

ECE2800J

Programming and Introductory Data Structures

Subtypes; Inheritance; Virtual Functions

Learning Objectives:

Understand what is a subtype and why they are useful

Know how to create subtype via inheritance

Understand what is a virtual function and know how to use it

Outline

- Introduction to Subtypes
- Creating Subtypes
- Creating Subtypes using C++ Inheritance Mechanism
- Virtual Functions

Subtypes

Introduction

- Suppose we have two types, S and T.
- S is a **subtype** of T, written “ $S <: T$ ”, if:
 - For any instance where an object of type T is expected, an object of type S can be supplied without changing the correctness of the **original** computation.
 - In other words, code written to correctly use T is still correct if it uses S.
- This is called the “substitution principle”.
- If $S <: T$, then we also say that “T is a **supertype** of S”.

Subtypes

Example

```
void add(istream &source) {  
    int n1, n2;  
    source >> n1 >> n2;  
    cout << n1+n2;  
}
```

```
add(inFile); //inFile has been declared  
             //as an ifstream and opened
```

- The function call `add(inFile)` is valid and works because `ifstream` is a **subtype** of `istream`
- `ifstream` can be supplied (substituted for `istream`) without changing the correctness.

Subtypes

Introduction

- Subtypes are different from the notion of "type-convertible".
 - For example, in any computation that expects a `double`, you can use an `int`.
 - However, the object isn't an `int` when it is used.
 - It is first "converted" to a `double` and its physical representation changes!
- However, if you use a subtype where a supertype is expected, it is **not converted** to the supertype
 - Instead, it is used as-is.

Benefits of Subtyping

- Code reuse

```
void add(istream &source) {  
    int n1, n2;  
    source >> n1 >> n2;  
    cout << n1+n2;  
}
```

Outline

- Introduction to Subtypes
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Subtypes

Creating

- In an Abstract Data Type, there are three ways to create a subtype from a supertype:
 1. Add one or more operations.
 2. **Strengthen** the **postcondition** of one or more operations.
 3. **Weaken** the **precondition** of one or more operations.

Subtypes

Creating by Adding New Methods

- The first way of creating a subtype is to **add some new method** to the subtype.
- Any code using the original supertype expects **only** the "old" methods, which are still available.
- The "new" method makes no difference.

Subtypes

Creating by Adding New Methods

- Example: we can create a subtype of `IntSet`, called `MaxIntSet`, by adding an operation `max()` that returns the maximum element in the set. The other part remains the same as `IntSet`.
 - Any code using `IntSet` can have `IntSet` be replaced with `MaxIntSet`. It won't call the `max()` method of `MaxIntSet`!

```
void foo(IntSet& is)
{
    ...
}
```

```
void main()
{
    MaxIntSet ms;
    foo(ms);
    ...
}
```

Subtypes

Creating by Strengthening Postcondition

- Second method: **Strengthen** the **postcondition** of one or more operations.
- The postconditions of a method are formed by two things:
 - The EFFECTS clause
 - Its return type
- One way of strengthening the postcondition is to strengthen the EFFECTS clause by promising everything you used to, plus extra.

Subtypes

Creating by Strengthening Postcondition

```
int A::f(int arg);  
    // REQUIRES: arg is positive  
    // and even.  
    // EFFECTS: returns arg/2.
```

- We can create a subtype of A, called B, by only changing function f of A.
- We strengthen the effects clause of A::f () by printing a message to the screen for each invocation, in addition to computing arg/2.

Subtypes

Creating by Strengthening Postcondition

- When `A::f()` is expected, we can also replace it with `B::f()`, since `B::f()` does all the things `A::f()` does with an extra message printing.
 - User's expectation is satisfied.
 - So B can substitute A.

```
int g(A& a)
{
    int arg = 2;
    return a.f(arg);
}
```

B::f(arg)

```
void main()
{
    B b;
    int c = g(b);
    ...
}
```

Subtypes

Creating

- Third method: **Weaken** the **precondition** of one or more operations.
- The preconditions of a method are formed by two things:
 - The REQUIRES clause
 - Its argument type
- One way of weakening the precondition is to weaken the REQUIRES clause.

Subtypes

Creating

```
int A::f(int arg);  
    // REQUIRES: arg is positive and even.  
    // EFFECTS: returns arg/2.
```

- You could weaken this REQUIRES clause by allowing:
 - Negative, even integers
 - Positive integers
 - All integers
 - ...

Why Weaken REQUIRES Create Subtype?

```
int A::f(int arg);  
    // REQUIRES: arg is positive and even.  
    // EFFECTS: returns arg/2.
```

- We can create a subtype of A, called B, which allows **all integers** for the function f of A.

```
int g(A& a) {  
    int arg = 2;  
    return a.f(arg);  
}
```

B::f(arg)

```
void main() {  
    B b;  
    int c = g(b);  
}
```



Why Weaken REQUIRES Create Subtype?

```
int A::f(int arg);
```

// REQUIRES: arg is positive and even.

// EFFECTS: returns arg/2.

- It is fine to call function g on an object b of subtype B.
 - When A::f() is expected, the argument (e.g., positive even integers) to A::f() is a subset of that to B::f() (e.g., integers). Then, that argument for A::f() works perfectly for B::f()!

```
int g(A& a) {  
    int arg = 2;  
    return a.f(arg);  
}
```

B::f(arg)

```
void main() {  
    B b;  
    int c = g(b);  
}
```

Outline

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Subclasses

Creating Subclasses using inheritance

- C++ has a mechanism to enable subtyping, called "**subclassing**", or sometimes **inheritance**.
- So, if we have some ADT class `foo`, and want to make a subtype class `bar`, we do so by saying:

```
class bar : public foo {  
    ...  
};
```

- This says: "`bar` is a `foo`, possibly with extra state, and possibly with new or redefined member functions.“
- We say that `bar` is a **derived class**, and it is **derived from** `foo`.

Subclasses

Creating Subclasses using inheritance

```
class bar : public foo {  
    ...  
};
```

- `public` means **public inheritance**. All public members of the base are also public in the derived class; all private members of the base are also private in the derived class
- We can also have **private inheritance**

```
class bar : private foo
```

- Then, all members of the base class are **private** in the derived class
- We normally use **public inheritance**. All the previous public member functions are still public

Subclasses

Creating Subclasses using inheritance

```
class MaxIntSet : public IntSet {  
    // OVERVIEW: a set of integers,  
    // where |set| <= 100  
public:  
    int max();  
    // REQUIRES: set is non-empty  
    // EFFECTS: returns largest element in  
    // set.  
};
```

- This creates a new type that has all of the behavior of IntSet, **plus** one new operation.
- MaxIntSet automatically inherits all of the IntSet methods and data elements.

Subclasses

Creating Subclasses using inheritance

- Conceptually, we have

MaxIntSet Object

IntSet members:

elts[], numElts,

insert(), remove(),...

New member of

MaxIntSet:

max()

Subclasses

Creating Subclasses using inheritance

- Unfortunately, MaxIntSet::max() is **not** a member of IntSet.

```
class IntSet {  
    // data members plus indexOf  
public:  
    // the public interface to the class.  
};
```

- All the data members are (by default) private. This means “they can be seen **only** by other members of **this** class”.
- All of the data members of IntSet are inaccessible to the additional members of the derived class MaxIntSet, and specifically MaxIntSet::max().

Subclasses

Creating Subclasses using inheritance

- Thankfully, we still have access functions that are public and could write it this way:

```
int MaxIntSet::max() {  
    int i;  
    for (i=INT_MAX; i>=INT_MIN; i--) {  
        if (query(i)) return i;  
    }  
}
```

- However, this function is **inefficient!**
- We'll have to query 2^{31} (i.e. $\frac{1}{2}$ of 2^{32}) numbers on average to find the maximum element in a randomly-constructed set!

Subclasses

```
int MaxIntSet::max() {  
    int i;  
    for (i=INT_MAX; i>=INT_MIN; i--) {  
        if (query(i)) return i;  
    }  
}
```

- C++ has a mechanism that allows us to get around this problem
 - The "**protected**" storage class.
 - If a member is "**protected**", it means "can be seen by all members of this class and **any derived** classes".

Subclasses

```
class IntSet {  
    protected:  
        // all of the data members plus indexOf  
    public:  
        // the public interface to the class.  
};
```

- Since MaxIntSet is derived from IntSet, the protected members of IntSet are visible to MaxIntSet.
- Other users of the IntSet class still **cannot** see the members.
- With this new structure, we can write max much more efficiently.

Subclasses

```
int MaxIntSet::max() {  
    int so_far = elts[0];  
    for (int i = 1; i<numElts; i++) {  
        if (elts[i] > so_far)  
            so_far = elts[i];  
    }  
    return so_far;  
}
```

```
int MaxIntSet::max() {  
    return elts[numElts-1];  
}
```

Unsorted
Array

Sorted
Array

Subclasses

Consequences of protected

- If we expose `IntSet`'s implementation to `MaxIntSet`, changing that implementation will break `MaxIntSet`.
- For example, if we switch `IntSet` from a sorted implementation to an unsorted one, `MaxIntSet::max()` will return the wrong value.
- Worse, it will compile correctly---you'll never know!

This shows the bad consequence of exposing detailed implementation

- **Protected** data members make derived classes extremely fragile, and it is a matter of taste as to whether it's worth doing.

Subclasses

- You can "extend" functionality in ways other than just adding methods – you can also **change** an individual method.
- In order to create **subtype**, you can't change it arbitrarily though; your subtype must still adhere to the **substitution principle**.
 - The new method must do everything the old method did, but it is allowed to do more as well. **strengthen the postconditions**
 - It must require no more of the caller than the old method did, but it can require less. **weaken the preconditions**

Subclasses

```
class SafeMaxIntSet : public MaxIntSet {  
    // OVERVIEW: a mutable set of integers,  
    // where |set| <= 100  
public:  
    int max();  
    // EFFECTS: if set is non-empty, returns largest  
    // element in set  
    // otherwise, returns INT_MIN.  
};
```

- In this method, we've both **weakened** the preconditions AND **strengthened** the postconditions of "old" max.

Subclasses

```
class SafeMaxIntSet : public MaxIntSet {  
    // OVERVIEW: a mutable set of integers,  
    //           where |set| <= 100  
public:  
    int max();  
    // EFFECTS: if set is non-empty, returns largest  
    //           element in set  
    //           otherwise, returns INT_MIN.  
};
```

- Preconditions: Old `max` required the set to be non-empty, new `max` doesn't.
- Postconditions: Old `max` returned the largest element of a non-empty set, new `max` does that, **plus** it returns `INT_MIN` for an empty set.

Subclasses

This new subtype correctly satisfies the **substitution principle**:
Code that was correctly written to use a `MaxIntSet` will work
unchanged if using a `SafeMaxIntSet`.

```
void foo()
{
    MaxIntSet a;
    a.insert(1);
    ...
    cout << a.max();
    ...
}
```

```
void foo()
{
    SafeMaxIntSet a;
    a.insert(1);
    ...
    cout << a.max();
    ...
}
```



Subclasses

```
class SafeMaxIntSet : public MaxIntSet {  
    // OVERVIEW: a mutable set of integers,  
    // where |set| <= 100  
public:  
    int max();  
    // EFFECTS: if set is non-empty, returns largest  
    // element in set  
    // otherwise, returns INT_MIN.  
};
```

- This defines a new class that is exactly like a `MaxIntSet`, except that it **replaces** or "**overrides**" the method `max`.
- The compiler decides which `max` to call by the type of the object to which we call `max`.

Subclasses

- So, if we declared one object of each type, calling the max method would give us the "right" one:

```
MaxIntSet      ms;  
SafeMaxIntSet ss;  
  
ss.max(); // calls SafeMaxIntSet::max()  
          // returns INT_MIN on empty set  
ms.max(); // calls MaxIntSet::max()  
          // is undefined on empty set
```

Subclasses

- The implementation of this new `max` is surprisingly simple:

```
int SafeMaxIntSet::max ()  {
    if (size ())
        return MaxIntSet::max ();
    else
        return INT_MIN;
}
```

- Most of the hard work is done by the "old" implementation of `max` (called `MaxIntSet::max`).
- This just covers the case where the set is empty.



Select All Correct Statements

- A. An ADT can be implemented as a class in C++.
- B. A class in C++ is always an ADT.
- C. A subtype can be implemented as a subclass in C++.
- D. A subclass in C++ is always an ADT subtype.



Outline

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Subclasses

Leaving behind subtypes

- Finally, it is possible to create **subclasses** that are **NOT subtypes** and don't follow the substitution principle.

```
class PosIntSet : public IntSet {  
    // OVERVIEW: a mutable set of positive integers  
public:  
    void insert(int v);  
    // EFFECTS: if v is positive  
    //           and s has room to include it,  
    //           s = s + {v}.  
    //           if v <= 0, throw int -1  
    //           if s is full, thrown int MAXELTS  
};  
void PosIntSet::insert(int v) {  
    if (v <= 0) throw -1;  
    IntSet::insert(v);  
}
```

Subclasses

Leaving behind subtypes

- Finally, it is possible to create **subclasses** that are **NOT subtypes** and don't follow the substitution principle.

```
class PosIntSet : public IntSet {  
    // OVERVIEW: a mutable set of positive integers  
public:  
    void insert(int v);  
    // EFFECTS: if v is positive  
    //           and s has room  
    //           s = s + {v}.  
    //           if v <= 0, thro  
    //           if s is full, t  
};  
void PosIntSet::insert(int v) {  
    if (v <= 0) throw -1;  
    IntSet::insert(v);  
}
```

Why is PosIntSet not a subtype?

Because code that is correctly written to use an IntSet could fail when using a PosIntSet, e.g., when inserting a negative number. It does not pass the substitution principle!

Subclasses

Leaving behind subtypes

- Unfortunately, the rules of C++ allow a **subclass** to be used wherever a **superclass** is expected.
- For example, the following code is perfectly legal:

```
PosIntSet s;  
IntSet* p = &s;  
IntSet& r = s;
```

- Because PosIntSet is a subclass of IntSet, it is perfectly legal to make these assignments.
- We have three variables: s is a PosIntSet, p is a pointer that points to precisely this PosIntSet, and r is a reference to this PosIntSet.

Subclasses

Leaving behind subtypes

```
try {  
    s.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

This will do exactly what
you expect:
"Exception thrown\n".

```
try {  
    r.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

Question: What will
this do?

Subclasses

Leaving behind subtypes

```
PosIntSet s;  
IntSet* p = &s;  
IntSet& r = s;
```

```
try {  
    r.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

- The type of `r` is declared to be “reference to an `IntSet`”, but it refers to a `PosIntSet`.
- **Apparent type:** the declared type of the reference. (`IntSet`)
- **Actual type:** the real type of the referent. (`PosIntSet`)
 - In this example, the **apparent type** and the **actual type** differ.
- In default situation, C++ chooses the method to run based on its apparent type.

Subclasses

Leaving behind subtypes

```
try {  
    s.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

This will do exactly what
you expect:
"Exception thrown\n".

```
try {  
    r.insert(-1);  
} catch (int i) {  
    cout << "Excepti...  
}
```

Answer: Because r's apparent type is
"reference-to-IntSet", this code calls
IntSet::insert(), which
happily inserts -1.
The same thing happens if we use the
pointer p.

```
PosIntSet s;  
IntSet* p = &s;  
IntSet& r = s;
```

Subclasses

Leaving behind subtypes

```
PosIntSet s;  
IntSet* p = &s;  
IntSet& r = s;
```

```
try {  
    s.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

This will do exactly what
you expect:
"Exception thrown\n".

```
try {  
    r.insert(-1);  
} catch (int i) {  
    cout << "Exception thrown\n";  
}
```

This breaks the abstraction of the set S,
which is **Very Bad**.

Virtual Functions

- There is a way to tell C++ to choose the actual type.
- In the class definition, we add the keyword **virtual** to the declaration of `insert`:

```
class IntSet {  
    ...  
public:  
    ...  
    virtual void insert(int v);  
    ...  
};
```

- This tells the compiler "someone might override my implementation: always check at run-time to see which version to call."

Virtual Functions

- You don't have to add `virtual` keyword when you **define** the function, i.e., the following is OK

```
void IntSet::insert(int v) { // OK  
    ...  
}
```

- You don't have to add the `virtual` keyword to `PosIntSet`'s definition, since "virtualness" is inherited just like everything else

```
class PosIntSet: public IntSet {  
    ...  
public:  
    void insert(int v); // OK  
    ...  
};
```

Virtual Functions

- Now consider:

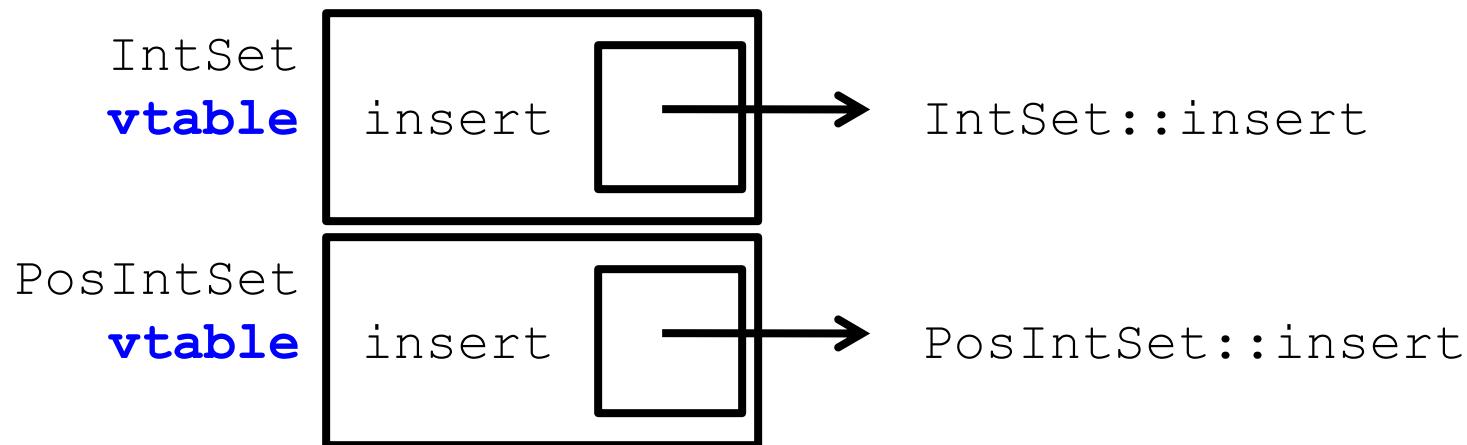
```
posIntSet s;  
IntSet* p = &s;  
IntSet& r = s;
```

```
p->insert(-1);
```

- p is declared as a pointer-to-IntSet, but it might really be pointing at some **derived class** type.
- The compiler will create code that checks the actual type of the object and calls the **right** function **at runtime**.

Virtual Functions

- Classes with virtual functions include information that allows you to figure out what type it is.
 - First, for each class with virtual functions, the compiler creates a **vtable** (or **virtual table**) with one function pointer for each virtual function initialized to the appropriate implementation.
 - Then, each instance of a class **with virtual methods** has both the class' state, **plus** a pointer to the appropriate vtable.



Subclasses

Static vs Dynamic

Using the following code:

```
IntSet foo;  
PosIntSet bar;
```

creates

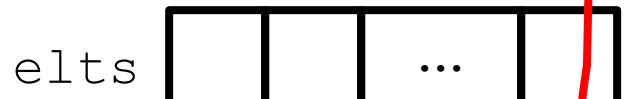
IntSet
vtable

insert IntSet::insert

PosIntSet
vtable

insert PosIntSet::insert

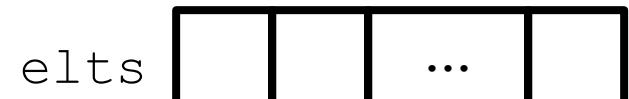
foo



numElts

vtable

bar



numElts

vtable

IntSet vtable

PosIntSet vtable

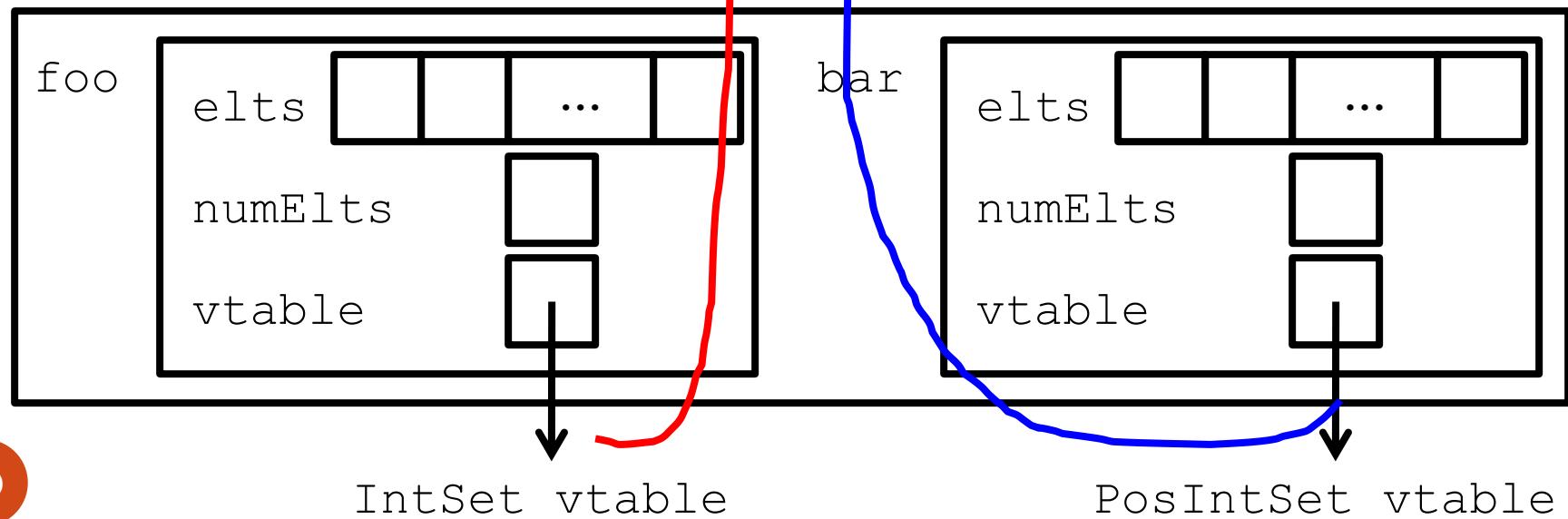
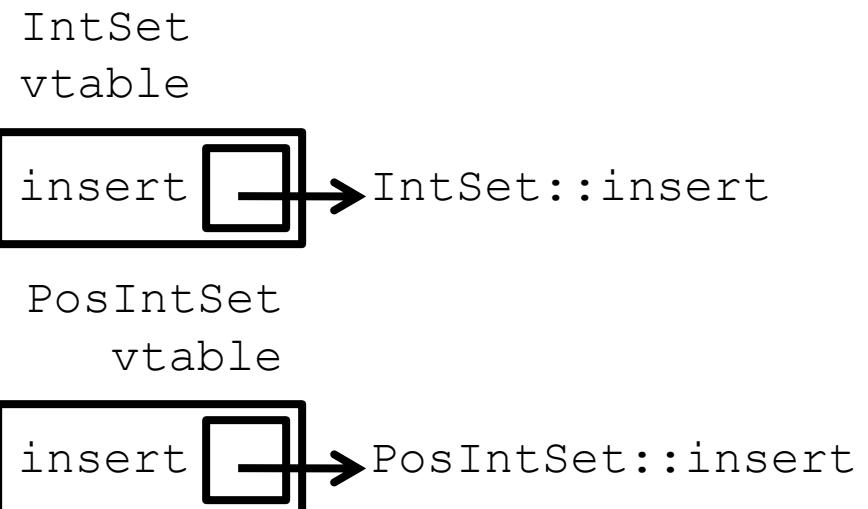
Subclasses

Static vs Dynamic

So, the code

```
IntSet &r = bar;  
r.insert(-1);
```

looks at bar's vtable, checks the insert entry, and calls PosIntSet::insert, rather than IntSet::insert.



Subclasses

Static vs Dynamic

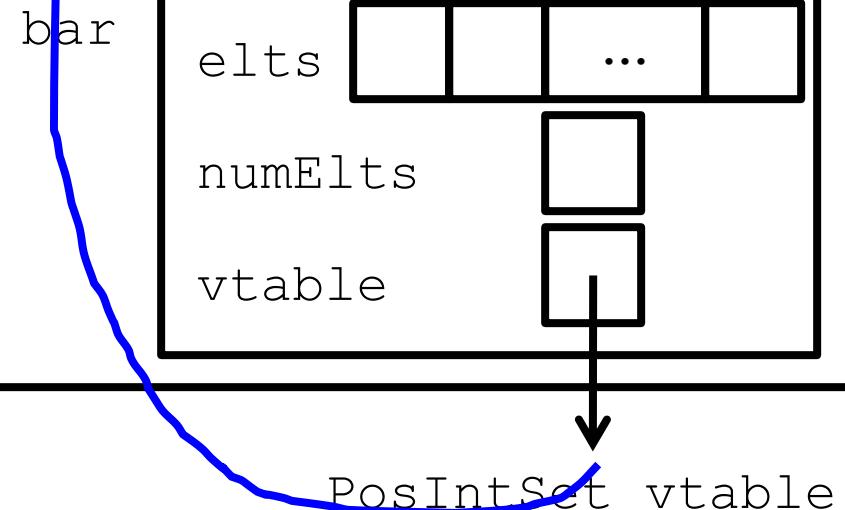
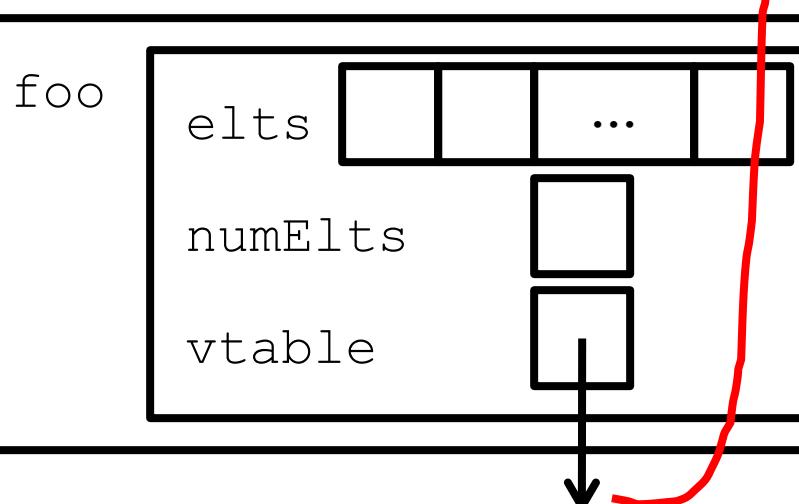
Note: Without the **virtual** keyword, there would be no vtable entry for insert.

IntSet
vtable

insert  `→ IntSet::insert`

PosIntSet
vtable

insert  `→ PosIntSet::insert`



References

- **Problem Solving with C++ (8th Edition)**, by *Walter Savitch*, Addison Wesley Publishing (2011)
 - Chapter 10.4 Introduction to Inheritance
 - Chapter 15.1 Inheritance Basics
 - Chapter 15.3 Virtual Functions in C++