# Compiler Design

## Lecture 20: Object Oriented Features

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Winter 2022

Some content inspired from Dr. Michel Schinz's lecture on Advanced Compiler Construction, EPFL 2016

Timestamp: 2023/03/27 11:08:00

# Object-Oriented features in Java

```java
class A {
  int x;
  float foo() {...}
}

class B extends A {
  int y;
  float foo() {...}
  float bar() {...}
}

class Main {
  void f(A a, B b) {
    a.foo();
    b.x;
  }
}
```

How does the compiler supports object oriented features?

- Where is `b.x` in memory?
- Where is the implementation of `a.foo()`?

# Object-Oriented Features

Object Layout

Method Dispatch

# Object Layout: Single inheritance

In a single-inheritage language, a class can only inherit from a single superclass.

For such languages, fields in an object can simply be laid out sequentially, starting from the ones from the superclass.

$\Rightarrow$ a field declared in a class will always be in the same location, no matter what the *instance type* of the object of that class is.

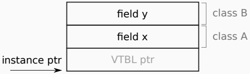
```
class A {
  int x;
  float foo() {...}
}

class B extends A {
  int y;
  float foo() {...}
  float bar() {...}
}

class Main {
  void f(A a, B b) {
    a.foo();
    b.y;
    b.x
    a.x;
  }
}
```

Object layout for A


Object layout for B




Field `x` is at the same offset from the start of the object in both cases!

Assuming instance pointer in `$t0`:

`b.y`:

```
lw $t1, 8($t0)
```

`b.x`:

```
lw $t1, 4($t0)
```

`a.x` (`a` can be instance of `A` or `B`):

```
lw $t1, 4($t0)
```

# Object Layout: Multiple inheritance

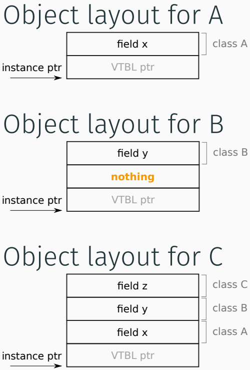
In the case of multiple-inheritage language, object layout becomes more complicated.

## Unidirectional object layout

```
class A {
  int x;
}

class B {
  int y;
}

class C extends A&B{
  int z;
}
```




Wasted space!

And requires to know, ahead of time, the entire class hierarchy.

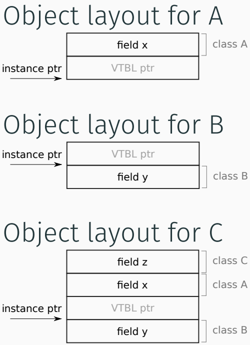
## Bidirectional object layout

Idea: store fields above *and* below the object instance pointer.

```
class A {
  int x;
}

class B {
  int y;
}

class C extends A&B{
  int z;
}
```




No more wasted space!

However:

- Requires to know, ahead of time, the entire class hierarchy;
- Might not always be possible to avoid wasted space.

## Accessor methods

In the context of multiple inheritance, we can take an alternative approach:

- lay out the fields from the class freely (in the most compact manner); and
- use getter and setter accessor methods and rely on the method dispatch mechanism.

The drawback: accessor methods are much slower than direct access to the fields.

# Object layout summary

Problem is easy in the case of single-inheritance languages (*e.g.* Java).

Problem becomes more complex in the case of a multiple-inheritance languages (*e.g.* C++):

- trade-off between speed and space;
- might require access to the whole class hierarchy $\Rightarrow$ close-world;
- or, for instance, rely on accessor methods / dispatching.

# Object-Oriented Features

Object Layout

Method Dispatch

# Method Dispatch

## Class/static methods

The problem: given a class and a method name (and its arguments), find the method's code to execute.

Trivially solved at compile time (static) with name analysis.

## Instance methods

The problem: given an object instance and a method name (and its arguments), find the method's code to execute.

Not possible (in general) to solve at compile time in the presence of inheritance: the specific method's code to execute depends on the runtime type of the object!

```
class A {
  void foo() {print(a)}
}

class B extends A {
  void foo() {print(b)}
}

class Main {
  void f {
    A a  = new A();
    B b1 = new B();
    A b2 = new B();
    a.foo();  // prints a
    b1.foo(); // prints b
    b2.foo(); // prints b
  }
}
```

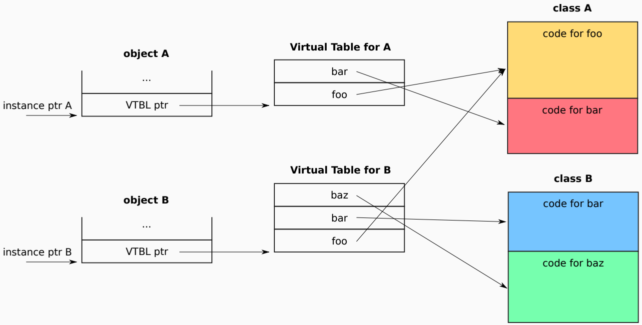
When calling `foo`, the runtime has to decide between the two implementations based on the instance type of the object.

This is generally what we refer to as dynamic dispatch.

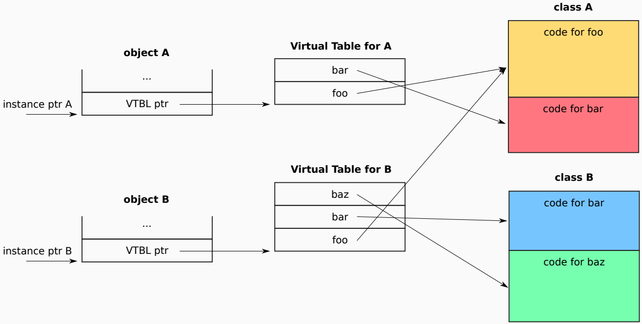
# Dynamic dispatch with Virtual tables

```
class A {
 void foo(){print("foo_a")}
 void bar()(prinf("bar_a")}
}
```

```
class B extends A {
 void bar(){print("bar_b")}
 void baz(){print("baz_b")}
}
```




Inherited methods from the superclass are at the same fixed position in the virtual table.




Assuming variable `p` declared with type A, code for `p.bar()`:

```
# assuming p stored in $t0
lw   $t1, 0($t0) // get virtual table pointer
lw   $t2, 4($t1) // get address of code for subroutine bar
jalr $t2         // jump&link to subroutine
```

Depending on the *instance type of p*, the corresponding `bar` method will be called.

# Accessing fields from an instance method

Consider the following example:

```
class A {
  int i;
  void inc() { i = i+1 }
}
```

How does the implementation of `inc` reach the instance variable `i`?

In fact, the code above looks more like this:

```
class A {
  int i;
  void inc() { this.i = this.i+1 }
}
```

Okay, but where do we get the reference `this` from?

It is implicitly passed as an argument to the instance method:

```
void inc(A this) { this.i = this.i+1 }
```

So when you write:

```
A a = ...;
a.inc();
```

What is really happening being the scence is that you virtually dispatch to the implemention of `inc` passing `p` as the first argument:

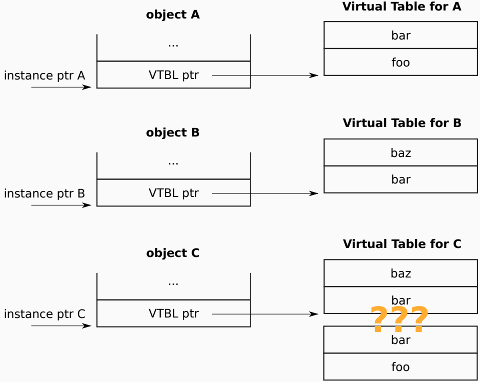
```
A a = ...;
a.inc(a);
```

# Multiple inheritance

What have been shown above works for single-inheritance.

However, in the presence of multiple-inheritance, problems start arising again as we cannot guarantee that the methods are always at the same fixed position in the virtual table:

```
class A {
 void bar(){...}
 void foo(){...}
}
class B {
 void bar(){...}
 void baz(){...}
}
class C extends A&B{
  void foo(){...}
}
```

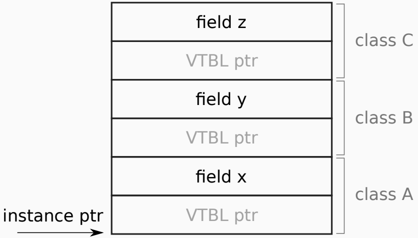



Back to square one!

Solutions exist: based on the idea of embeddeding layout of superclasses into the subclass.

```
class A {
  int x;
}
class B {
  int y;
}
class C extends A&B{
  int z;
}
```

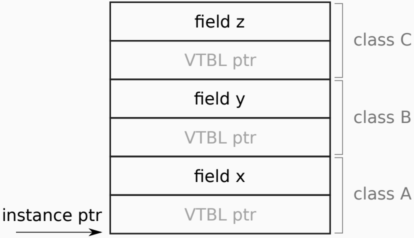
Layout for C:



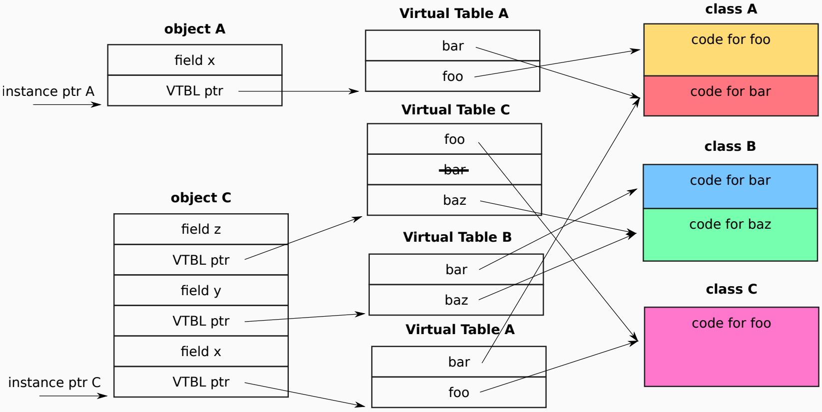

There is one virtual table for each super class in the object and the virtual table is chosen based on the static type of the instance `ptr`.

```
class A {
 int x;
 void bar(){...}
 void foo(){...}
}
class B {
 int y;
 void bar(){...}
 void baz(){...}
}
class C extends A&B{
 int z;
 void foo(){...}
}
```

Layout for C:



Layout and virtual tables for object A and C:




Key property: instance methods of given class are always in the same location in the corresponding virtual table.

Hih-level Code:

```
A aa = new A();
B bb = new B();
C cc = new C();
A ac = new C();
B bc = new C();

aa.bar();
bb.bar();
// cc.bar(); error!
ac.bar();
bc.bar();
cc.foo();
```

```
# aa.bar()
lw   $t0, 0($aa) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1

# bb.bar()
lw   $t0, 0($aa) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1

# ac.bar()
lw   $t0, 0($ac) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1

# bc.bar()
lw   $t0, 0?8?($bc) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1

# cc.foo()
lw   $t0, 0($cc) // virtual table
lw   $t1, 4($t0) // address of foo
jalr $t1
```

**Problem** When looking for the virtual table for an object of static type B, we sometimes need an offset of 0 and sometimes an offset of 8!

**Solution**: we add an offset to the instance pointer based on the static type which will bring us to the right table.

This happens during the type cast! (could be implicit)

Hih-level Code:

```
A aa = new A();
B bb = new B();
C cc = new C();
A ac = (A) new C();
B bc = (B) new C();

aa.bar();
bb.bar();
// cc.bar(); error!
ac.bar();
bc.bar();
cc.foo();
```

Hih-level Code:

```
A aa = new A();
B bb = new B();
C cc = new C();
A ac = (A) new C();
B bc = (B) new C();

aa.bar();
bb.bar();
// cc.bar(); error!
ac.bar();
bc.bar();
cc.foo();
```

```
# A ac = new C();
addi $ac, $ac, 0
# B bc = new C();
addi $bc, $bc, 8
# C cc = new C();
addi $cc, $cc, 16

# aa.bar()
lw   $t0, 0($aa) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1
# bb.bar()
lw   $t0, 0($aa) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1
# ac.bar()
lw   $t0, 0($ac) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1
# bc.bar()
lw   $t0, 0($bc) // virtual table
lw   $t1, 4($t0) // address of bar
jalr $t1
# cc.foo()
lw   $t0, 0($cc) // virtual table
lw   $t1, 4($t0) // address of foo
jalr $t1
```

## Final notes

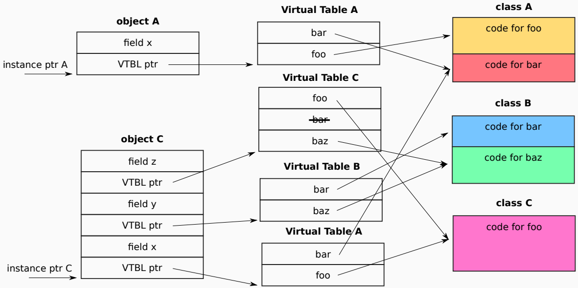
Typecasts introduce the offset! and they are everywhere:

- Assignment (implicit or explicit);
- Method selection from multiple superclass;
- Field access (implicit or explicit).

Hih-level Code:

```
A aa = new A();
B bb = new B();
C cc = new C();
A ac = (A) new C();
B bc = (B) new C();

aa.bar();
bb.bar();
((A)cc).bar();
ac.bar();
bc.bar();
cc.foo();
... ((B)cc).y;
```



This is not the end of the story, but we won't cover more in this lecture. Additional techniques exist to make this efficient:

- Trampoline (used commonly in C++ implementations);
- Row displacement tables;
- Inline caching (great when using a Just-In-Time (*JIT*) compiler).

Summary:

- Single-inheritance languages are easy to implement
    - Layout the fields sequentially in the object;
    - Use a single virtual table to perform dynamic dispatch.
- Multiple-inheritance brings some challenges but solutions exist
    - Embedded layout;
    - Together with Trampoline, row displacement tables or inline caching.