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Making Inheritance Work: C++ Issues

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Contents:

Recording

These slides accompany a recorded video: Play Video

1 Base Class Function Members

Even if you override a function, the inherited bodies are still available to you.

```cpp
class Person {
public:
  string name;
  long id;
  void print(ostream& out) {
    out << name << " " << id << endl;}
};

class Student: public Person {
public:
  string school;
  void print(ostream& out) {Person::print(out);
                   out << school << endl;}
}
```

Base Class Constructors

This technique is often used in constructors so that subclasses will only need to initialize their own new data members:

```cpp
class Person {
public:
  string name;
  long id;
  Person (string n, long i)
    : name(n), id(i)
  {}
};

class Student: public Person {
public:
  string school;
  Student (string name, long id, School s)
    : Person(name, id), school(s)
  {}
}
```

2 Assignment and Subtyping

2.1 Implementing Data Member Inheritance

Inheritance of data members is achieved by treating all new members as extensions of the base class:

```cpp
class Person {
public:
  string name;
  long id;
};

class Student: public Person {
public:
  string school;
}
```

Extending Data Members

- When a compiler processes data member declarations, it assigns a byte offset to each one.

- Inherited members occur at the same byte offset as in the base class

- so code like `p->name` can translate the same whether `p` points to a Person or a Student.

  - `p->name` is translated as "add 0 to the address in p"
  - `p->id` is translated as "add 4 to the address in p"

Assignment & Extension

In most OO languages, we can do

```
superObj = subObj;
```

but not

```
subObj = superObj;
```

- Assigning to a superclass object discards the extra data

    - Presumably, (Smith, 456782) is still a valid Person
    - Even if it loses the information about Smith being a student

- Assigning to a subclass object requires the system to invent data.

- If we assign Jones to a student object, what value should the system copy into the school?

3 Virtual Destructors

As we've seen, subclasses can add new data members.

What happens if we add a pointer:

gradStudent.cpp +

```cpp
class Person {
 public:
   string name;
   long id;
 };

 class Student: public Person {
 public:
   string school;
 }


 class GraduateStudent: public Student {
 private:
   Transcript* undergradRecords;
 public:
   ...
   GraduateStudent (const GraduateStudent& g);
   GraduateStudent& operator= (const GradudateStudent&);
   ~GraduateStudent();
 };

 GraduateStudent::GraduateStudent (const GraduateStudent& g)
    : name(g.name), id(g.id), school(g.school),
      undergradRecords(new Transcript(*(g.undergradRecords))
 {}

 GraduateStudent& operator= (const GradudateStudent& g)
 {
   if (this != &g)
     {
       Student::operator=(g);
```

```
        delete undergradRecords;
        undergradRecords = new Transcript(*(g.undergradRecords));
      }
    return *this;
  }

  GraduateStudent::~GraduateStudent()
  {
    delete undergradRecords;
  }
```

and we don't want to share?

Deleting Pointers and Inheritance

Consider the following two delete statements:

```
Person* g1 = new GraduuateStudent(...);
GraduateStudent* g2 = new GraduateStudent(...);
    ⋮
delete g1;  // compiler-generated ~Person() is called
delete g2;  // ~GraduateStudent() is called
```

- Both calls are resolved by compile-time binding

- Therefore the first delete leaks memory – undergraduateRecords is not cleaned up

- The fix would seem to be to force dynamic binding on the destructors

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Making the Destructor Virtual

The trick is that this has to be done at the top of the inheritance hierarchy

virtualDestruct.cpp   `+`

```
class Person {
 public:
    virtual ~Person() {}
    string name;
    long id;
};

 class Student: public Person {
 public:
    string school;
 }


 class GraduateStudent: public Student {
 private:
    Transcript* undergradRecords;
 public:
       ⋮
    GraduateStudent (const GraduateStudent& g);
    GraduateStudent& operator= (const GraduateStudent&);
    ~GraduateStudent();
 };
```

even though,

- at the time we wrote that class, there may have been no obvious need for a destructor

- this seems to violate the Rule of the Big 3

    - We'll look at the other two of the big 3 in just a moment

4 Virtual Assignment

If subclasses can introduce new data members, should assignment be virtual so that we can guarantee proper copying of those extended data members?

Virtual Assignment Example

```
void foo(Person& p1, const Person& p2)
{
    p1 = p2;
}

GraduateStudent g1, g2;
   ⋮
foo(g1, g2);
```

- If *p1* and *p2* "really" have *underGraduateRecord* fields, shouldn't we make sure those get copied properly during assignment?
    - Seems reasonable in this case.
    - But it means that assignment and copying will behave very differently, which is likely to catch programmers by surprise.

What's the Problem with Virtual Assignment?

If you try it, the inherited members aren't what you might expect:

[inherAsst.cpp] `+`

```
class Person {
 public:
    virtual ~Person() {}
    virtual Person& operator= (const Person& p);
    string name;
    long id;
};

class Student: public Person {
 public:
    string school;
    virtual Person& operator= (const Person& p); // inherited from Person
    // Student& operator= (const Student& s); // generated by compiler
}

class GraduateStudent: public Student {
 private:
    Transcript* undergradRecords;
```

```cpp
public:
    ...
    GraduateStudent (const GraduateStudent& g);
    virtual Person& operator= (const Person& p); // inherited from Person
    // Student& operator= (const Student& s); // inherited from Student
    GraduateStudent& operator= (const GradudateStudent&);
    ~GraduateStudent();
};
```

You actually wind up with multiple overloaded assignment operators in the subclasses.

What's the Problem with Virtual Assignment? (cont.)

- To make this work, you will need to implement both the virtual and the normal operators

- Implementing the virtual one is tricky because you might not get a GraduateStudent on the right:

```cpp
void foo(Student& s1, const Student& s2)
{
    s1 = s2;
}

Student s;
GraduateStudent g;
    ...
foo(g, s); // problem: s has no undergraduateRecords field
```

Recommendation

- There's no clear consensus in the C++ community about making assignment virtual.

- I recommend against it just because it's potentially confusing.

    - Try to avoid using assignment in situations where the "true" data type on the left is uncertain.

5 Virtual constructors

- Constructors can never be made virtual

- This can lead to problems when we need to create a copy.

Example: evaluating a cell reference

[cellrefnode.h] +

```cpp
class CellReferenceNode: public Expression
{ // represents a reference to a cell
private:
    CellName value;

public:
    CellReferenceNode () {}
        <:\smvdots:>
```

```
    // Evaluate this expression
      virtual Value* evaluate(const SpreadSheet&) const;
        <:\smvdots:>
```

```
  // Evaluate this expression

  Value* CellReferenceNode::evaluate(const SpreadSheet& s) const
  {
    Cell* cell = s.getCell(value);
    Value* v = (Value*)cell->getValue();
    if (v == 0)
      return new ErrorValue();
    else
      return v;
  }
```

- We would be better off returning a copy of the spreadsheet cell's value rather than the actual one.

- Each Cell owns (does not share) its Value

- Cell may therefore delete that Value

- don't want to risk some other code doing so

- But how do we make a copy?

Not like this!

```
  Value* theCopy = new Value(*v);
```

- How big is a Value?

- Would lose all data members in *v* required for its particular subtype of Value

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Better, but Not the "OO Way"

```
  Value* newCopy;
  if (typeid(*v) == typeid(NumericValue)) {
    newCopy = new NumericValue (v->getNumericValue());
  } else if (typeid(*v) == typeid(StringValue)) {
    newCopy = new StringValue (v->render(0));
  } else if (typeid(*v) == typeid(ErrorValue)) {
    newCopy = new ErrorValue();
    ⋮
```

(We'll see how typeid works shortly.)

5.1 Cloning

Solution is to use a simulated "virtual constructor", generally referred to as a `clone()` or `copy()` function.

```
Value* CellReferenceNode::evaluate(const SpreadSheet& s) const
{
  Cell* cell = s.getCell(value);
  Value* v = (Value*)cell->getValue();
  if (v == 0)
    return new ErrorValue();
  else
    return v->clone();
}
```

clone()

`clone()` must be supported by all values:

```
class Value {
public:
      ⋮
  virtual Value* clone() const;
      ⋮
};
```

Implementing clone()

Each subclass of Value implements `clone()` as a copy construction passed to `new`.

```
Value* NumericValue::clone() const
{
  return new NumericValue(*this);
}
```

```
Value* StringValue::clone() const
{
  return new StringValue(*this);
}
```

6 Downcasting

Suppose that I want to be able to test any two Values to see if they are equal

- We'll define "equal" here as meaning that they are the same kind of value and would appear the same when rendered.

Example: Value::operator==

We want to explicitly require all subclasses of Value to provide this test:

```
class Value {
      ⋮
  virtual bool operator== (const Value&) const;
};
```

The operator == compares two shapes. Its signature is: `(const Value*, const Value&) => bool`

Inheriting ==

```
class NumericValue: public Value {
     ⋮
class StringValue: public Value {
      ⋮
```

Both classes inherit the == operator. The signatures are

```
(const NumericValue*, const Value&) =>  bool
(const StringValue*, const Value&) => bool
```

Using the Inherited ==

```
NumericValue n1, n2;
StringValue s1, s2;
bool b = (n1 == n2)
      && (s1 == s2)
      && (n1 == s1);
```

The last clause suggests a problem.

- How do we compare values of different subtypes?

- Should we even allow it?

Implementing an asymmetric operator

We might implement == for `NumericValue` as:

```
bool NumericValue::operator==
    (const Value& v)
{
  return d == v.d;
};
```

- But in a call like (`n1 == s1`), `v.d` does not make sense.

- In fact, this will get a compile error

Implementing an asymmetric operator (cont.)

The problem is that we can easily define

```cpp
bool NumericValue::operator== (const NumericValue& v)
```

but

```cpp
bool NumericValue::operator== (const Value& v)
```

seems impossible, as we cannot anticipate all the values that will ever be defined.

6.1 RTTI

Working around the == asymmetry

The C++ standard defines a mechanism for *RTTI* (Run Time Type Information).

```cpp
bool NumericValue::operator== (const Value& v)
{
  if (typeid(v) == typeid(NumericValue)) {
      const NumericValue &nv =
                  (const NumericValue&)v;
      return d == nv.d;
  } else
    return false;
};
```

- Note that `typeid()` can be applied both to objects and to types.

- But it can only be used with types/objects that have at least one virtual function.

RTTI: typeid and downcasting

RTTI also allows you to test to see if v is from a subclass of `NumericValue`

```cpp
if (typeid(NumericValue).before(typeid(v))
```

or to perform safe *downcasting*:

```cpp
NumericValue* np = dynamic_cast<NumericValue*>(&v);
if (np != nullptr)
   {// v really was a NumericValue or
    //   subclass of NumericValue
        ⋮
    }
```

- The term "downcasting" refers to the fact that we are moving "down" in hour inheritance hierarchy (assuming we draw the base class at the tops).
    - Upcasting is always safe (and usually is done implicitly)
    - Downcasting can be dangerous if we don't check to see if the object really is what we think it will be.

Downcasting Should Not Be a Crutch

Downcasting is often a tempting way to patch a poor initial choice of virtual "protocol" functions.

- 95% of the time, it's a bad idea

- often leads to subtle, hard to trace bugs

Oddly, though, downcasting is far more widely accepted in Java than in C++.

7 Single Dispatching & VTables

Equality Again

Earlier, we looked at the problem of comparing two spreadsheet `Values`:

```
class Value {
    ⋮
  virtual bool isEqual (const Value&) const;
};
```

```
class NumericValue: public Value {
    ⋮
  virtual bool isEqual (const Value&) const;
};
```

We saw that problems are caused by `NumericValue::isEqual` getting a parameter of type `Value&` rather than `NumericValue&`.

Why is this so hard?

Why can't we select the best fit from among:

```
class NumericValue: public Value {
    ⋮
  virtual bool isEqual (const NumericValue&) const;
  virtual bool isEqual (const StringValue&) const;
  virtual bool isEqual (const ErrorValue&) const;
};
```

The answer stems from how dynamic binding is implemented.

7.1 Single Dispatching

Almost all OO languages offer a *single dispatch* model of message passing:

- the dynamic binding is resolved according to the type of the single object to which the message was sent ("dispatched").

- In C++, this is the object on the left in a call: `obj.foo( ... )`

- There are times when this is inappropriate.

- But it leads to a fast, simple implementation

VTables

- Each object with 1 or more virtual functions has a hidden data member.

- a pointer to a *VTable* for it's class

- this member is always at a predictable location (e.g., start or end of the object)
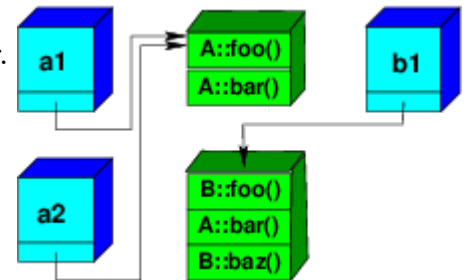
Compiling Virtual Function Declarations

- Each virtual function in a class is assigned a unique, consecutive index number.

- `(*VTable)[i]` is the address of the class's method for the i'th virtual function.

Example of VTable Use

```
class A {
public:
  A();
  virtual void foo();
  virtual void bar();
};

class B: public A {
public:
  B();
  virtual void foo();
  virtual void baz();
};
```

`foo()`, `bar()`, and `baz()` are assigned indices 0, 1, and 2, respectively.

Consider the code:

```
A* a = ???;   // might point to an A or a B object
a->foo();
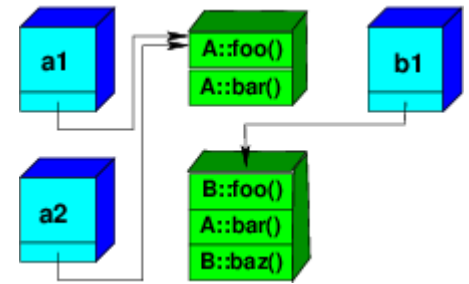```

## Example: VTable Structure

- The call `a->foo()` is translated as

```
*(a->VTABLE[0])();
```

- The call `a->bar()` is translated as

```
*(a->VTABLE[1])();
```

Notice that this works regardless of whether *a* points to an A object or a B object.

- "works" in this case means "does dynamic binding"

Implementing RTTI

- The address of the VTable is a unique identifier for each class known to the compiler

- This makes the vtable an ideal for implementing RTTI

  - and explains why RTTI is only available for classes with at least one virtual function

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