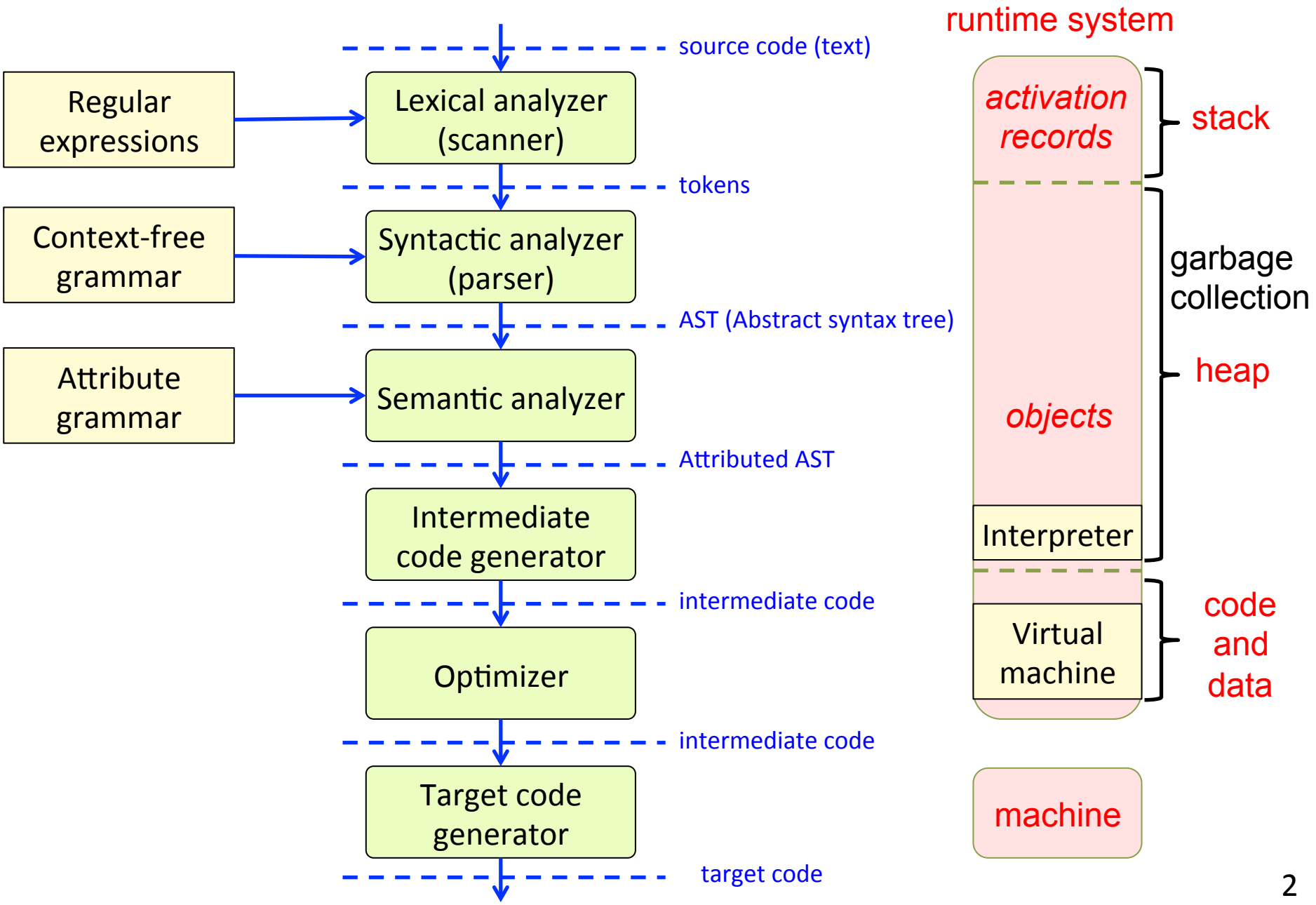
EDAN65: Compilers, Lecture 13

Runtime systems for object-oriented languages

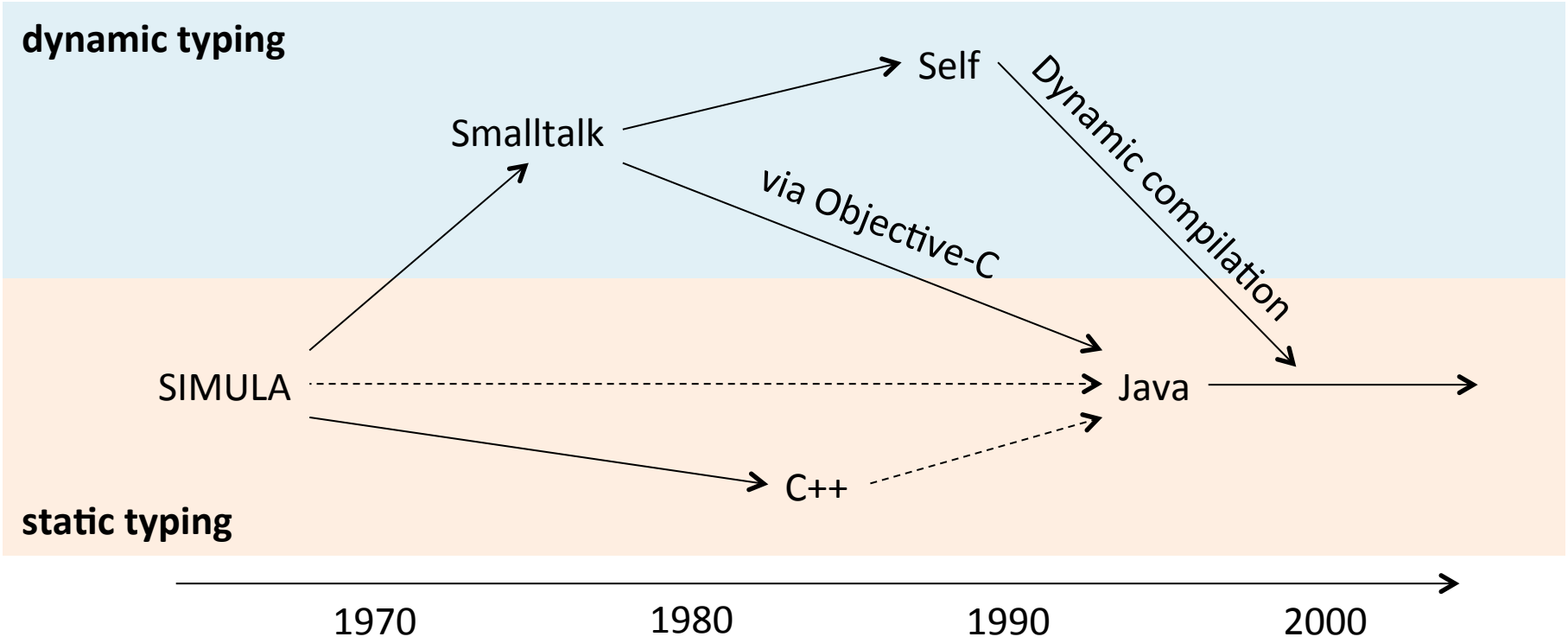
Görel Hedin

Revised: 2015-10-12

This lecture



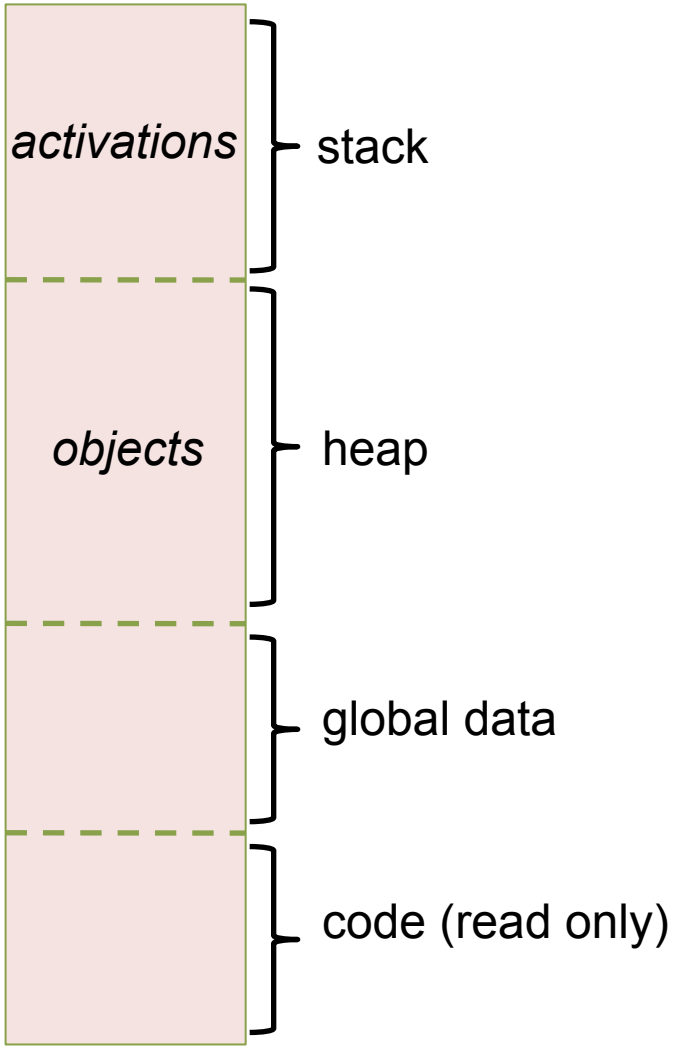
Some influential OO languages



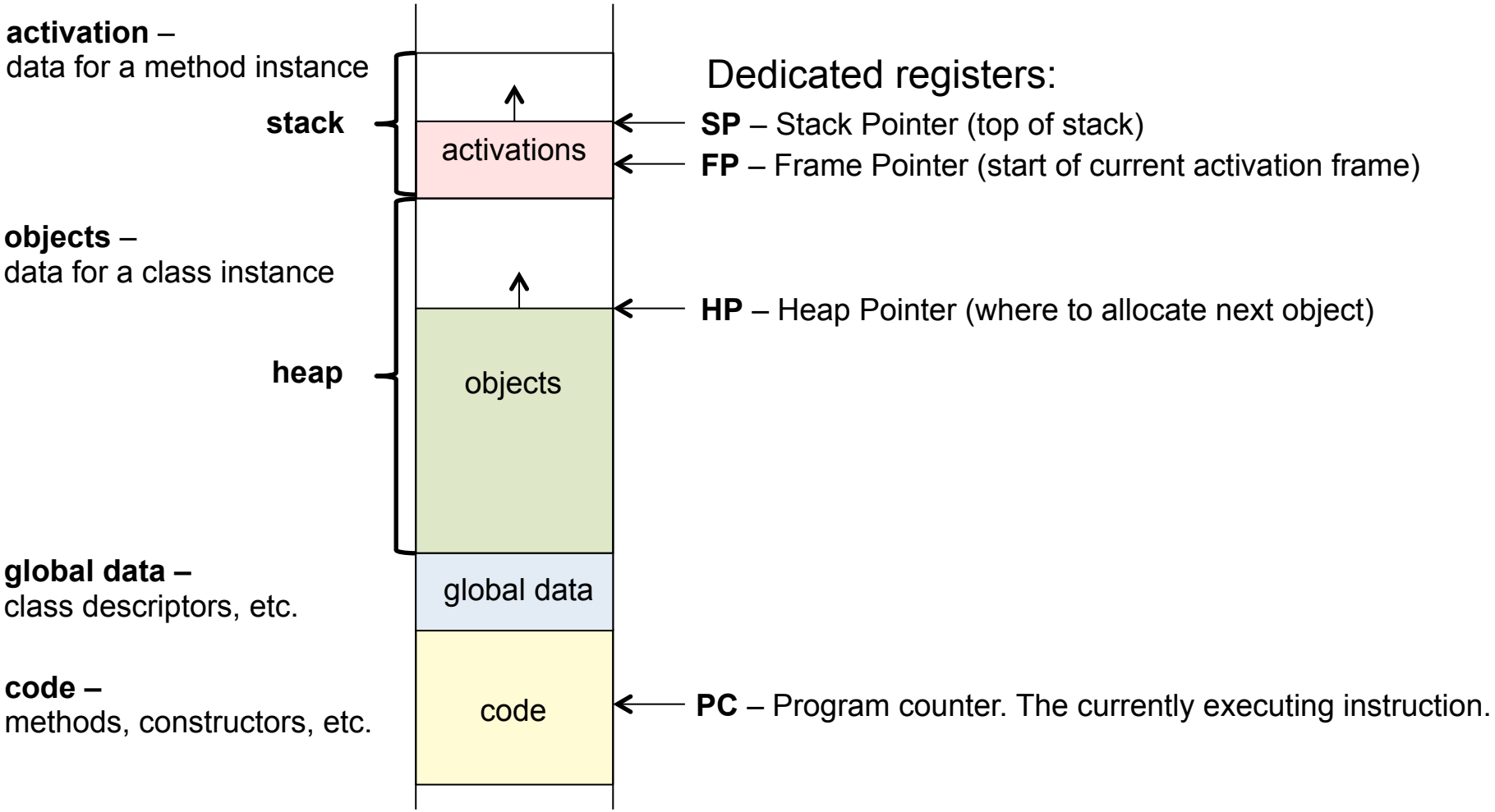
Dynamic typing
At runtime, every object has a type

Static typing
At runtime, every object has a type.
At compile-time, every variable has a type.
At runtime, the variable points to an object of at least that type.

Example memory segments

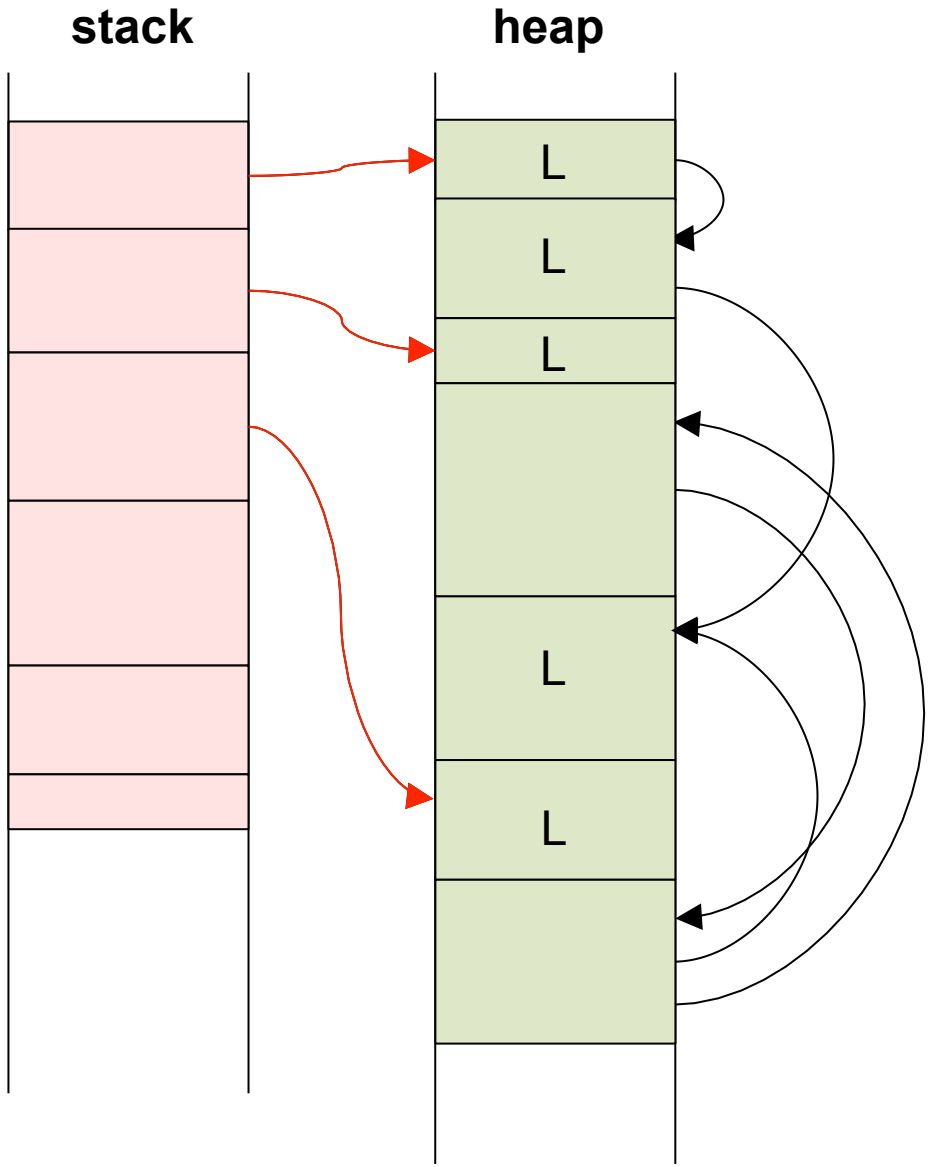


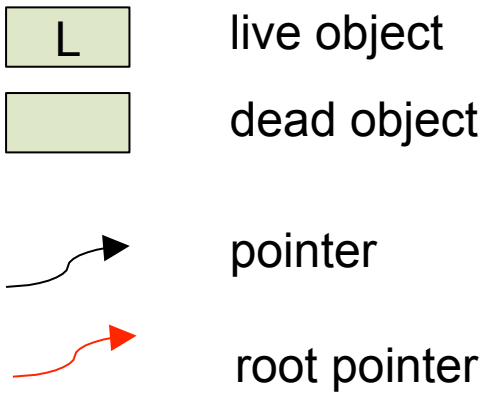
Typical memory usage for OO languages



The figure shows typical use for statically loaded languages like Simula and C++. For languages with dynamic loading (like Java, Smalltalk, ...), class descriptors and code are placed on the heap, rather than in the global data and code segments.
To support threads, each thread has its own stack. Typical stack size: 1 MB. Typical heap size: 80 MB.

The heap



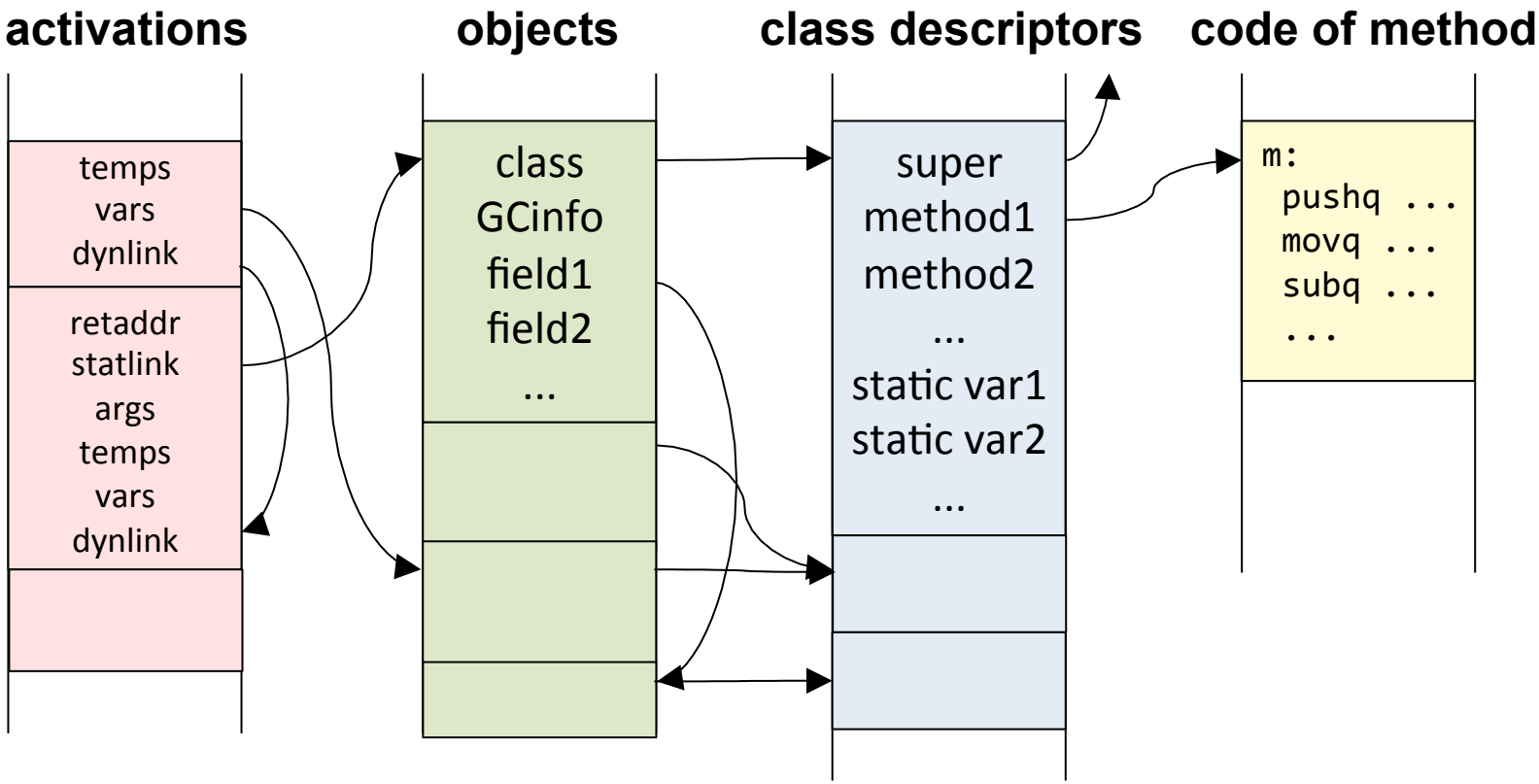


Live objects are those reachable from **root pointers**.

Dead objects can be garbage collected.

Fragmentation: unused memory inside the heap

Typical layouts



A method activation
The static link ("this" pointer) is viewed as an extra argument.
Uses static link to access fields and methods.
Variables, args and temps can point to objects.

An object
Has pointer to the class descriptor (for accessing methods).
GCinfo is used by the garbage collector.
Can have fields that point to objects.

A class descriptor
Can access super class through the super pointer.
Has pointers to its methods.
Can have static variables.

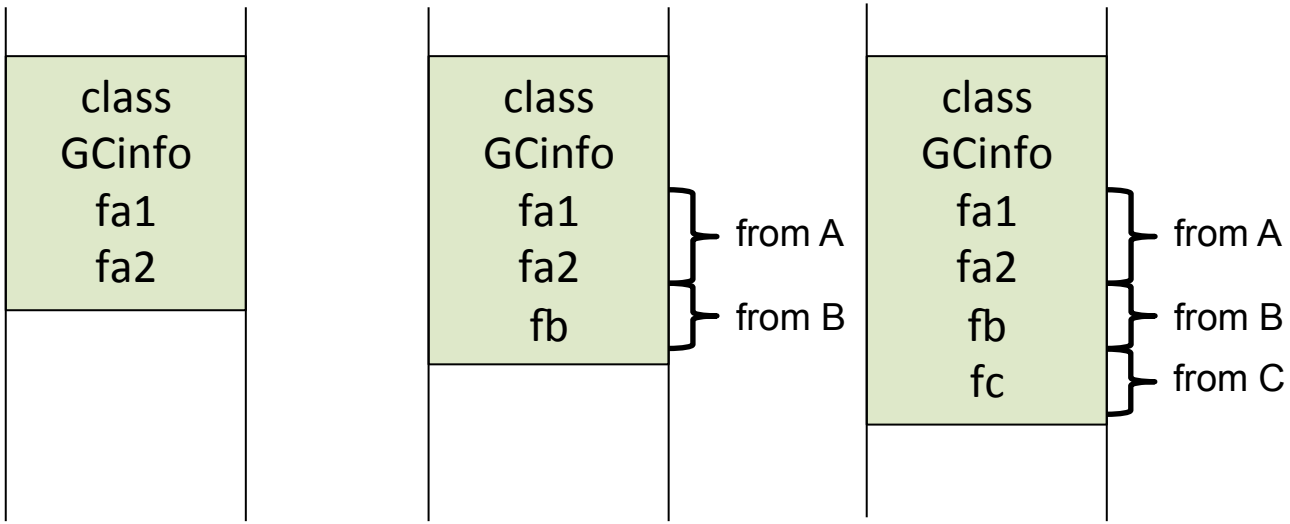
Inheritance of fields, prefixing

source code

```
class A {
  int fa1;
  int fa2;
}
```

```
class B extends A {
  int fb;
}
```

```
class C extends B {
  int fc;
}
```



Prefixing
Fields of the superclass are placed in front of local fields ("prefixing"). Each field is thus located at an offset computed at compile time, regardless of the dynamic type of the object.

Field addresses

```
fa1   16(obj)
fa2   24(obj)
fb    32(obj)
fc    40(obj)
```

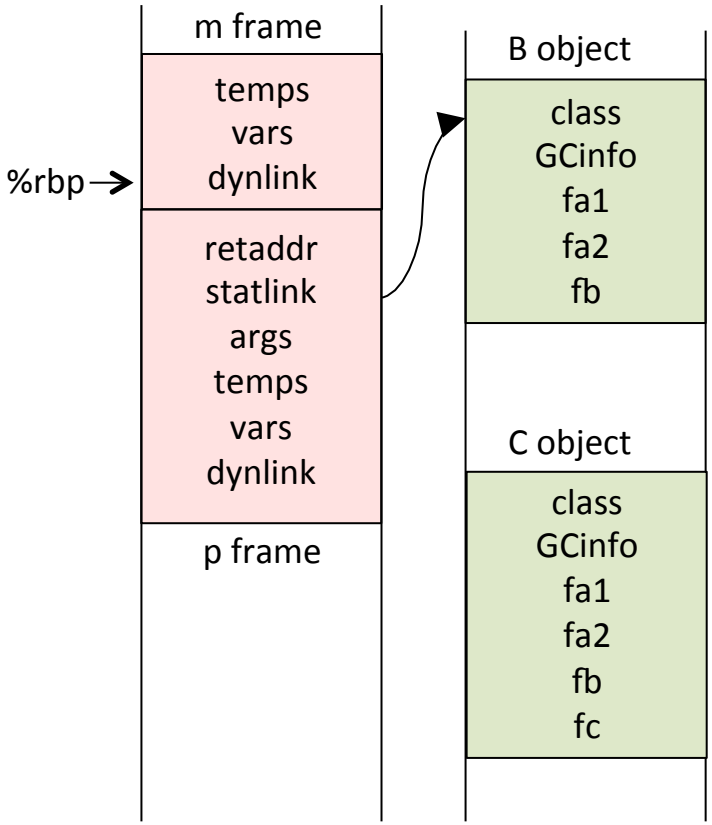
Access to fields (single inheritance)

source code

```
class A {
  int fa1;
  int fa2;
  void m() {
    fa1 = fa2;
    ...
  }
}
```

```
class B extends A {
  int fb;
}
```

```
class C extends B {
  int fc;
}
```



The code for m knows the static type of the object (A), but not the dynamic type (B or C in this case).

Because of prefixing, the code for m can access fa1 and fa2 through an efficient indirect access, using a fixed offset, without knowing the dynamic type of the object.

```
void p(A a) {
  a.m();
}
```

```
# Example code, assuming statlink ("this") is at 16(%rbp):
A-m:
  ...
  movq 16(%rbp), %rax     # this -> rax
  movq 24(%rax), 16(%rax) # fa2 -> fa1
```

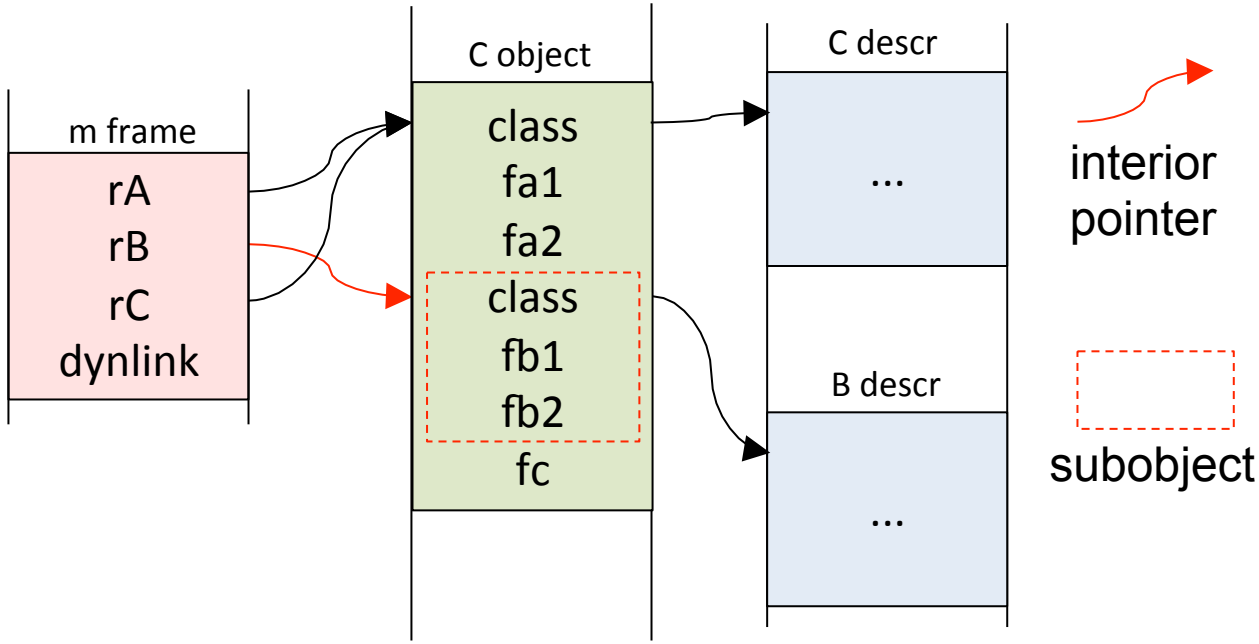
Access to fields (multiple inheritance, C++)

source code

```
class A {
  int fa1;
  int fa2;
}
```

```
class B {
  int fb1;
  int fb2;
}
```

```
class C extends A, B {
  int fc;
}
```




```
void m() {
  A rA = new C();
  B rB = rA;
  C rC = rA;
}
```

Interior pointers and subobjects

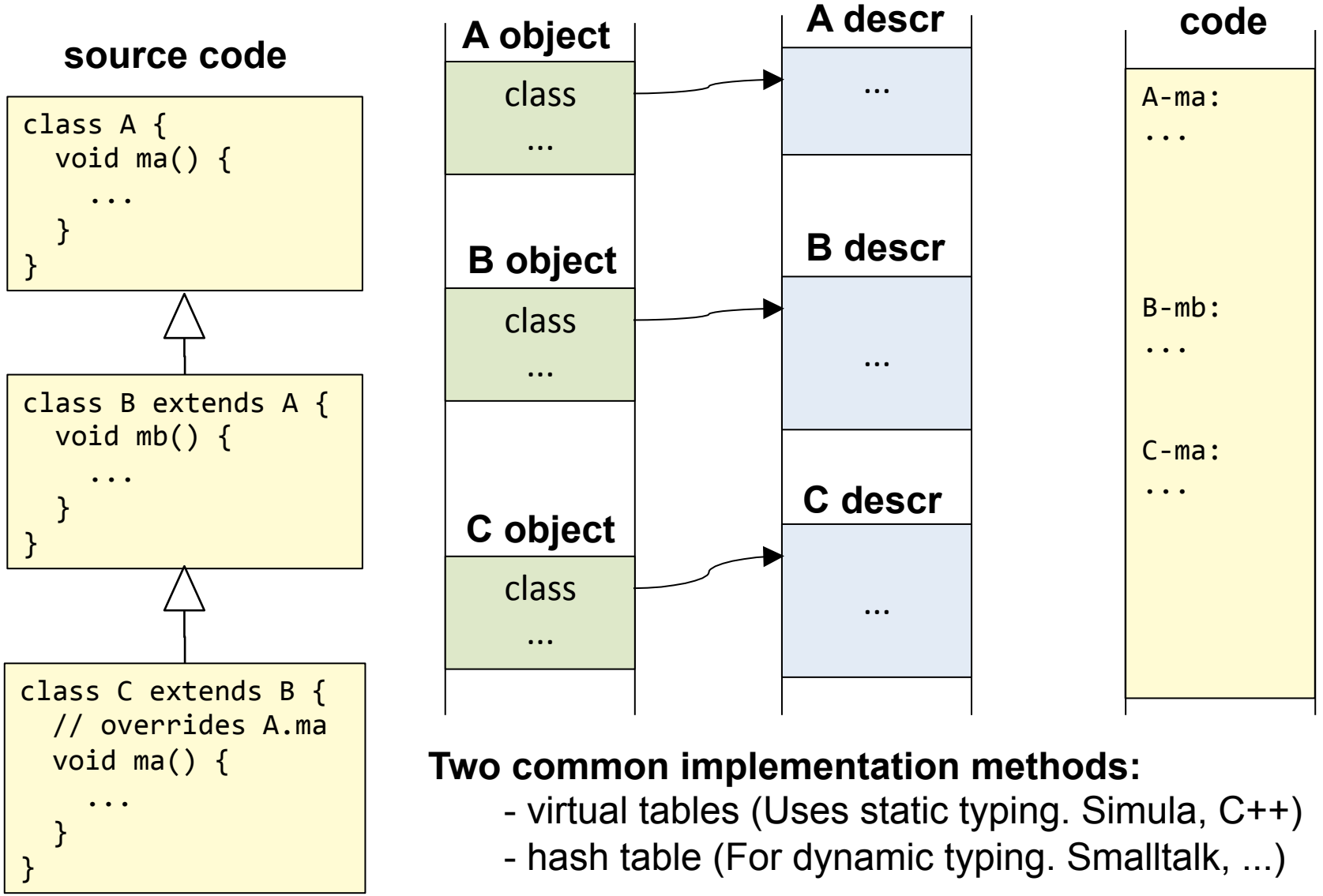
Parts of the class hiearchy are treated like single inheritance:
rA and rC point to the full C object.

For remaining parts, allocate subobjects inside the main object.
rB points to the *interior* of the C object, to the B subobject.

Gives problems for garbage collector:
The GC needs to identify full objects. Solvable, but expensive.

Dynamic dispatch

(Calling methods in presence of inheritance and overriding)

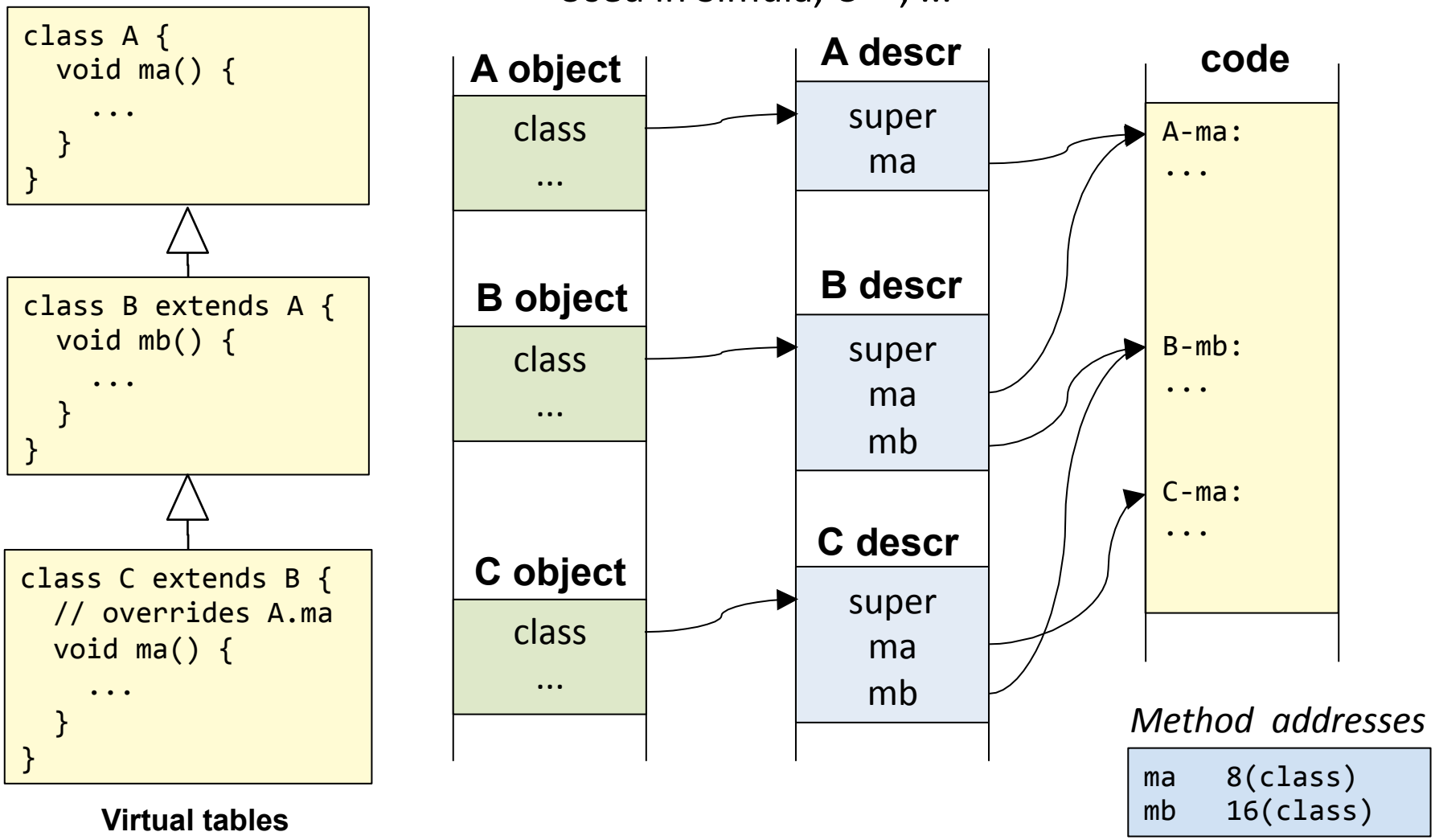


Two common implementation methods:

- virtual tables (Uses static typing. Simula, C++)
- hash table (For dynamic typing. Smalltalk, ...)

Virtual tables

Used in Simula, C++, ...



Virtual tables

Class descriptor contains *virtual table* (often called "vtable").

Pointers to superclass methods are placed in front of locally declared methods ("prefixing").

Each method pointer is located at an offset computed at compile time, using the static type.

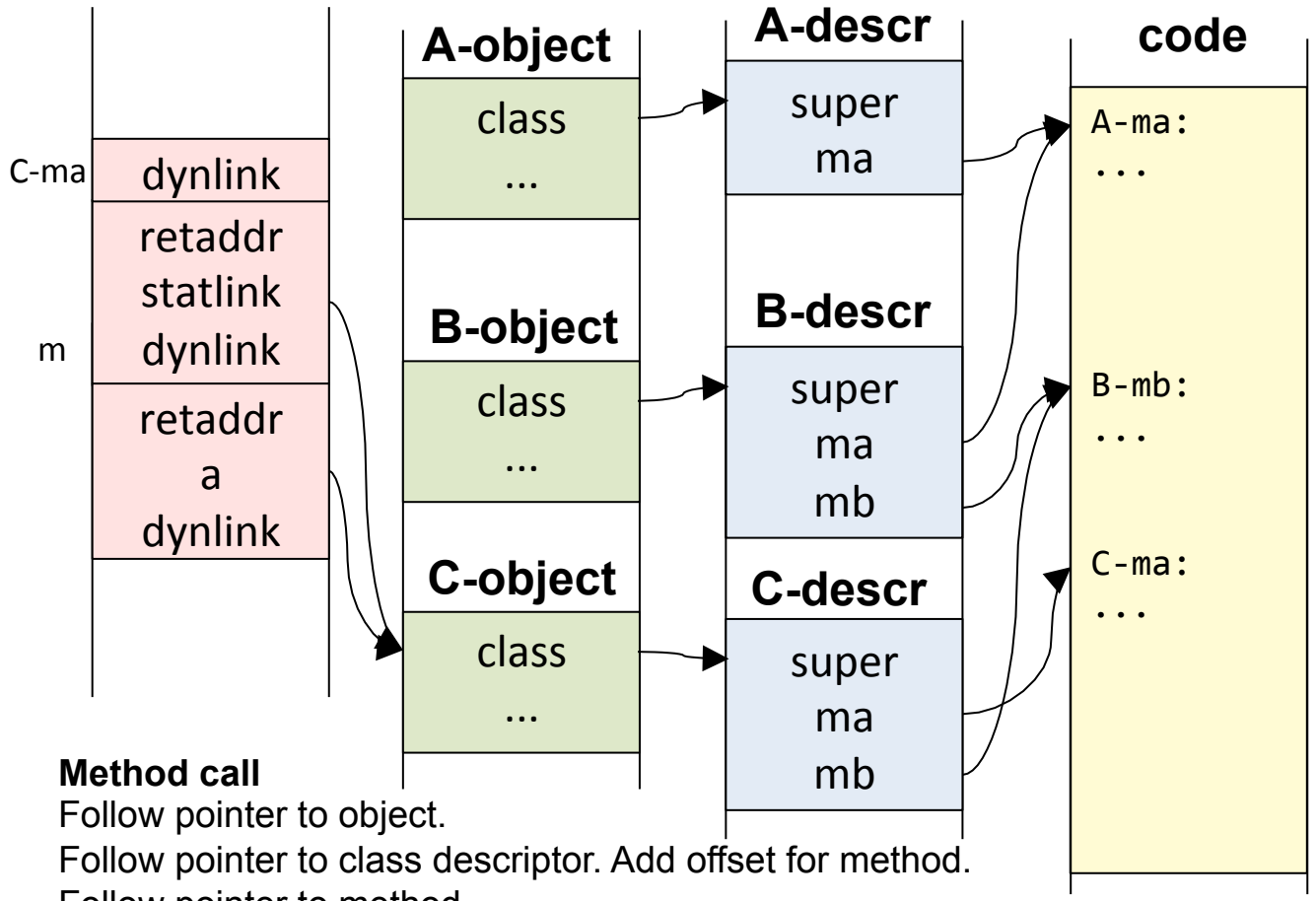
Calling a method via the virtual table

```
class A {
  void ma() {
    ...
  }
}
```

```
class B extends A {
  void mb() {
    ...
  }
}
```

```
class C extends B {
  // overrides A.ma
  void ma() {
    ...
  }
}
```

```
void m(A a) {
  a.ma();
}
```



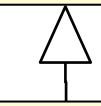
Method call
Follow pointer to object.
Follow pointer to class descriptor. Add offset for method.
Follow pointer to method.

```
m:
  ...
  movq 16(%rbp), %rax     # a -> rax
  pushq %rax              # push the static link (this)
  movq (%rax), %rax       # class descriptor -> rax
  callq 8(%rax)           # call ma
```

Dynamic dispatch through hash table

methods and vars have
no static types

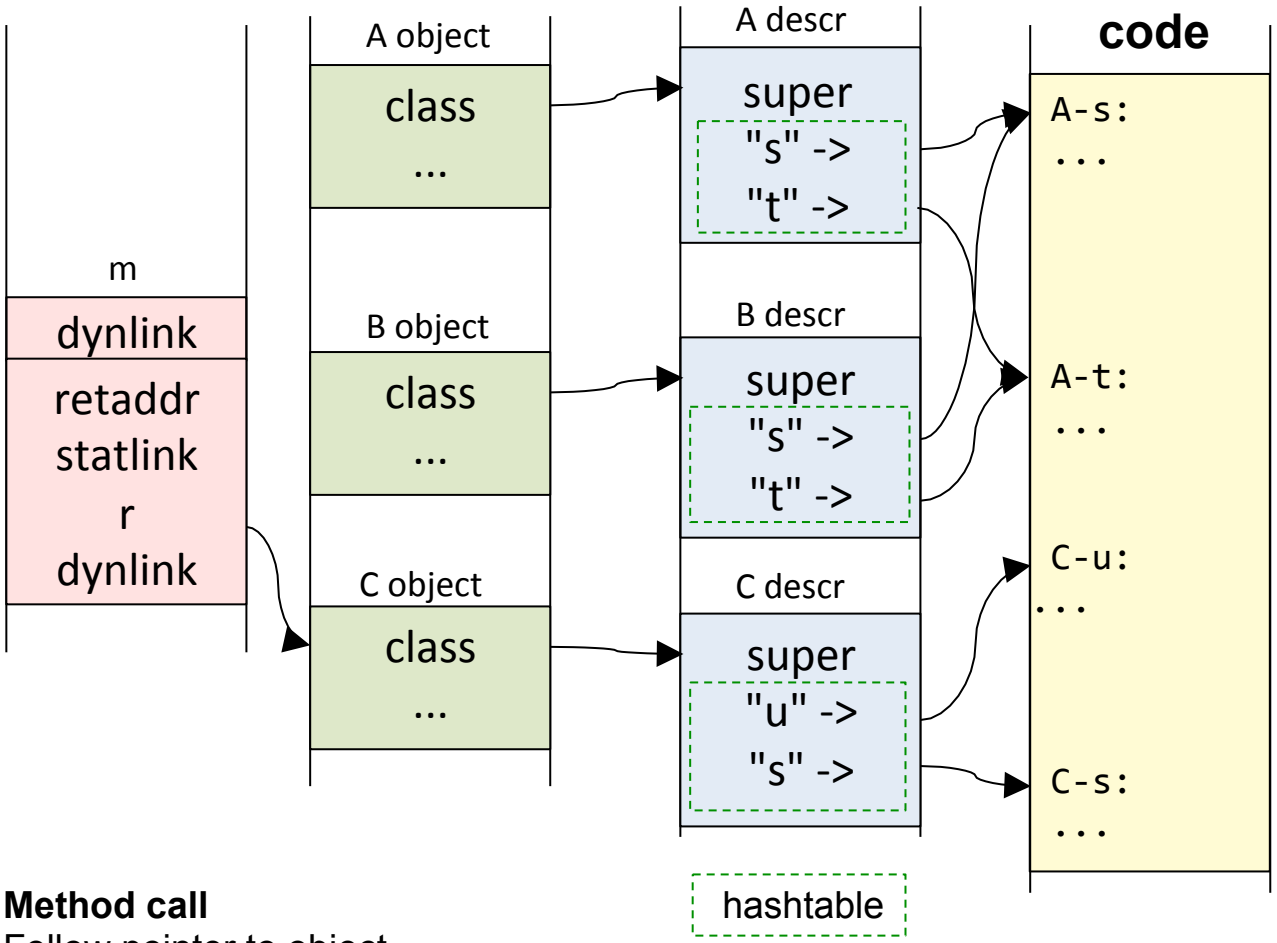
```
class A {
  method s() {...}
  method t() {...}
}
```



```
class B extends A {
  method t() {...}
}
```

```
class C {
  method u() {...}
  method s() {...}
}
```

```
class ... {
  method m(r) {
    r.s();
  }
}
```



Method call
Follow pointer to object.
Follow pointer to class descriptor. Lookup method pointer in hashtable.

Does not rely on static types.
Can be used for dynamically typed languages.
Slow if not optimized.

Comparison, dynamic dispatch

Virtual tables
Can implement multiple inheritance by adapting prefixing, similarly to field access.
Cannot be used for dynamically typed languages.
Fast calls – only an indirect jump.

Hash tables
No problem with multiple inheritance.
Can be used for dynamically typed languages.
Slow calls – need to do hash table lookup.

Optimization of OO languages

Common conventional optimization techniques (for C):
Inlining (avoid calls, get more code to optimize over)
Common subexpression elimination
Move loop invariant code to outside of the loop

Difficult to optimize OO with conventional techniques
Many small methods – not much to optimize in each
Virtual methods slower to call
Virtual methods difficult to inline – actual method not known until runtime

If methods could be inlined...
... we could save the expensive calls
... we would get larger code chunks to optimize over

Approaches to optimization of OO code

Static compilation approaches
Analysis of complete programs: "whole world analysis"
Find methods to be inlined. Then optimize further.
Not used in practice: cannot be used with dynamic loading.

Dynamic compilation approaches
Inline methods at runtime (self-modifying code)
Dynamic compilation and optimization (at runtime)
Use simple conventional optimization techniques
(must be fast enough at runtime)
Very successful in practice (Java, CLR, Javascript, ...)
Can beat optimized C for some benchmarks.

Other important optimizations in OO

Dynamic type tests (casts, instanceOf)

Synchronization and thread switches

Garbage collection

Interpretation vs Compilation in Java

Interpreting JVM
portable but slow

JIT – Just-In-Time compilation
compile each method to machine code the first time it is executed
requires very fast compilation – no time to optimize

AOT – Ahead-of-time compilation
Generate machine code for a complete program, before execution. This is "normal" compilation, the way it is done in C, C++, ...
Problem to use this approach for Java: cannot support dynamic loading.

Adaptive optimizing compiler
Run interpreter initially to get profiling data
Find "hot spots" which are translated to machine code, and then optimized
May outperform AOT compilers in some cases!
The approach used today in the SUN/Oracle JVM, called "HotSpot".

Inline call caches

a way to optimize method calls at runtime

Based on hash table lookup

Do a normal (slow) lookup. Finds method, say Bus-m.

Guess that the next call will be for an object of the same type (Bus), i.e., to Bus-m.

Replace the method call with a direct call to Bus-m, with the receiver as argument.

Add a prologue to the method, Bus-m-prologue, that checks if the argument is of the guessed type (Bus).

If not, do a normal (slow) lookup.

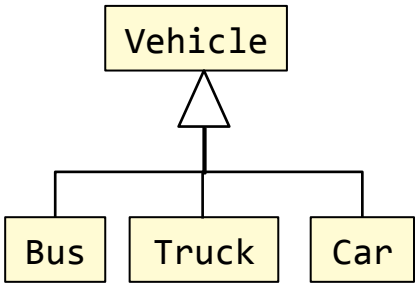
Original calling code

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  v.m();
}
```

optimize →

Optimized calling code

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  Bus-m-prologue(v);
}
```

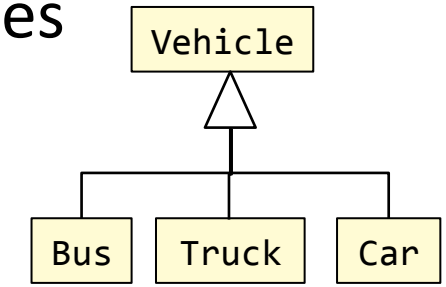


Called method:

```
Bus-m-prologue:
 if (receiver is not a Bus)
    receiver.m(); // Ordinary slow lookup
Bus-m:
  normal method body
  ...
```

Polymorphic inline caches (PICs)

a generalization of inline call caches



Handle several possible object types
Inline the prologues into the calling code.
Check for several types.

Inlined call cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  Bus-m-prologue(v);
}
```

optimize →

Called method:

```
Bus-m-prologue:
  if (!receiver is a Bus)
    receiver.m(); // normal lookup
Bus-m:
  normal method body
  ...
```

Polymorphic inlined cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  if (v is a Bus)
    Bus-m(v)
  else if (v is a Car)
    Car-m(v)
  else
    v.m(); // normal lookup
}
```

Called methods:

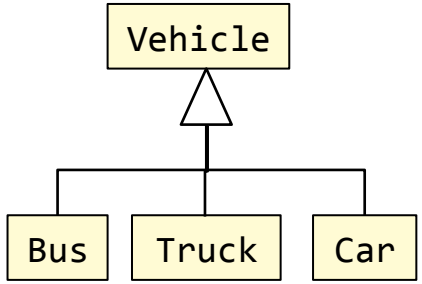
```
Bus-m:
  ...
Car-m:
  ...
```

Inlining method bodies

Can be done after inlining calls

Inlining method bodies

Copy the called methods into the calling code



Polymorphic inlined cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  if (v is a Bus)
    Bus-m(v)
  else if (v is a Car)
    Car-m(v)
  else
    v.m(); // normal lookup
}
```

Called methods:

```
Bus-m:
  ...
Car-m:
  ...
```

optimize →

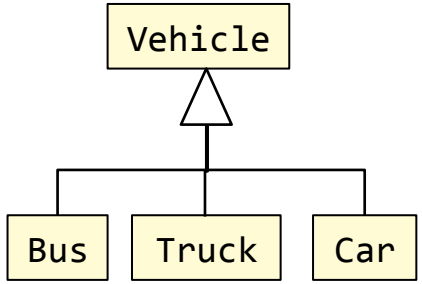
Polymorphic inlined cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  if (v is a Bus)
    ... // code for Bus-m
  else if (v is a Car)
    ... // code for Car-m
  else
    v.m(); // normal lookup
}
```

Methods:

```
Bus-m:
  ...
Car-m:
  ...
```

Further optimization



Now there is a large code chunk at the calling site

Ordinary optimizations can now be done

- common subexpression elimination
- loop invariant code motion
- …

Polymorphic inlined cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  if (v is a Bus)
    Bus-m(v)
  else if (v is a Car)
    Car-m(v)
  else
    v.m(); // normal lookup
}
```

Called methods:

```
Bus-m:
  ...
Car-m:
  ...
```

optimize →

Polymorphic inlined cache

```
Vehicle v = ...;
while (...) {
  v = aList.get();
  if (v is a Bus)
    ... // code for Bus-m
  else if (v is a Car)
    ... // code for Car-m
  else
    v.m(); // normal lookup
}
```

Methods:

```
Bus-m:
  ...
Car-m:
  ...
```

Dynamic adaptive compilation

Keep track of execution profile

Add PICs dynamically
Order cases according to frequency
Inline the called methods if sufficiently frequent
Optimize the code if sufficiently frequent

Adapt the optimizations depending on current profile

Dynamic adaptive compilation

Techniques originated in the Smalltalk and Self compiler

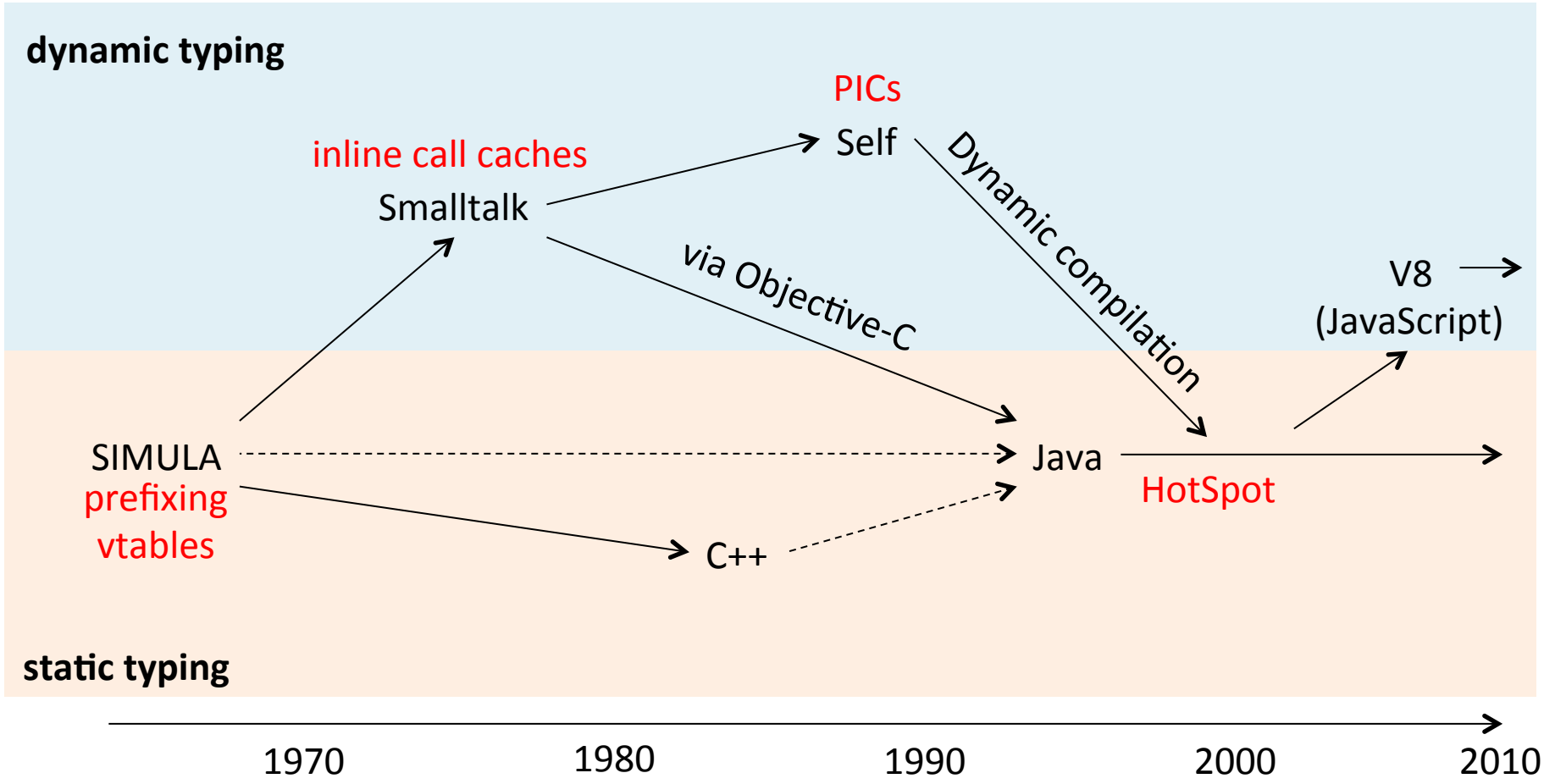
Adapted to Java in SUN/Oracle's HotSpot JVM
Techniques originally developed for dynamically typed languages useful also for statically typed languages!
Dynamic adaptive optimizations may outperform optimizations possible in a static compiler!

Client vs Server compiler
Local optimizations vs heavy inlining and other memory intensive optimizations.

Warm-up vs. Steady state
Slower when the program starts (warm-up). Fast after a while (steady-state).

A huge success:
Fast execution in spite of fast compilation and dynamic loading.
Now used in other major languages like C# (CLR platform), Javascript, etc.
Many languages compile to Java Bytecode to take advantage of the HotSpot JVM.

Major advances in OO implementation



Summary questions

- What is the difference between dynamic and static typing?
- Is Java statically typed?
- What is a heap pointer?
- How are inherited fields represented in an object?
- What is prefixing?
- How can dynamic dispatch be implemented?
- What is a virtual table?
- Why is it not straightforward to optimize object-oriented languages?
- What is an inline call cache?
- What is a polymorphic inline cache (PIC)?
- How can code be further optimized when call caches are used?
- What is meant by dynamic adaptive compilation?