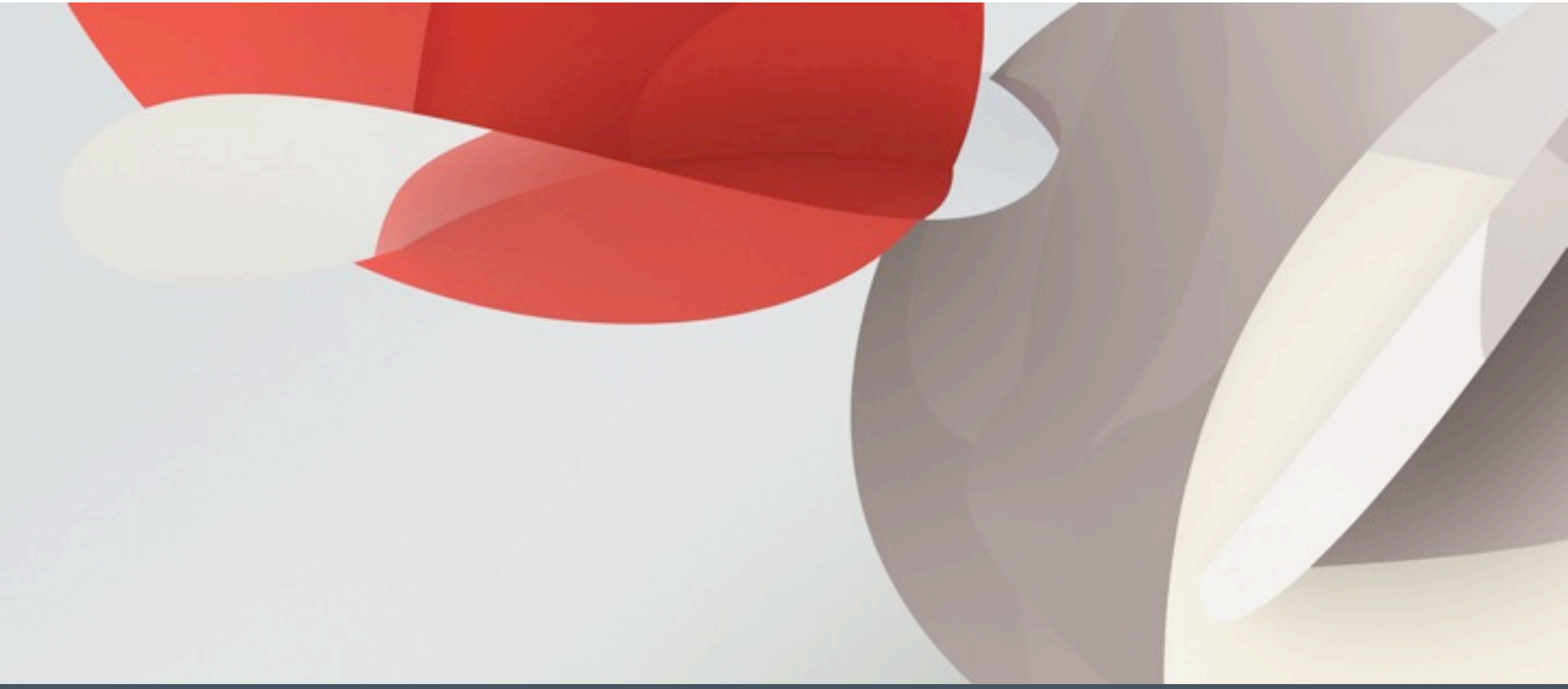

Recap from Seasoning Talk

- Goal: No Raw Pointers
- Indirection through pointers
  - Changes semantics of copy, assignment, and equality
  - Incidental data structures
  - Thread safety concerns
  - Inefficient
  - Shared pointer as good as a global variable

Another Deep problem

- Inheritance is intrusive

“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 (const auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
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void draw(const int& x, ostream& out, size_t position)
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class object_t {
  public:
    object_t(const int& x) : self_(x)
    { }

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

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

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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);
}
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void draw(const int& x, ostream& out, size_t position)
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    out << string(position, ' ') << "</document>" << endl;
}
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```
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_;
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using document_t = vector<object_t>;

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    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)
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    draw(document, cout, 0);
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class object_t {
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    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)
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    struct int_model_t {
        int_model_t(const int& x) : data_(x) { }
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        { draw(data_, out, position); }

        int data_;
    };

   unique_ptr<int_model_t> self_;
};
```

client | library

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

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

    object_t x = func();
}
```

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

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

    object_t x = 0;

    x = func();
}
```

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class object_t {
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int main()
{
    document_t document;
    document.reserve(5);

    document.emplace_back(0);
    document.emplace_back(1);
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```
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_(new int_model_t(*x.self_))
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private:
    struct string_model_t {
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        { draw(data_, out, position); }

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

  private:
```

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

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      int data_;
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      virtual 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
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      { draw(data_, out, position); }

      int data_;
  };
```

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);
}
```

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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)))
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    object_t(const object_t& x) : self_(x.self_->copy_())
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cout | guidelines | defects

```
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_(new model<T>(move(x)))
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{ out << string(position, ' ') << x << endl; }

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

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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); }

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```
   unique_ptr<concept_t> self_;
};

using document_t = vector<object_t>;

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

```
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);
}
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```
class my_class_t {
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Polymorphic Use

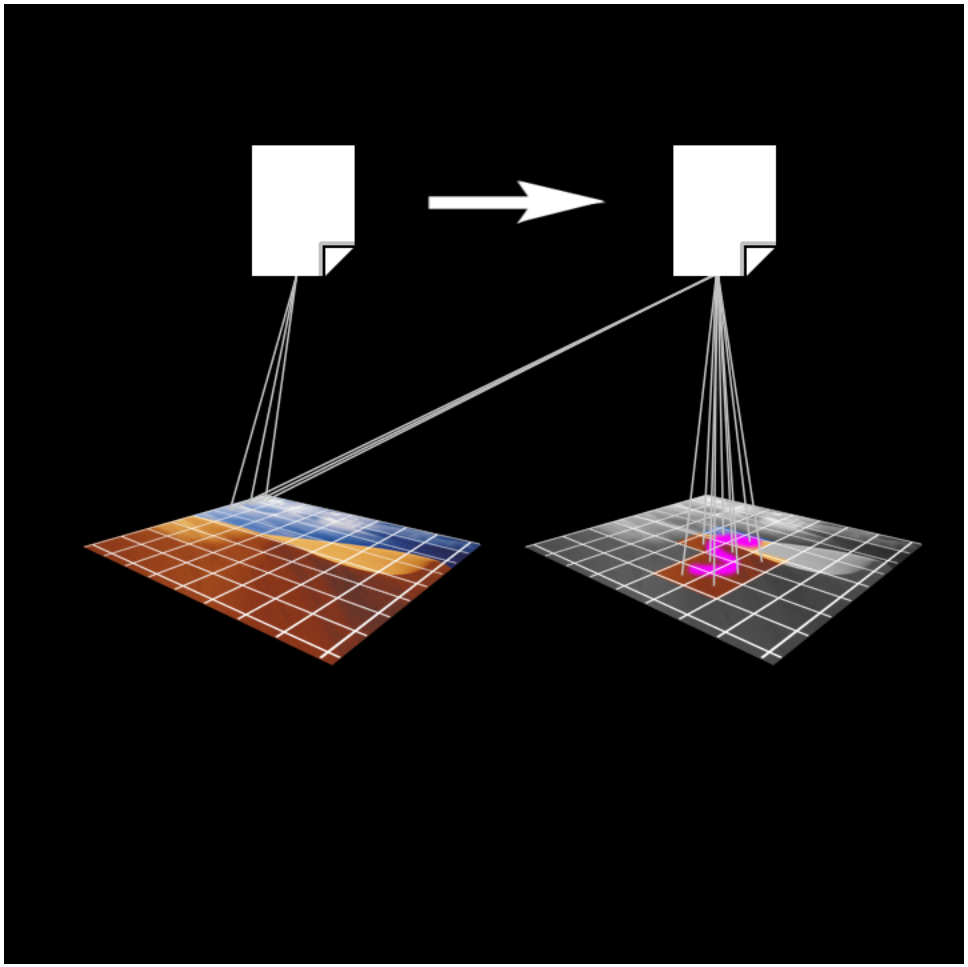
- Shifting polymorphism from type to use allows for greater reuse and fewer dependencies
- Using regular semantics for the common basis operations, copy, assignment, and move helps to reduce shared objects
- Regular types promote interoperability of software components, increases productivity as well 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

Adobe

Photoshop History



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using document_t = vector<object_t>;

void draw(const document_t& x, ostream& out, size_t position)
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    out << string(position, ' ') << "<document>" << endl;
    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(); }
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        model(T x) : data_(move(x)) { }
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void undo(history_t& x) { assert(x.size()); x.pop_back(); }
```

```
    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_;
    };

  unique_ptr<concept_t> self_;
};

using document_t = vector<object_t>;

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

using history_t = vector<document_t>;

void commit(history_t& x) { assert(x.size()); x.push_back(x.back()); }
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    };
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    for (const auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;
```

```
        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); }

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        virtual ~concept_t() = default;
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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;
```

```
    { 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>
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        concept_t* copy_() const { return new model(*this); }
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        { draw(data_, out, position); }

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    { 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:
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      { draw(data_, out, position); }

      T data_;
  };

 unique_ptr<concept_t> 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; }
  object_t& operator=(object_t&&) noexcept = default;

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

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```

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

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

```
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_())
    { }
    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 {
```

```
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    };
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```

```
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 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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client | library

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

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{ 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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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

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 {
```

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 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_;
    };
```

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;
        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); }

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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_;
};
```

```
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_;
};
```

```
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_;
};
```

```
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_;
};
```

```
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_;
};
```

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```
{ 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

Compared To Inheritance Based Design

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

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

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

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

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

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

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

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

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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_;
```

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

        T data_;
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```

```
  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 : concept_t {
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        { draw(data_, out, position); }

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

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using document_t = vector<object_t>;
```

```
    object_t(T x) : self_(make_shared<model<T>>(move(x)))
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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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using document_t = vector<object_t>;
```

```
    { }

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

        T data_;
    };

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};

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

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   shared_ptr<const concept_t> self_;
};

using document_t = vector<object_t>;

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

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

  private:
    struct concept_t {
        virtual ~concept_t() = default;
        virtual void draw_(ostream&, size_t) const = 0;
    };
    template <typename T>
    struct model : 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 (const auto& e : x) draw(e, out, position + 2);
```

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

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

```
  private:
    struct concept_t {
        virtual ~concept_t() = default;
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    template <typename T>
    struct model : concept_t {
        model(T x) : data_(move(x)) { }
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    out << string(position, ' ') << "</document>" << endl;
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void draw(const document_t& x, ostream& out, size_t position)
{
    out << string(position, ' ') << "<document>" << endl;
    for (const auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}
```

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

using document_t = vector<object_t>;

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

using history_t = vector<document_t>;
```

```
        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_;
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   shared_ptr<const concept_t> self_;
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    out << string(position, ' ') << "</document>" << endl;
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    };
    template <typename 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_;
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   shared_ptr<const concept_t> self_;
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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 (const auto& e : x) draw(e, out, position + 2);
    out << string(position, ' ') << "</document>" << endl;
}

using history_t = vector<document_t>;

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

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

using history_t = vector<document_t>;

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

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

using history_t = vector<document_t>;

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

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


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