O

O S E

E

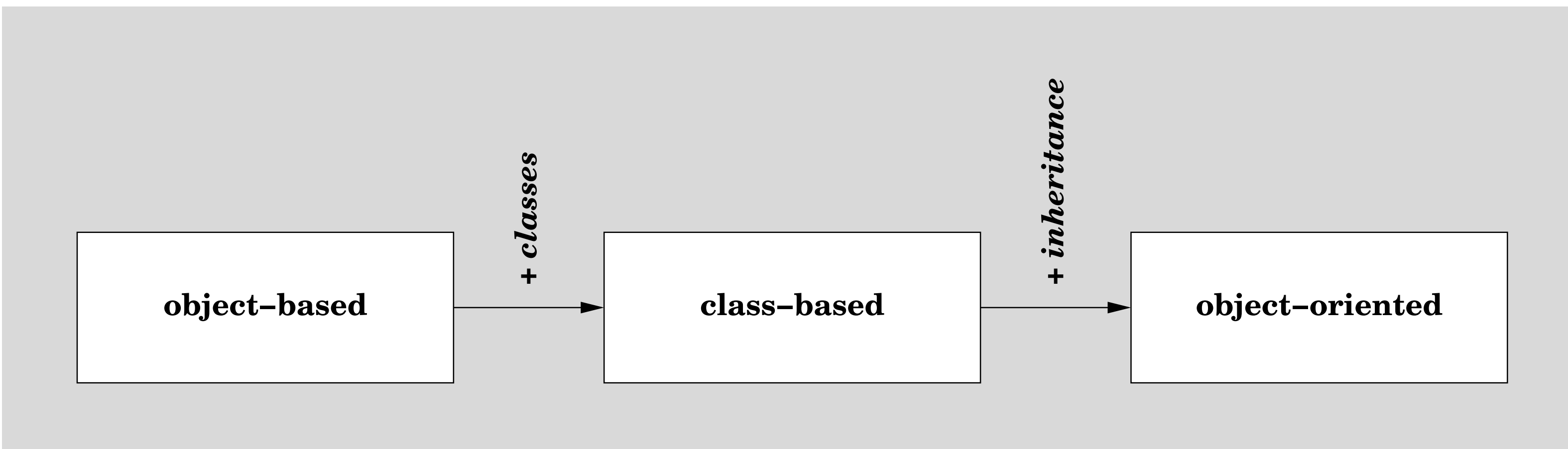
Object Orientation

Operating-System Engineering

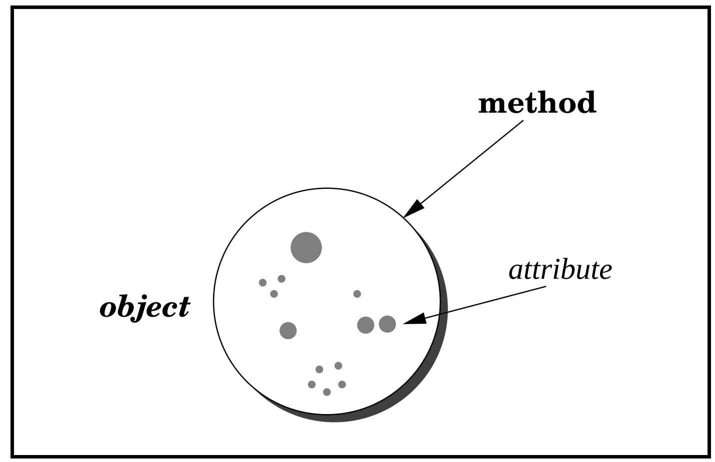
Object-Oriented Design [2]

Object-oriented design is a method of design encompassing the process of object-oriented decomposition and a notation for depicting both logical and physical as well as static and dynamic models of the systems under design.

Classification [7]



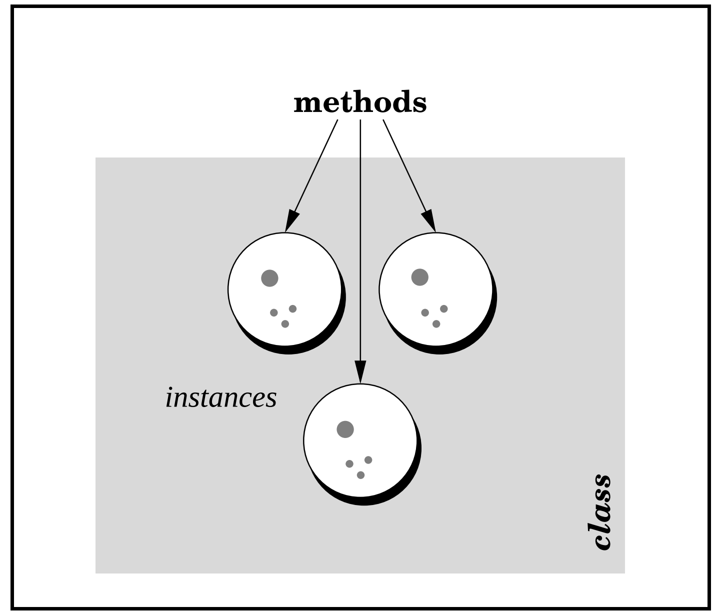
Object-Based



- implies the capability of *data abstraction*
  - methods provide access to attributes
  - attributes represent instance variables
- methods define the object's external interface
  - similar to an abstract data type (ADT)
- objects are unique instances, having only in common the need for memory

Class-Based

- objects are <u>instances</u> of classes
  - a class defines a set of *common properties*
  - properties are attributes of a class
  - classes may be compared to types



- a <u>meta-description</u> specifies the interface
  - describing a uniform management
  - indicating further data abstractions

- depending on the programming language employed, a class may be an ADT

Object-Oriented

- implies the <u>composition of abstract data types</u> on the basis of *inheritance*
  - new classes are constructed by the reuse of (an) existing class(es)
  - properties of the existing class(es) are inherited to the new class
  - a new class adds properties and/or redefines inherited properties

- objects instantiated from classes composed in that way are *polymorphous*
  - according to the <u>class hierarchy</u>, a single object relates to several classes
  - the object will be type compatible to more than one class

- inheritance allows for the *specialization* of the inherited class(es)

Object Orientation = Objects + Classes + Inheritance

- an object-oriented programming language must provide *linguistic support*
  - it must enable the programmers to describe common properties of objects
    - such a language is referred to as an object-based programming language
  - it is called object-oriented only if class hierarchies can be built by inheritance
    - so that the objects can be instances of classes that have been inherited
  - it allows the modeling of an object as a polymorphous entity
- object orientation is unattainable using imperative programming languages[1]

[1] Notwithstanding, from time to time there are comments stating the development of object-oriented systems using e.g. the C programming language. This is in contradiction to the classical definition of object orientation [7].

Synonyms of the “Theory of Heredity”

base class	. . . .	*derived class*
superclass	. . . .	*subclass*
parent class	. . . .	*child class*
inheriting class	. . . .	*inherited class*
common class	. . . .	*specialized class*
“upper class”	. . . .	“lower class”

Distinctness of Heredity

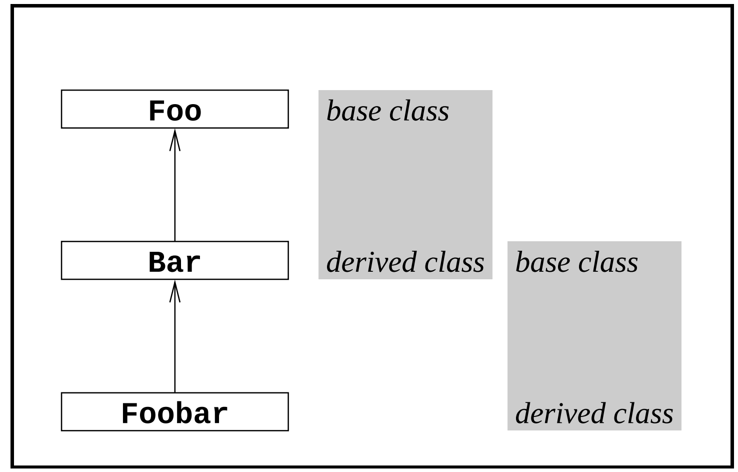
- inheritance appears in various shapes and is of different consequences:

  - *single inheritance* 9
  - *multiple inheritance* 10
    * *multiple inclusion* 11
    * *sharing* 12

- any of these kinds serves the construction of a <u>class hierarchy</u>

Single Inheritance

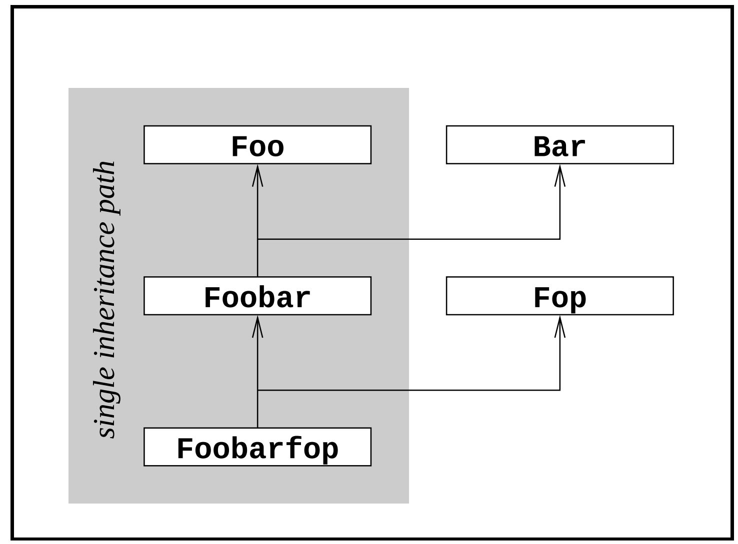
- a class is derivable from only one base class
  - only a single set of attributes to inherit
  - method redefinition/overloading is simple



- the class hierarchy is narrow but may be deep
  - a derived class may serve as a base class
- brings about fairly efficient implementations at the expense of reusability
  - class reuse implies *composition*, method redefinition, and kind of delegation
  - only the very base class appears to be reusable without any add-to

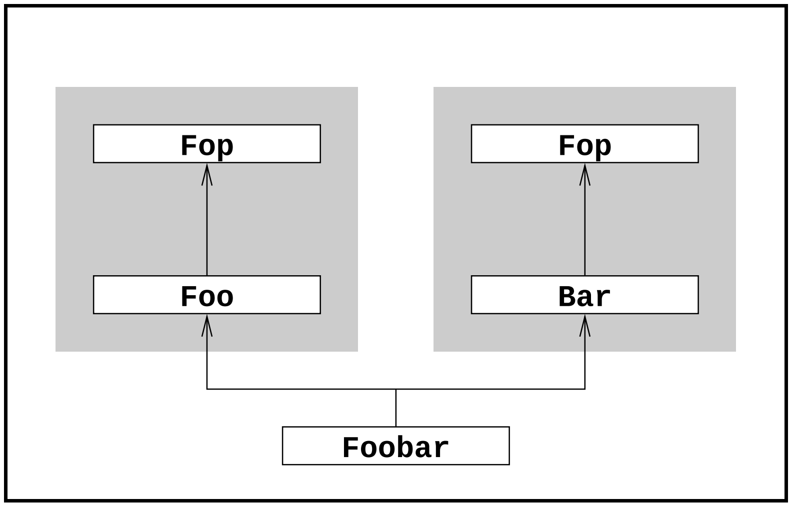
Multiple Inheritance

- a class is derivable from many base classes
  - many sets of attributes to inherit
  - method redefinition/overloading is crucial
  - classes can be inherited several times
- the class hierarchy may be deep and wide
  - a concept for *implementation unification*

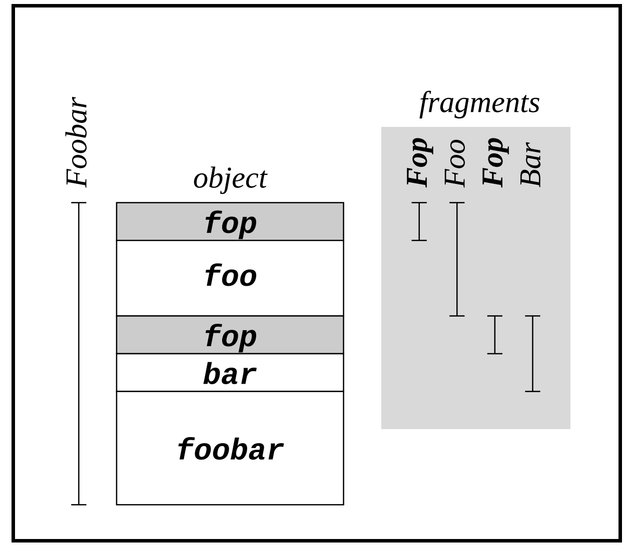


- brings about better reusability at the expense of an efficient implementation
  - class reuse is still limited to the very base class, but there are many of which

Multiple Inheritance

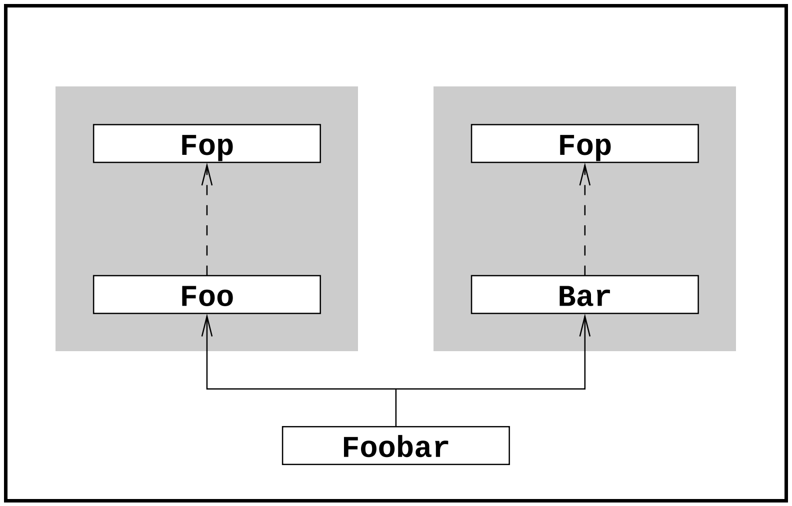


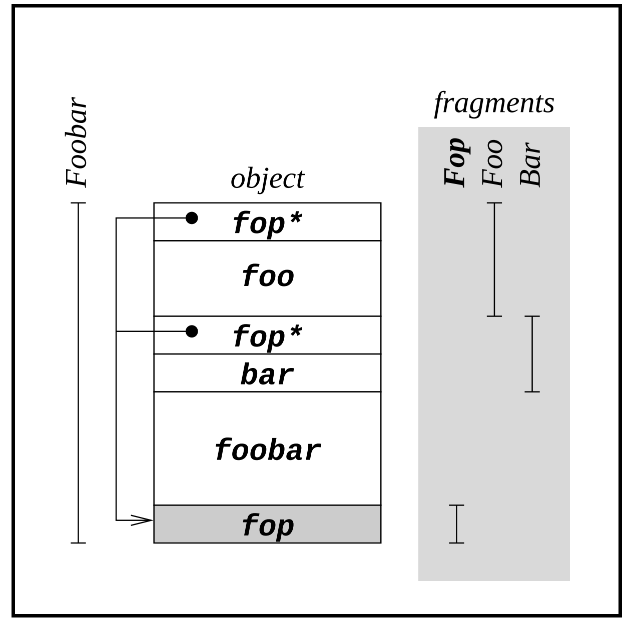
Multiple Inclusion



- the attributes of classes inherited several times are included several times
- the final object contains copies of object fragments of the same class

Multiple Inheritance Sharing





- the attributes of classes inherited several times are included once only
- the final object contains copies of pointers to the shared object fragment(s)

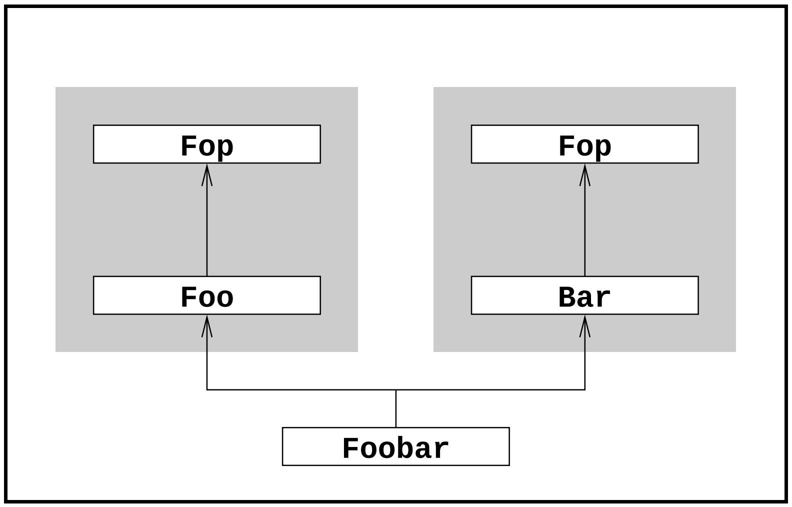
Object Layout

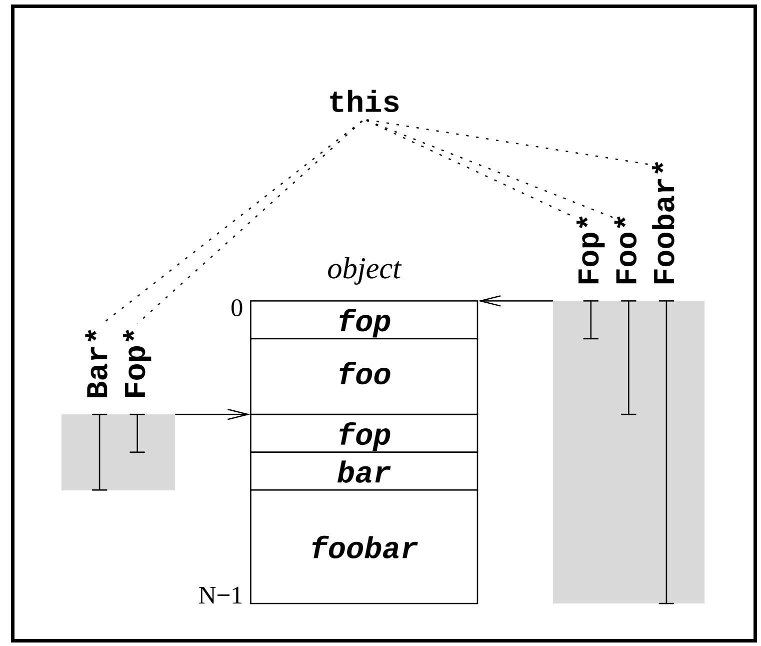
- a method applied to an object is implicitly supplied with the object's address
  - within the single inheritance path, `this`[2] is identical for all the classes
  - taking multiple inheritance branches into account, `this` becomes variable
- multiple inheritance may entail pointer manipulation upon method invocation
  - from derived to base class: adding some delta
  - from base to derived class: subtracting some delta → p. 16

[2] In C++, the pointer to the instance of a class (i.e., object) the invoked method is actually applied to.

Object Layout

`this`-Polymorphism





- from `Foobar` to `Foo::Fop` ⇒ `this` remains unchanged
- from `Foobar` to `Bar::Fop` ⇒ `this` $+=$ `sizeof(Foo)`

Object Layout — this-Adjustment

- Foo is on the single inheritance path: this pass through

```
class Foobar : public Foo, public Bar {
  int foo () {
    return Foo::foo() + 4711;
  }

  int bar () {
    return Bar::bar() + 42;
  }
};
```

```
foo__6Foobar:
  pushl 4(%esp)
  call  foo__3Foo
  addl  $4711,%eax
  addl  $4,%esp
  ret
```

```
bar__6Foobar:
  movl  4(%esp),%eax
  testl %eax,%eax
  jne   .L4
  xorl  %eax,%eax
  jmp   .L5
  .p2align 4,,7
.L4:
  addl  $4,%eax
.L5:
  pushl %eax
  call  bar__3Bar
  addl  $42,%eax
  addl  $4,%esp
  ret
```

- Bar is a multiple inheritance branch: (cond.) adjustment

Late Binding

- the <u>association at runtime</u> of which method is going to be applied to an object
  - the object's methods are bound at the point in time of object instantiation

- for methods to be capable of late binding, three preconditions must hold:
  1. they must have been defined in (the external interface of) a base class,
  2. the method's base class(es) must be inherited by some derived class(es),
  3. and they must be redefined by the derived class(es)

- also called *dynamic binding*—but must not be mixed up with dynamic loading

Late Binding

C++ Case Study

```
class Foo {
public:
  virtual int foo () = 0;
};
```

```
class Bar {
public:
  virtual int bar () = 0;
};
```

```
int foobar (Foo* fp, Bar* bp) {
  return fp->foo() + bp->bar();
};
```

```
class Foobar : public Foo, public Bar {
  int foo () {
    return 4711;
  }

  int bar () {
    return 42;
  }
};
```

```
Foobar fb;
```

Late Binding C++ → x86

- the compiler implements the *common model*
  - treats all virtual methods identical

```
fb:
  .zero 8
  ⋮
  movl $_vt$6Foobar$3Bar,fb+4
  movl $_vt$6Foobar,fb
  ⋮
```

```
Foobar fb;
```
[3]

- the compiler implements the *thunk model*
  - gives priority to the single inheritance path
  - handicaps multiple inheritance branches

```
fb:
  .zero 8
  ⋮
  movl $__vt_6Foobar,fb
  movl $__vt_6Foobar.3Bar,fb+4
  ⋮
```

[3] gcc -O6 -S -fno-rtti -fno-exceptions -fomit-frame-pointer

Late Binding — Method Redefinition

```
int Foobar::foo () {
  return 4711;
}
```

```
foo__6Foobar:
  movl $4711,%eax
  ret
```

```
int Foobar::bar () {
  return 42;
};
```

```
bar__6Foobar:
  movl $42,%eax
  ret
```

- the generated code is the same for the common model and the thunk model
- that a method is subjected to late binding is transparent to the method itself

Late Binding — Common Model (1)

- every class containing a virtual function has a *virtual-function table* of "call descriptors"
  - a triple of offset, ?, and function pointer

```
class Foobar : public Foo, public Bar {
  int foo ();
  int bar ();
};
```

```
_vt$6Foobar:
  .value 0
  .value 0
  .long  0
  .value 0
  .value 0
  .long  foo__6Foobar
```

```
_vt$6Foobar$3Bar:
  .value -4
  .value 0
  .long  0
  .value -4
  .value 0
  .long  bar__6Foobar
```

- the caller adjusts the object pointer (`this`)
  - no matter which path/branch will be taken

Late Binding — Common Model (2)

- overhead at the caller's site:
  - adjustment of `this`
- indirect function call

```
int foobar (Foo* fp, Bar* bp) {
  return fp->foo() + bp->bar();
};
```

```
foobar__FP3FooP3Bar:
   subl    $20,%esp
   pushl   %esi
   pushl   %ebx
   movl    32(%esp),%edx
   movl    36(%esp),%ebx
   addl    $-12,%esp
   movl    (%edx),%ecx
   movswl  8(%ecx),%eax
   addl    %eax,%edx
   pushl   %edx
   movl    12(%ecx),%eax
   call    *%eax
   movl    %eax,%esi
   addl    $-12,%esp
   movl    (%ebx),%edx
   movswl  8(%edx),%eax
   addl    %eax,%ebx
   pushl   %ebx
   movl    12(%edx),%eax
   call    *%eax
   addl    %esi,%eax
   addl    $32,%esp
   popl    %ebx
   popl    %esi
   addl    $20,%esp
   ret
```

- single inheritance path:
  - an adjustment by 0
  - avoidable overhead

Late Binding — Thunk Model (1)

- every class containing a virtual function has a *virtual-function table*
  - of function pointers

```
class Foobar : public Foo, public Bar {
  int foo ();
  int bar ();
};
```

```
__vt_6Foobar:
  .long 0
  .long 0
  .long foo__6Foobar
```

```
__vt_6Foobar.3Bar:
  .long -4
  .long 0
  .long __thunk_4_bar__6Foobar
```

- thunks relate to multiple inheritance branches
  - every virtual method in it has such a thunk
  - the thunk adjusts the object pointer (`this`)
  - after that, it jumps to the redefined method

```
__thunk_4_bar__6Foobar:
  addl $-4,4(%esp)
  jmp  bar__6Foobar
```

Late Binding — Thunk Model (2)

- overhead at the caller's site:
  - location of the virtual-function table pointer
  - location of the redefined method

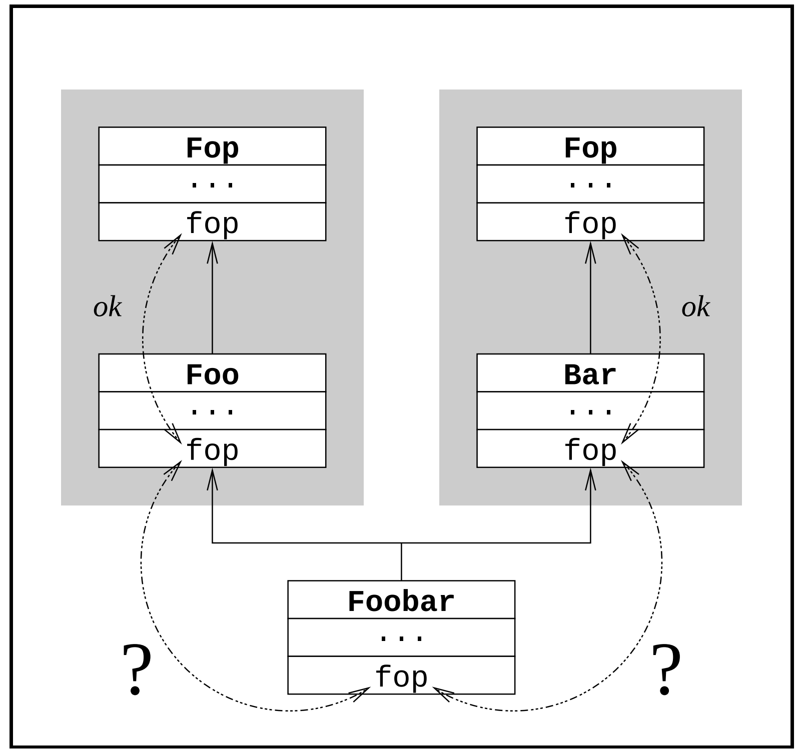
```
int foobar (Foo* fp, Bar* bp) {
  return fp->foo() + bp->bar();
};
```

```
foobar__FP3FooP3Bar:
  pushl %esi
  pushl %ebx
  movl  12(%esp),%eax
  movl  16(%esp),%ebx
  movl  (%eax),%edx
  pushl %eax
  movl  8(%edx),%eax
  call  *%eax
  movl  %eax,%esi
  movl  (%ebx),%eax
  pushl %ebx
  movl  8(%eax),%eax
  call  *%eax
  addl  %esi,%eax
  addl  $8,%esp
  popl  %ebx
  popl  %esi
  ret
```

- adjustment of `this` where really required
- indirect function call

Inheritance Ambiguity

- redefinition of a multiple inherited method
  - unproblematic using single inheritance
  - problematic using multiple inheritance
- the subclass needs to rename the methods
  - i.e., associate them with unique names
  - linguistic support would be nice to have
    - as provides Eiffel, but not C++
- the conflict can't be resolved automatically



Inheritance differs from Subtyping

subtyping

- a *supertype* defines the fundamental properties of an entity
- a *subtype* serves the refinement of these properties
- supertype operations must be redefined by the subtype to be visible
- as a consequence, identical operations at both type levels lead to redundancy

inheritance

- at first sight, a {super,sub}class is very similar to a {super,sub}type
  - <u>but</u> superclass methods are not obliged to be redefined by the subclass
- superclass properties are “passed through” to subclasses and beyound
- this corresponds to *hierarchical structuring* of incremental machine design

Varieties of Inheritance

implementation inheritance i.e. **class inheritance**

- is also known as *subclassing* and considered promoting <u>software reuse</u>
- is subjected to the risk of making derived classes more *fragile* [6]
  - the implementation becomes more likely to depend on base class details
  - the class hierarchy corresponds to the *open/close principle* [4]
- can be made “stable” by designing base classes to be “semi-abstract” **!**

interface inheritance

- corresponds to *subtyping* if a superclass was designed as <u>abstract base class</u>
  - methods need to be redefined in subclasses to enable object instantiation
- implies *late binding*, thus provides overhead-prone high flexibility/dynamics

Open/Close Principle

- <u>inside</u> the hierarchy of heredity is all access to attributes unrestricted
  - e.g. instance variables may be read/written by any subclass
  - the typical case of *implementation inheritance*
- from <u>outside</u> is all attribute access restricted, it must be enabled explicitly
  - e.g. by specifically providing access functions to instance variables
  - the “closed classes” together can be considered an ADT
- base classes are open to the derived classes but closed to the clients

“Semi-Abstract Classes”

- class attributes are directly visible but not directly accessible
  - clients are aware of the internal (data) structure of a class
  - attribute access happens only through methods[4] (i.e., access functions)
  - changes made at base-class level will not impair derived classes

- proximity to an *abstract data type* (ADT) is given
  - base classes have a *stable interface*, syntactically and semantically
  - a base-class implementation may be fragile without affecting derived classes

- attributes will be closed to any kind of public, except to “their” methods

[4] Method call optimization is left to the compiler, e.g. by *inlining* of the method implementation. The interrelationship between base class and derived class(es) is defined by a *functional hierarchy*.

“Semi-Abstract Classes” C++ $\xrightarrow{2.96}$ x86

```
class Fop {
  int _fop;
public:
  Fop ()             { _fop = 0; }
  int fop () const { return _fop; }
};

class Foo : public Fop {
  int _foo;
public:
  Foo (int i)       { _foo = i; }
  int foo () const { return fop() - _foo; }
};

class Bar : public Fop {
  int _bar;
public:
  Bar (int i)       { _bar = i; }
  int bar () const { return fop() + _bar; }
};
```

```
class Foobar : public Foo, public Bar {
public:
  Foobar(int f, int b) : Foo(f), Bar(b) {}
  int foobar () { return foo() + bar(); }
};
```

```
int foobar () {
  return Foobar(4711, 42).foobar();
}
```

```
foobar__Fv:
  movl $-4669,%eax
  ret
```

“Semi-Abstract Classes” C++ $\xrightarrow{2.91}$ x86

```cpp
class Fop {
  ...
};

class Foo : public Fop {
  ...
};

class Bar : public Fop {
  ...
};

class Foobar : public Foo, public Bar {
  ...
};

int foobar () {
  return Foobar(4711, 42).foobar();
}
```

```asm
foobar__Fv:
  subl $16,%esp
  movl $0,(%esp)
  movl $4711,4(%esp)
  movl $0,8(%esp)
  movl $42,12(%esp)
  movl 4(%esp),%eax
  movl (%esp),%edx
  subl %eax,%edx
  movl 8(%esp),%eax
  addl $42,%eax
  addl %edx,%eax
  addl $16,%esp
  ret
```

Polymorphism

. . . at type level

- objects of derived classes are *type compatible to* the base class(es)
- that is to say, subclass objects are also superclass objects
  - the reverse is not true, i.e., superclass objects are no subclass objects
  - a superclass object is kind of a fragment of a subclass object

. . . at function level

- methods of base classes are *applicable to* objects of the derived classes
- subclass methods redefine superclass methods subjected to late binding[5]
  - the final redefinition (i.e., specialization) becomes effective

[5] Not every method must be necessarily subjected to late binding, as e.g. is the case of Eiffel. In contrast, in C++ late binding must be explicitly enabled by specifying a method to be *virtual*.

Inheritance is Inclined to Break Encapsulation [5]

- base class dependancy may limit flexibility and, ultimately, reusability[6]
  - base classes define at least part of their derived-classes' "physics"
  - derived classes may become bound up with base class implementations
  - changes made in a base class may affect the derived class
- a way out of this dilemma is to consequently employ *interface inheritance*
  - that is to say, to inherit only from (semi-) abstract classes
- the alternative is to favor *object composition* over implementation inheritance

[6] A further disadvantage of implementation inheritance may be that one can't change the implementations inherited from bases classes at runtime, because inheritance is defined only at compile-time.

Object Composition

- object composition is defined dynamically at runtime through *object interfaces*
  - composition requires objects to respect each others' interfaces
  - objects are accessed solely through their interfaces, ensuring encapsulation
  - any object can be replaced by another object of the same type

- an effect on system design is that classes and class hierarchies remain small
  - they will be less likely to grow into "unmanageable monsters"
  - at the expense of a larger number of objects **!**

- the system behavior depends on object inter-relationships, not on classes

Delegation

- a way of making composition as powerful for reuse as inheritance
  - *two* objects are involved: a receiving object forwards requests to its delegate
  - analogous to derived classes deferring requests to base classes[7]
- behaviors can be composed at runtime, just as to make changes
  - dynamic and highly parameterized software is the outcome
  - software that is not easy to understand and prone to runtime inefficiencies
- works best when used in highly stylized ways—i.e., in “standard patterns”

[7] With inheritance, an inherited operation implicitly refers to the receiving object through, e.g., the `this` member variable. With delegation, the same effect is achieved by having the receiver in charge of passing itself to the delegate to let the delegated operation refer to the receiver.

Reusing Functionality in Object-Oriented Systems

white-box reuse i.e., <u>reuse by subclassing</u>

- defines the implementation of one class in terms of (an)other class(es)
  - implementation or class inheritance
- refers to *visibility*, i.e. base class internals are visible to derived classes

black-blox reuse i.e., <u>reuse by composition</u>

- new functionality is obtained by assembling objects to a more complex one
  - requires well-defined object interfaces
- no internal details of objects are visible to the outside

Design Patterns

- description of an "important and recurring design in object-oriented systems" [3]

  name a *handle*, describes a design problem, its solutions, and consequences in a word or two.

  problem describes when to apply the pattern, explains the problem and its context.

  solution describes the elements that make up the design, their relationships, responsibilities, and collaborations.

  consequences are the results and trade-offs of applying the pattern.

- patterns capture design experience in a form that people can use effectively

Object-Oriented Design vs. Buildings and Towns

Each pattern describes a problem which occurs over and over again in our environment, and then describes the core of the solution to that problem, in such a way that you can use this solution a millions times over, without ever doing it the same way twice. [1]

Summary

- try to comply with the “principles of (reusable) object-oriented design” [3]:
  1. *program to an interface, not an implementation*
  2. *favor object composition over class inheritance*
- interface inheritance should not only be put on a level with abstract classes
  - late binding abstracts from implementation and from variance
  - variance at runtime is not always what needs to be provided
  - abstraction from implementation is what remains as a must
- object-oriented systems programming largely depends on compiler quality

Bibliography

[1] C. Alexander, S. Ishikawa, M. Silverstein, M. Jacobsen, I. Fiksdahl-King, and S. Angel. *A Pattern Language*. Oxford University Press, NY, 1977.

[2] G. Booch. *Object-Oriented Analysis and Design with Applications*. Benjamin/Cummings, Redwood City, CA, second edition, 1994.

[3] E. Gamma, R. Helm, R. E. Johnson, and J. Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley, Reading, MA, 1995. ISBN 0-201-63361-2.

[4] B. Meyer. *Object-Oriented Software Construction*. Prentice Hall, Upper Saddle River, NJ, second edition, 1997. ISBN 0-13-629155-4.

[5] A. Snyder. Encapsulation and Inheritance in Object-Oriented Languages. In *Proceedings of the International Conference on Object-Oriented Programming Systems, Languages, and Applications (OOPSLA)*, pages 258–268, Portland, OR, Nov. 1986. ACM Press.

[6] C. A. Szyperski. *Component Software: Beyound Object-Oriented Programming*. Addison-Wesley, 1999.

[7] P. Wegner. Classification in Object-Oriented Systems. *ACM, SIGPLAN Notices*, 21(10):173–182, 1986.