

# VE280 Programming and Elementary Data Structures

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## Subtypes; Inheritance; Virtual Functions



# Learning Objectives

- Understand what is a subtype and why they are useful
- Know how to create a subtype via inheritance
- Understand what is a virtual function and know how to realize polymorphism

# Outline

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

- Supertype: Number
- Subtypes: Integer, rational number, real number, ...

```
Number double_val(Number x) {  
    return x*2;  
}
```

# 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;  
}
```





## Select all correct answers:

- **A.** The type `int`, is not a subtype of `double`, but it is a subtype of `long`.
- **B.** The type `string` is a supertype of the type representing a C string.
- **C.** If C is a subtype of B and B is a subtype of A, then an instance of C can substitute to an instance of A.
- **D.** If C is a supertype of B and B is a supertype of A, then an instance of C can substitute to an instance of A.



# Outline

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

# 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

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

# 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| <= MAXELTS  
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;  
}
```



Unsorted  
Array

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

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| <= MAXELTS  
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| <= MAXELTS
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();  
    ...  
}  
...  
MaxIntSet a;  
foo(a);
```

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



# Subclasses

```
class SafeMaxIntSet : public MaxIntSet {  
    // OVERVIEW: a mutable set of integers,  
    //           where |set| <= MAXELTS  
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 that the set is empty.



Select all correct answers:

- **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

- Introduction to Subtypes
- Creating Subtypes
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- Introduction to Virtual Functions



# 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 non-negative,
    //           and s has room to include it,
    //           s = s + {v}.
    //           if v is negative throw int -1
    //           if s is full throw 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 non-negative  
    //           and s has room  
    //           s = s + {v}.  
    //           if v is negative  
    //           if s is full th  
};  
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

```
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";  
}
```

**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

```
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";  
}
```

**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`.

# 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 shouldn't add the `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

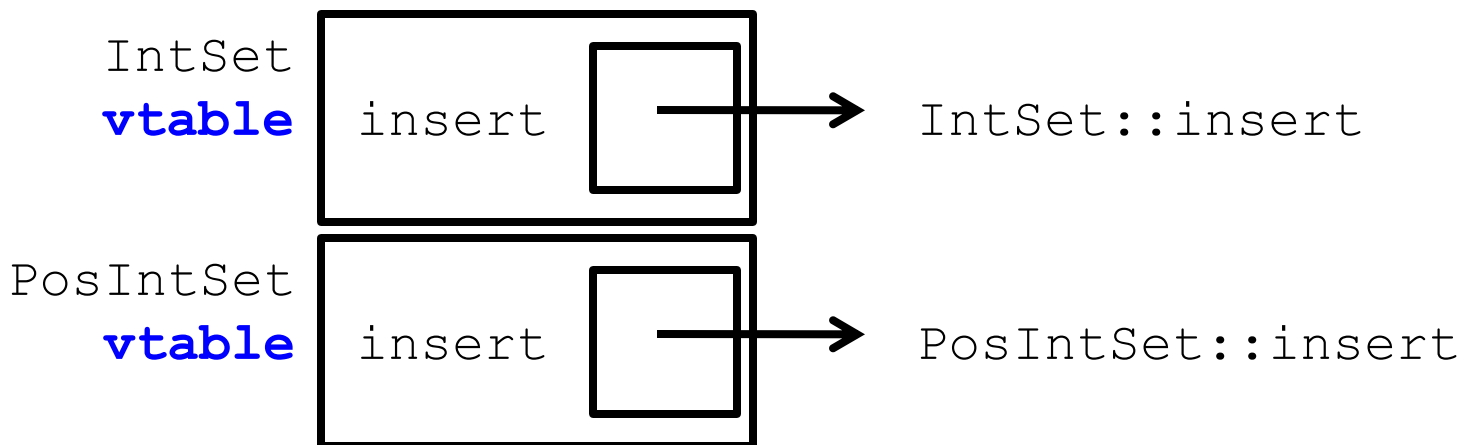
- Now consider:

```
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

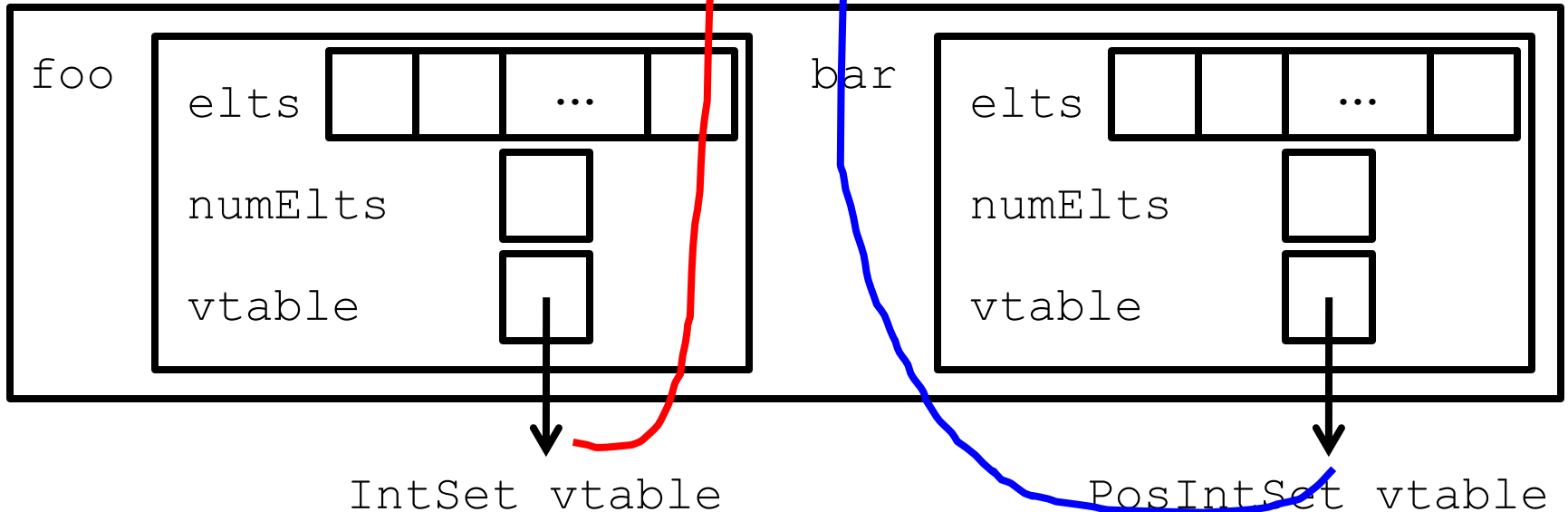
Using the following code:  
**IntSet foo;**  
**PosIntSet bar;**  
creates

IntSet  
vtable

insert  → IntSet::insert

PosIntSet  
vtable

insert  → PosIntSet::insert



# 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.

IntSet  
vtable

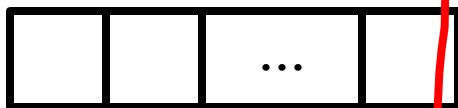
insert  → IntSet::insert

PosIntSet  
vtable

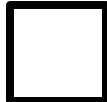
insert  → PosIntSet::insert

foo

elts



numElts



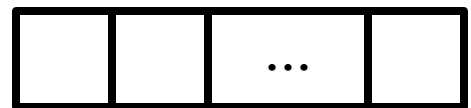
vtable



IntSet vtable

bar

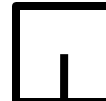
elts



numElts



vtable

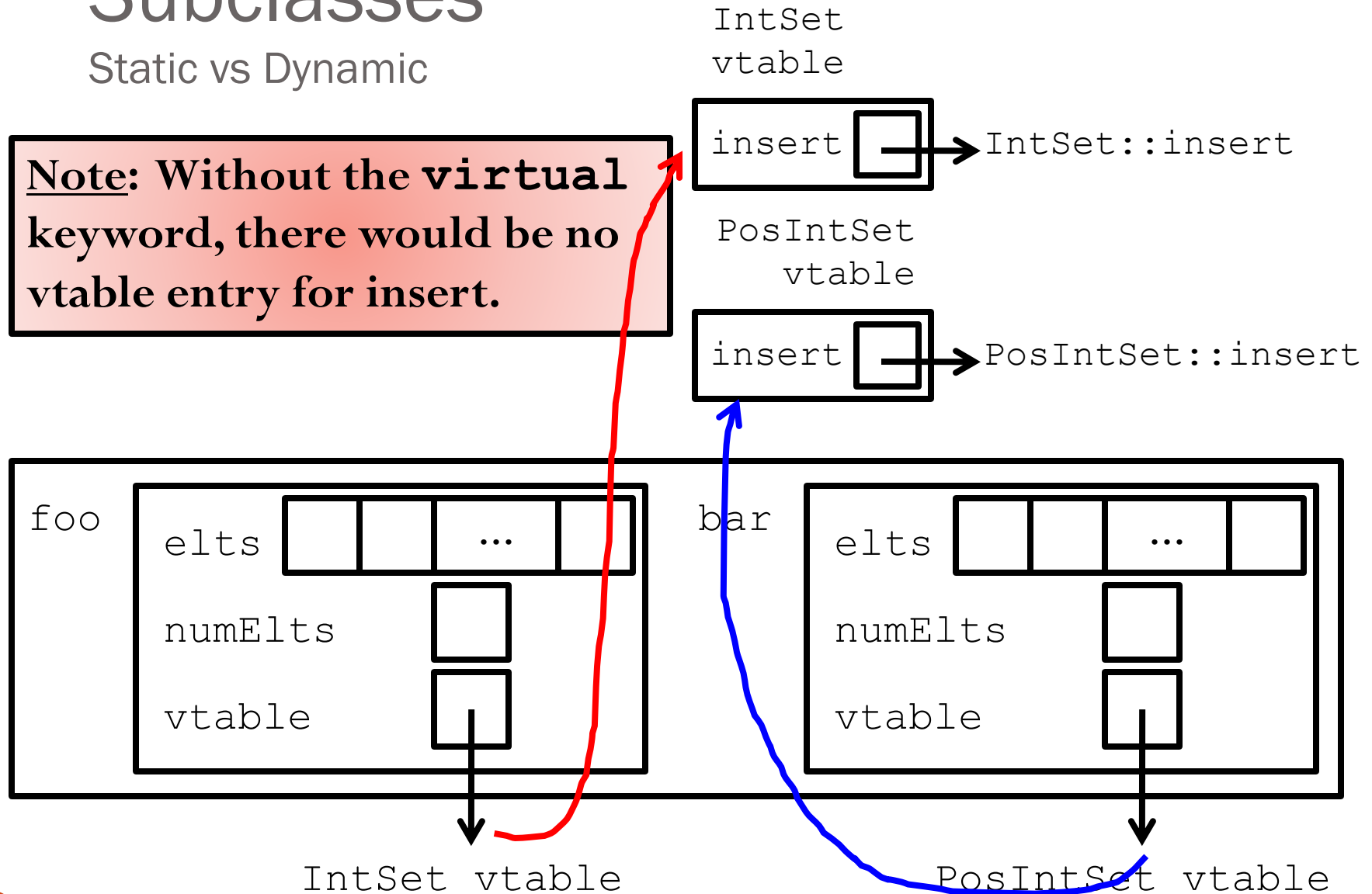


PosIntSet vtable

# Subclasses

Static vs Dynamic

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





Class A has a non-virtual function  $f$ . Its child class B redefines  $f$  as a virtual function. Class C is a child class of B, which redefines  $f$ .

Select all the correct answers.

If pointer  $p$  of type A points to a value of type B, after  $p \rightarrow f()$ ,

- **A.** Function  $f$  of class B is called.
- **B.** Function  $f$  of class A is called.

If pointer  $p$  of type B points to a value of type C, after  $p \rightarrow f()$ ,

- **C.** Function  $f$  of class B is called.
- **D.** Function  $f$  of class C is called.



# Specifier override

- Example:

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

- Ask compiler to check that you are really overriding a virtual method



# References

- **Problem Solving with C++ (8<sup>th</sup> 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++**