Smalltalk Implementation

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The Image

The object heap

The Virtual Machine

The underlying system (e.g., Mac OS X)
The ST language interpreter
The object-memory manager

Outline:

- Describe a simple implementation
  - Representation of objects in memory
  - The "bytecode" representation of ST code
  - The bytecode interpreter
- Memory management / garbage collection algorithms
- Optimization Techniques

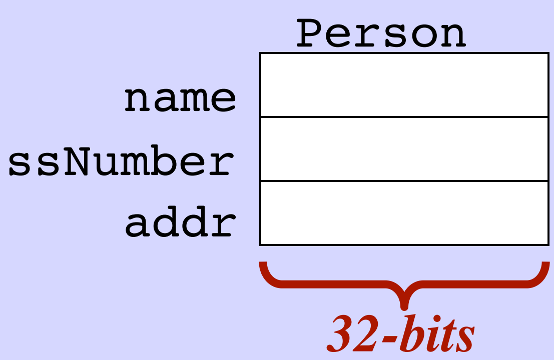
References

- Smalltalk-80: The Language and its Implementation, by Goldberg and Robson (Part IV), Addison-Wesley, 1983.
- Smalltalk-80: The Language, by Goldberg and Robson (Chapter 21), Addison-Wesley, 1989.
- Smalltalk-80: Bits of History, Words of Advice, ed. Glen Krasner, Addison-Wesley, 1983.
- Generation Scavenging: A Non-Disruptive High Performance Storage Reclamation Algorithm, by David Ungar, ACM Software Engineering Notes/SIGPLAN Notices: Software Engineering Symposium on Practical Software Development Environments, Pittsburgh, PA, 1984.
- Efficient Implementation of the ST-80 System, by Peter L. Deutsch and Allan M. Schiffman, POPL-84, Salt Lake City, UT, 1984.
- Architecture of SOAR: Smalltalk on a RISC, by Ungar, Blau, Foley, Samples, Patterson, 11th Annual Symposium on Computer Architecture, Ann Arbor, MI, 1984.
- The Design and Evaluation of a High Performance Smalltalk System, by David M. Ungar, MIT Press, ACM Distinguished Dissertation (1986), 1987.

Representing Objects

Object = Block of memory (i.e., “struct”, “record”)

Field = Offset into record (“instance variable”)

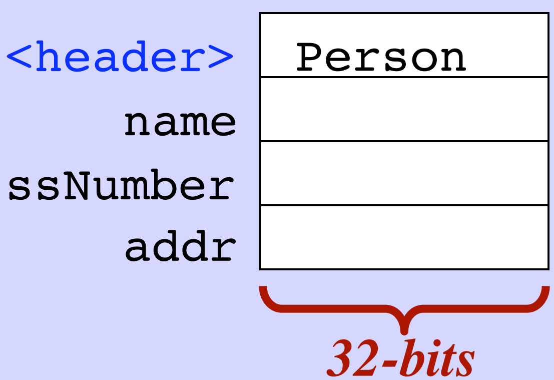


Representing Objects

Object = Block of memory (i.e., “struct”, “record”)
Field = Offset into record (“instance variable”)

Header

A “hidden” field, included in every object.
Tells the class of the object (and other stuff).



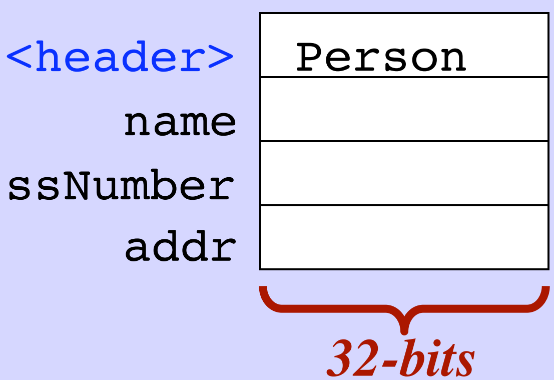
Representing Objects

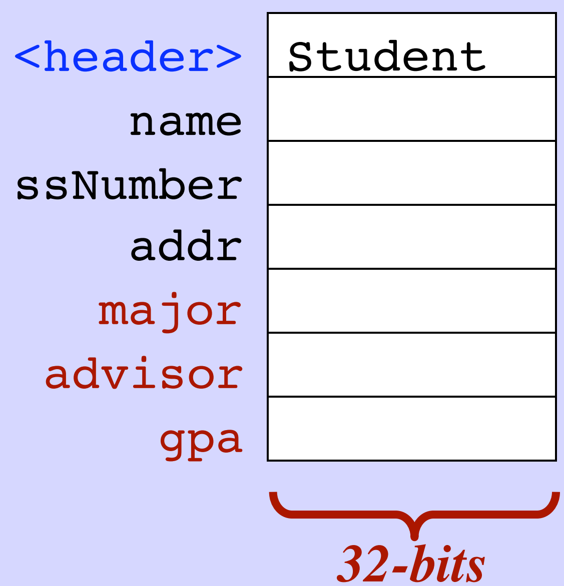
Subclassing:

Existing fields in the same locations

New fields added to end of record

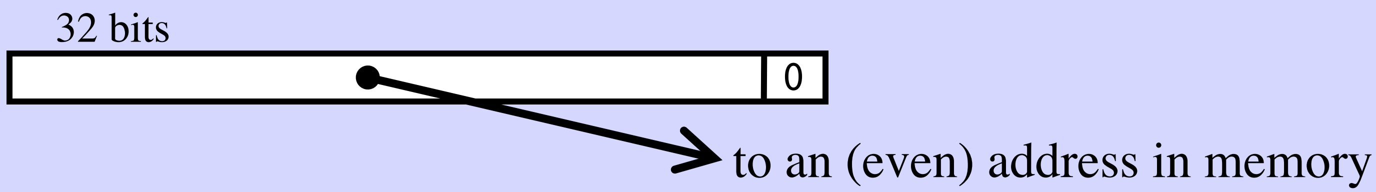
Example: Student is a subclass of Person



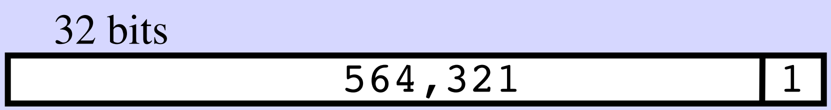


Tagged Values

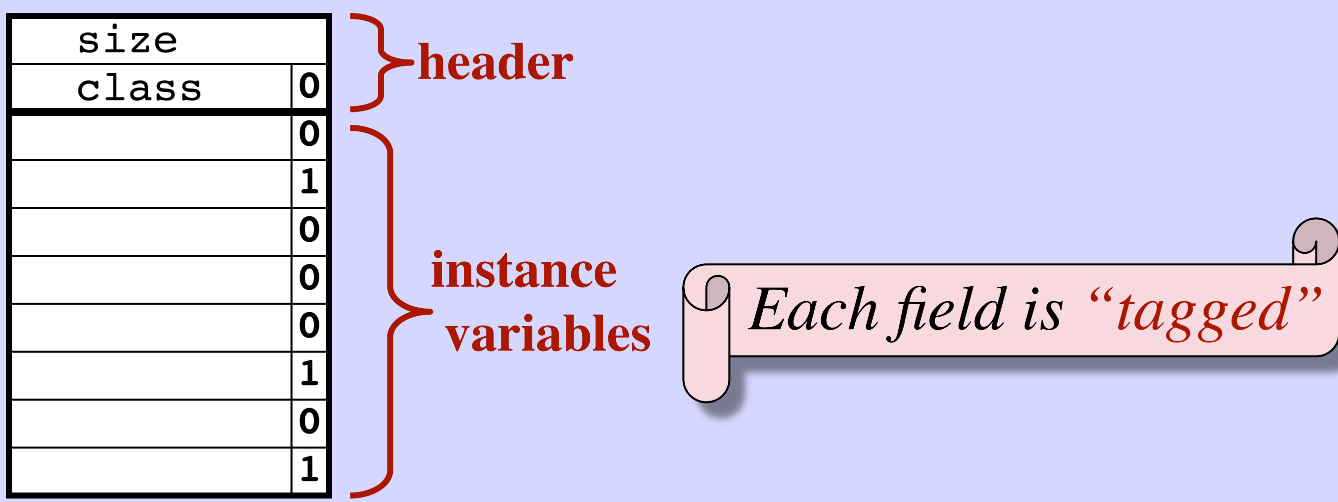
Object-Oriented Pointers (OOPs)



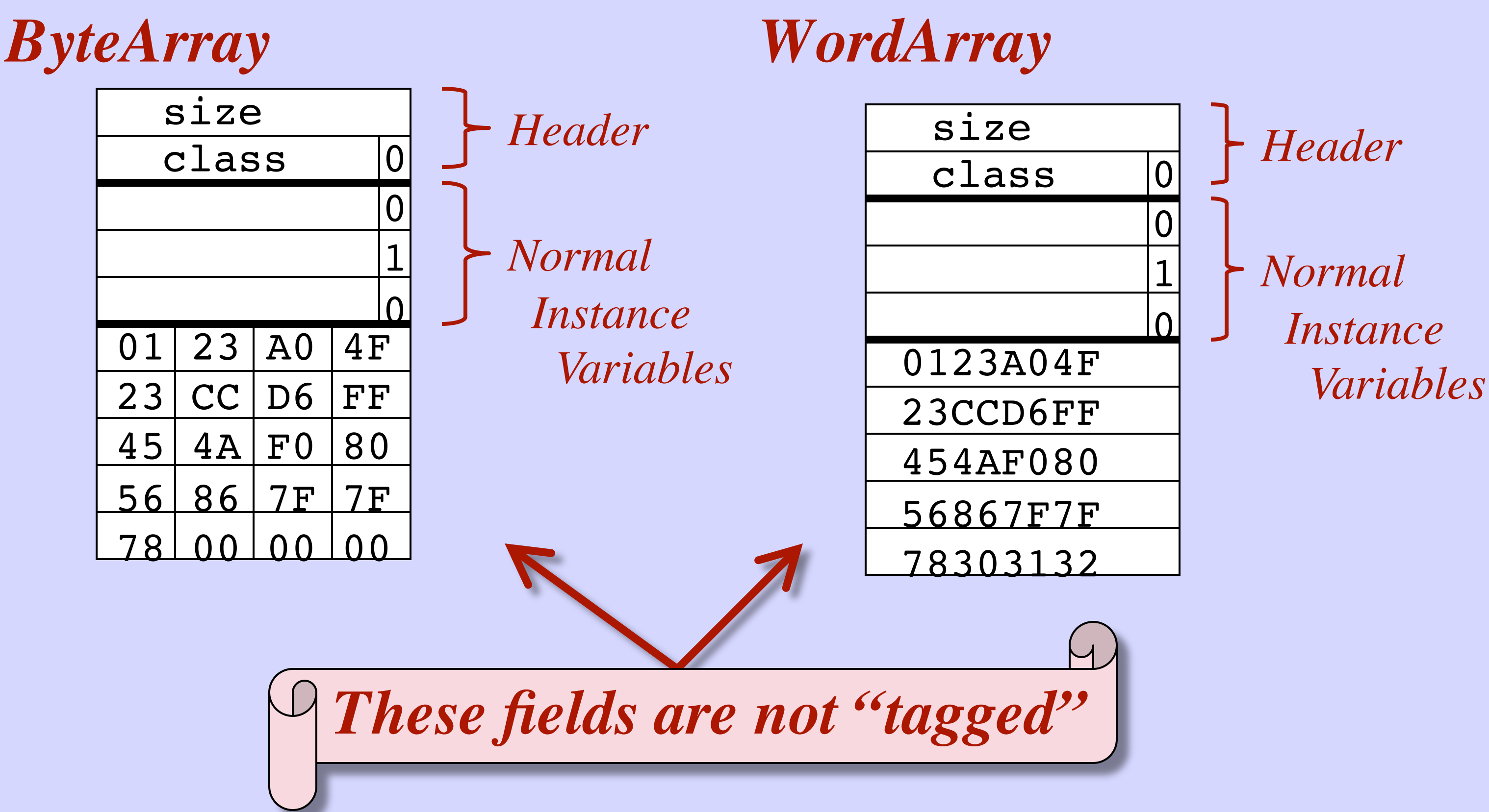
SmallIntegers (-1,073,741,824 .. 1,073,741,823)



Objects



Other formats for objects (containing “raw” bits)



Bytecodes

The instructions of the virtual machine (VM) interpreter

The VM executes one bytecode instruction after another.

Note: "*execute*" = "*interpret*" = "*emulate*"

A real machine executes instructions.

The VM executes bytecodes.

Like machine language instructions

- Comparable level of detail
- 1 to 4 bytes long
- Tight encoding into the available bits (CISC architecture)

(Java used ST's approach VM, bytecodes, etc.)

The Compiler

Translates methods (i.e., Strings) into instances of a class called

CompiledMethod

Contains a sequence of bytes (the “bytecodes” to execute)

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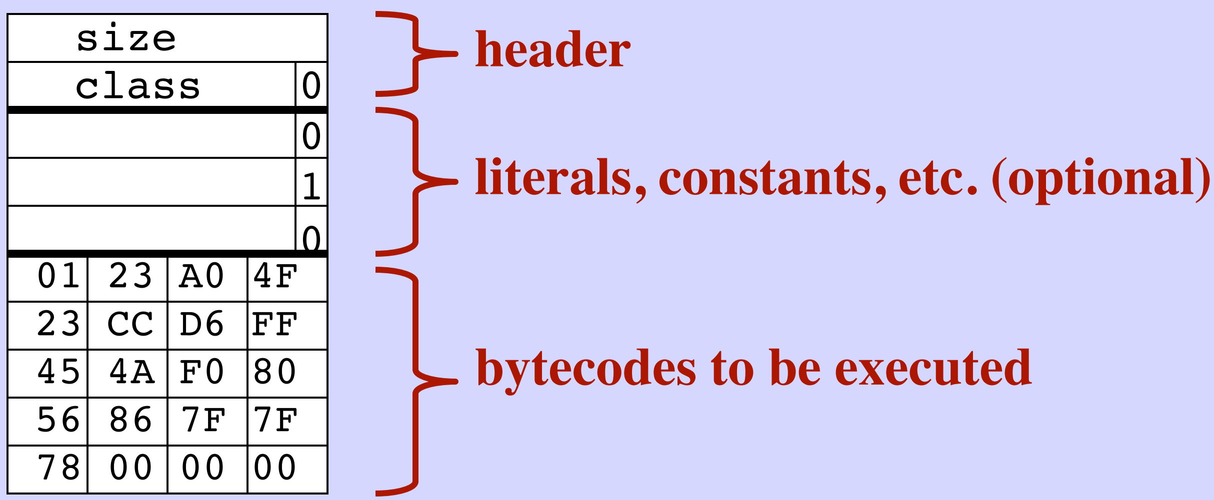
Translates methods (i.e., Strings) into instances of a class called

CompiledMethod

Contains a sequence of bytes (the "bytecodes" to execute)

CompiledMethod is subclass of ***ByteArray***.



Class Symbol

Symbols are used for method selectors.

```
'hello'        'at:put:'
#hello         #at:put:
```

Like the class ***String***.
Symbol is a subclass of ***String***.

Consider a string `'hello'` … there may be many ***Strings*** with these chars.
Consider the symbol `#hello` … there is only one ***Symbol*** with these chars.

There is a system-wide collection of all ***Symbol*** objects.
All ***Symbol*** objects are kept in this "symbol table".

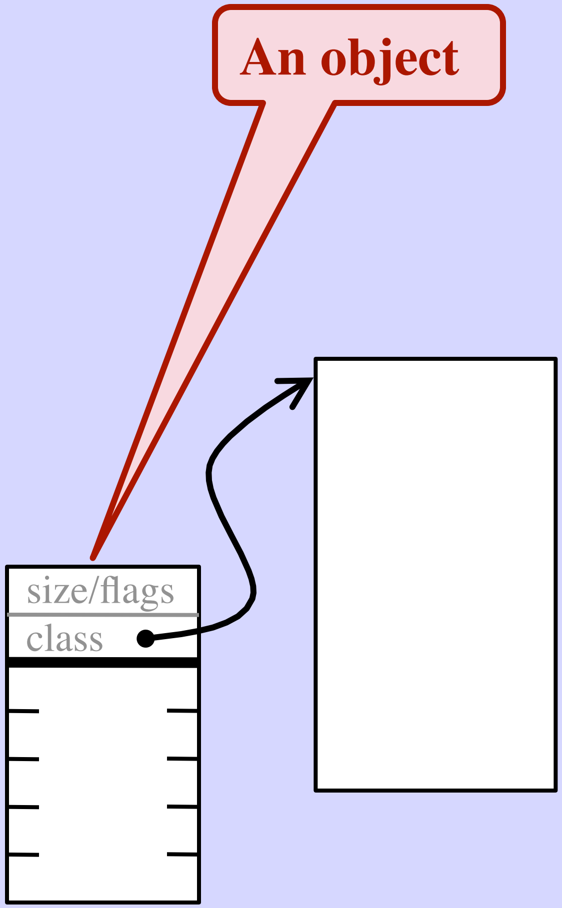
String

`'hello'` and `'hello'` may be two different objects.
= will compare characters, one-by-one.
You should always use = to test *Strings*.

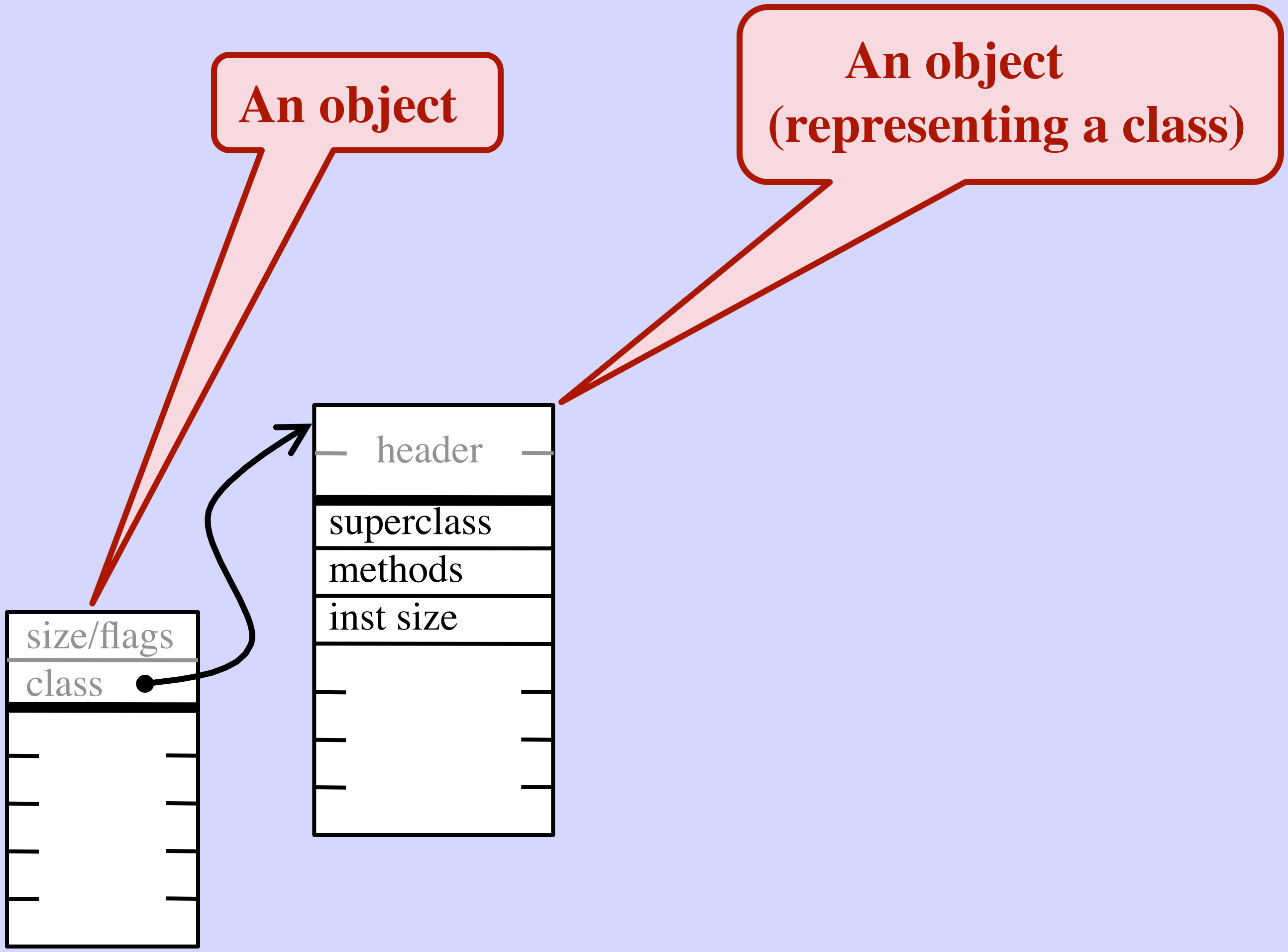
Symbol

You can always rely on == , which is fast!

Representing Classes



Representing Classes



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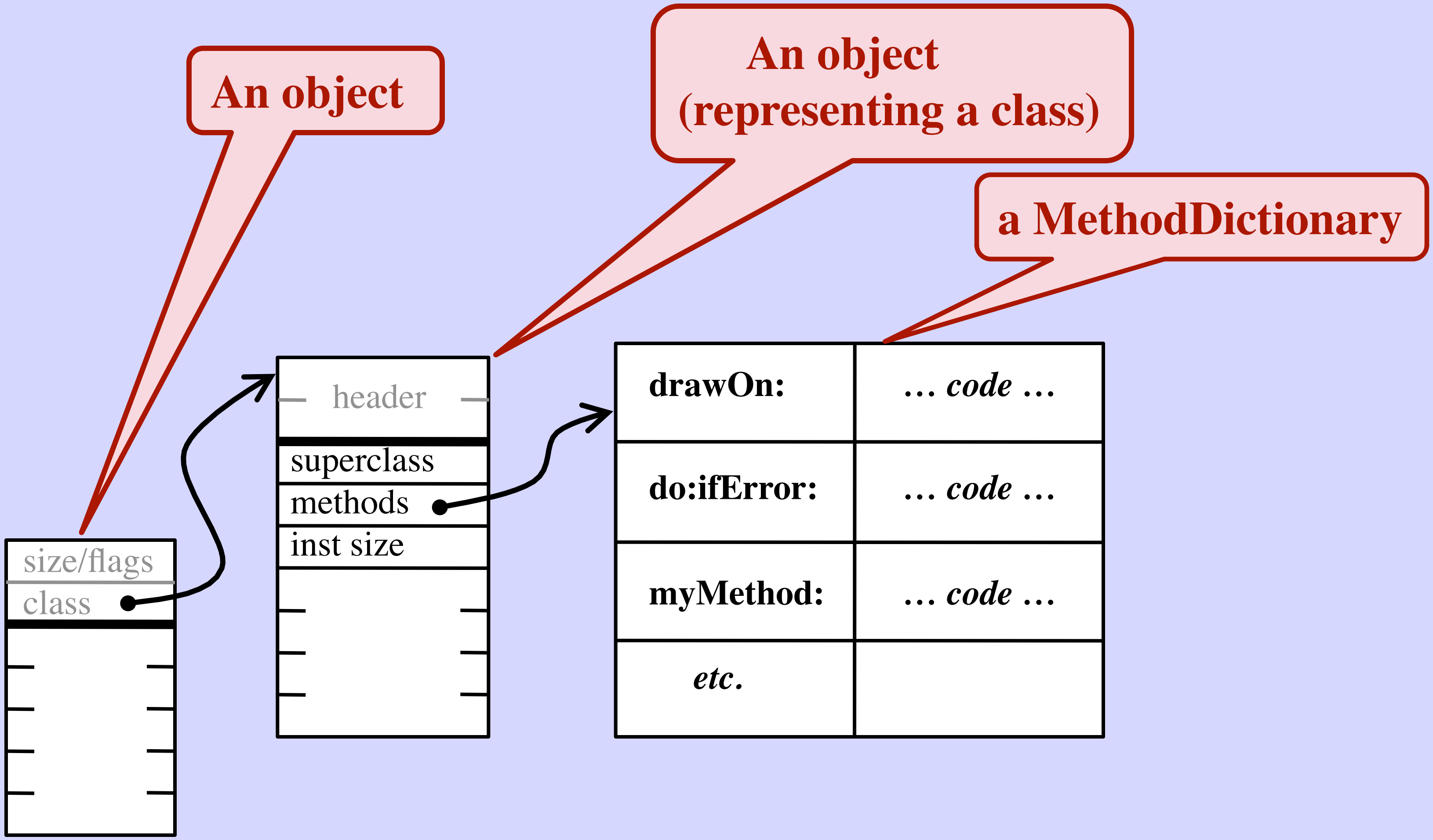

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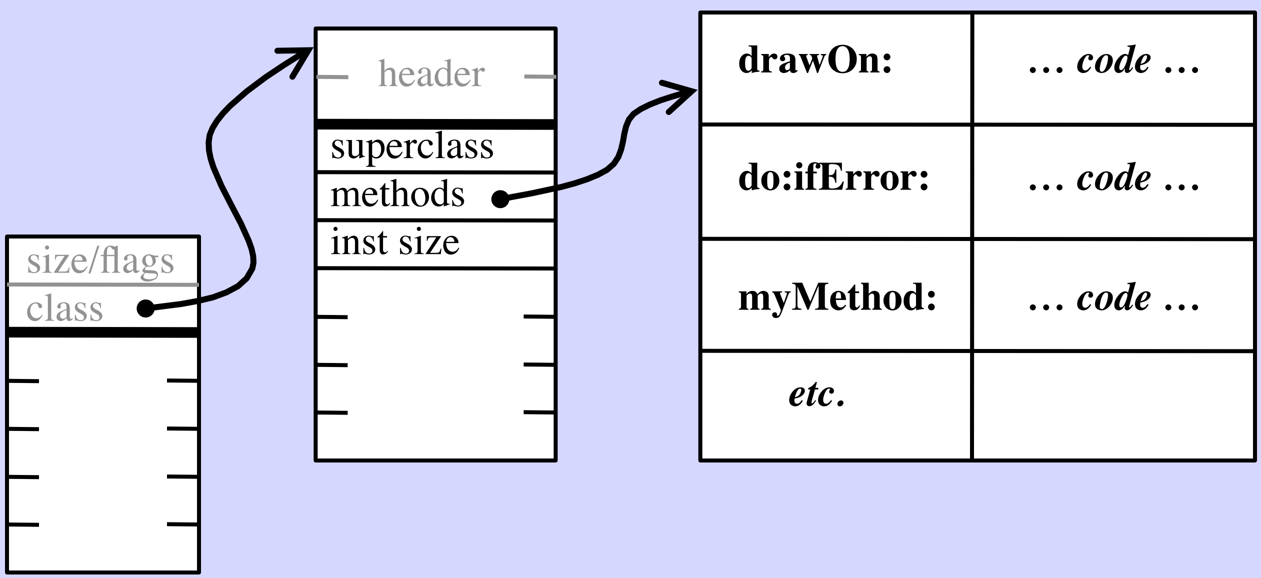

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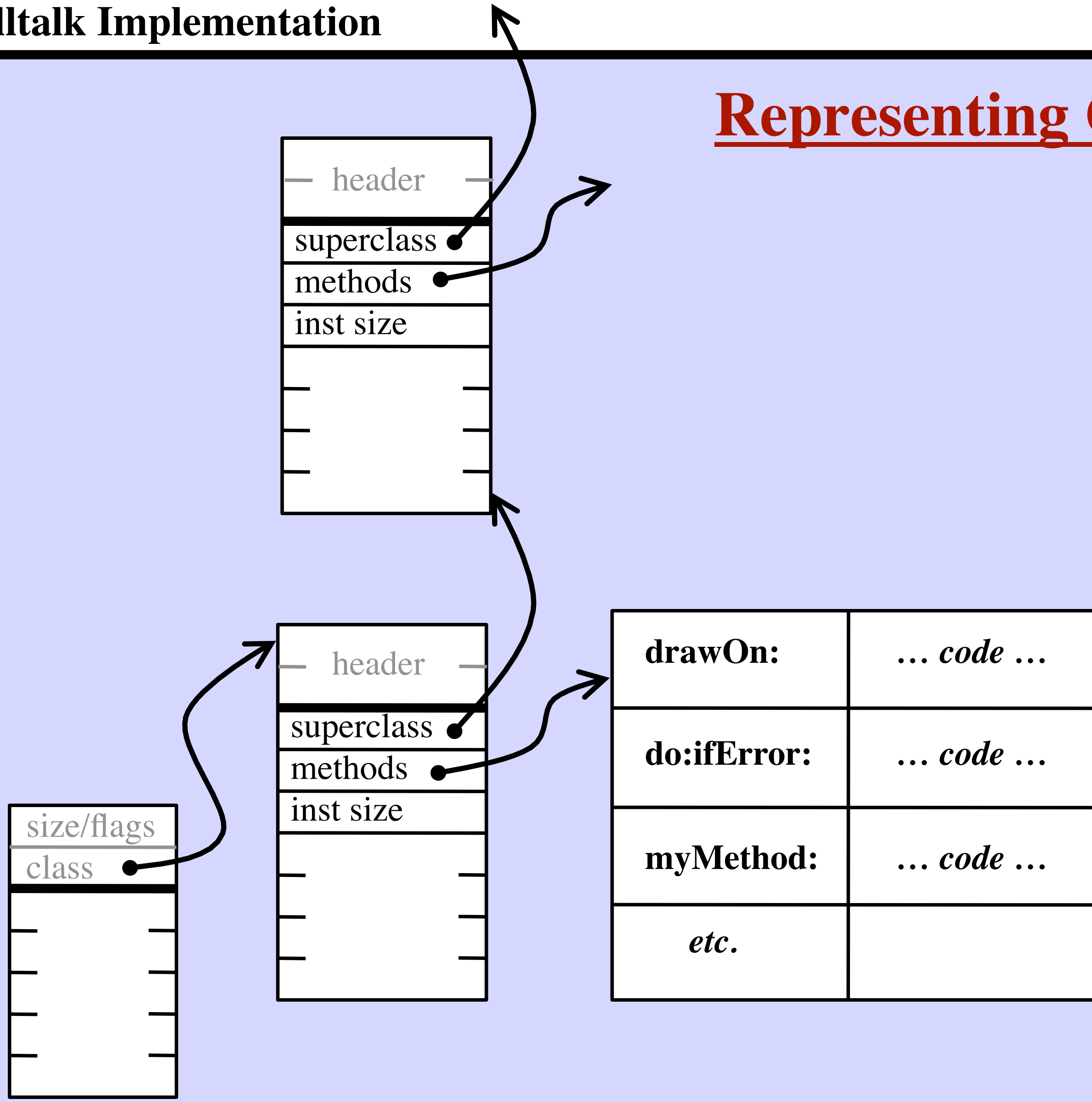

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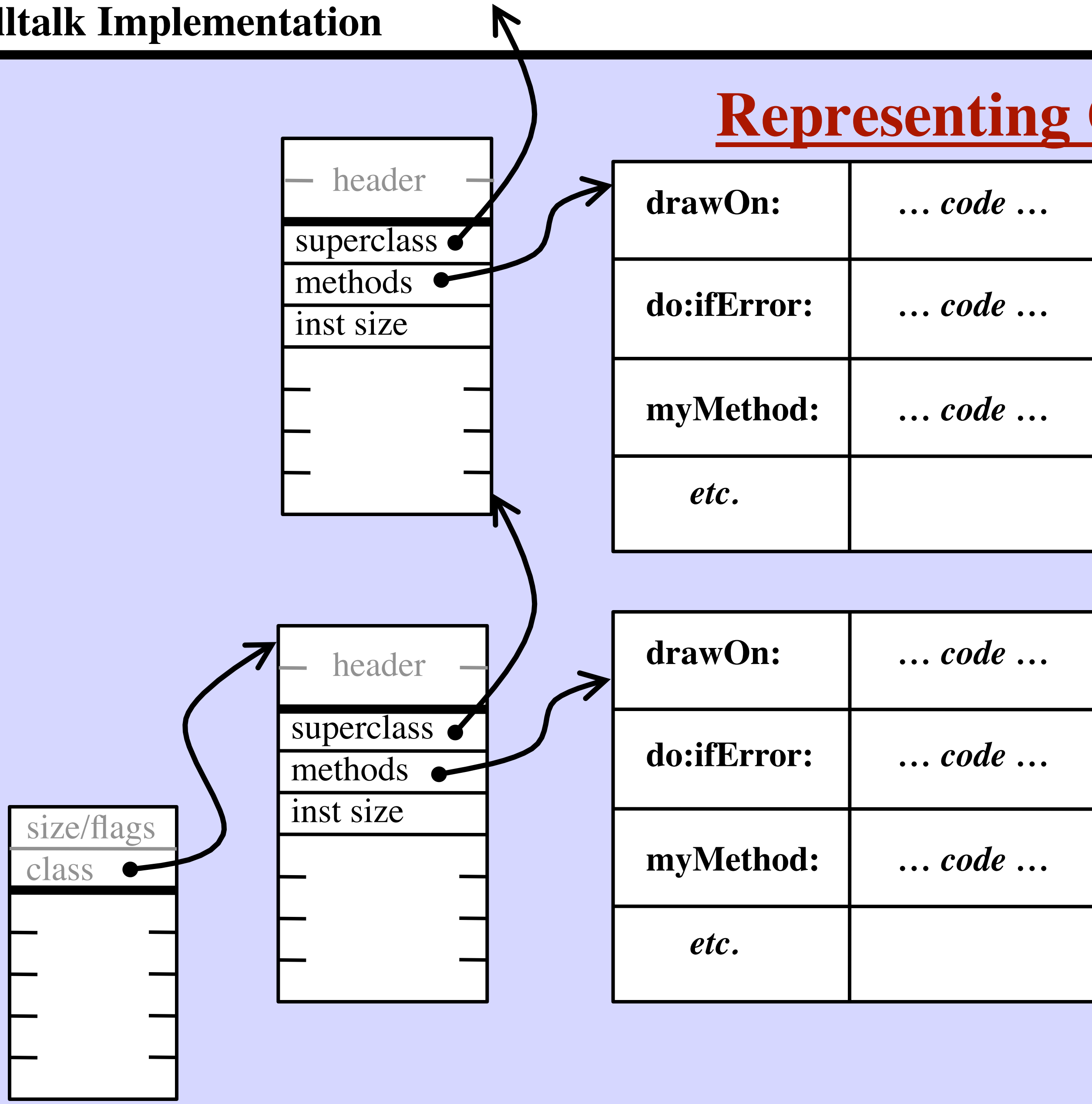

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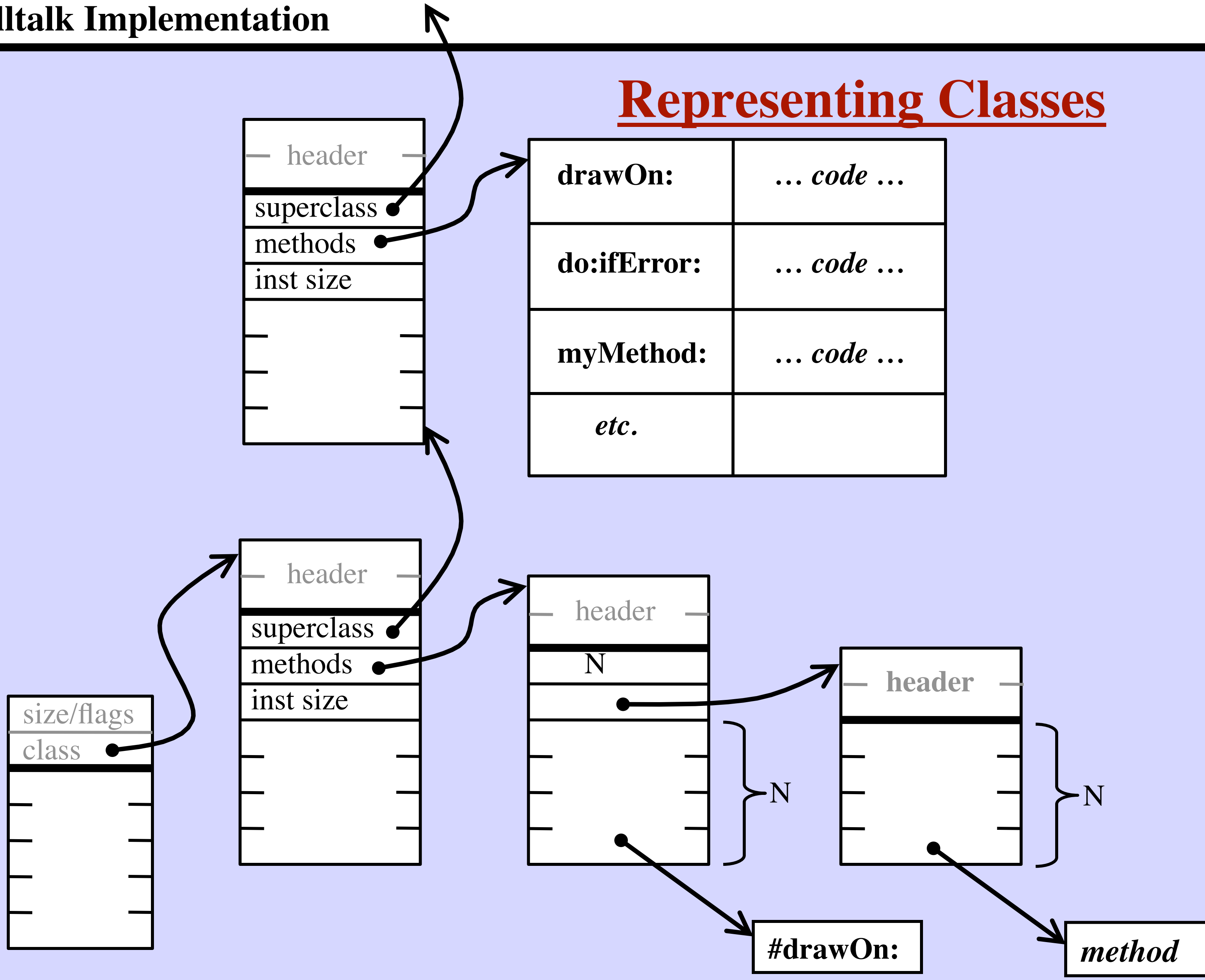
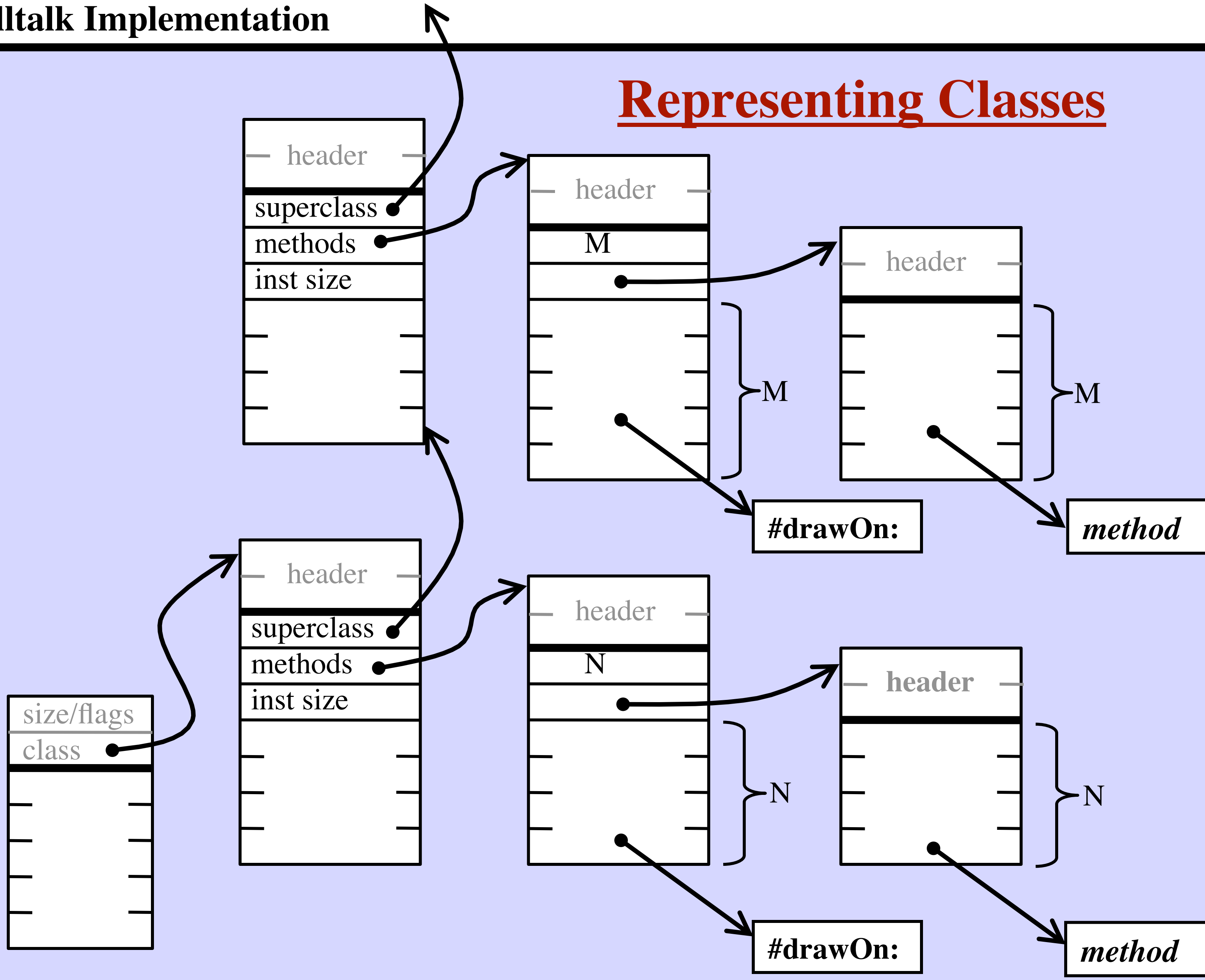


Representing Classes



Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

Compiler produces:

Stack Machine Architectures

Typical instructions:

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pop
add
call
return
jump
```

Example Source:

```
     4 + y
```

Compiler produces:

```
push 4
push y
add
```

Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

```
x := 4 + y;
```

Compiler produces:

```
push 4
push y
add
pop x
```

Stack Machine Architectures

Typical instructions:

```
push
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add
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return
jump
```

Example Source:

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x := 4 + y;
```

Compiler produces:

```
push 4
push y
add
pop x
```

Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

```
x := 4 + y * z;
```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

```
x := 4 + y * z;
```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

Example Source:

```
x := 4 + foo(a,b+c) * z;
```

Compiler produces:

Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

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x := 4 + y * z;
```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

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x := 4 + foo(a,b+c) * z;
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Compiler produces:

```
push 4

push z
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add
pop x
```

Stack Machine Architectures

Typical instructions:

```
push
pop
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return
jump
```

Example Source:

```
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```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

Example Source:

```
x := 4 + foo(a,b+c) * z;
```

Compiler produces:

```
push 4
push b
push c
add
push z
mult
add
pop x
```

Stack Machine Architectures

Typical instructions:

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push
pop
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Example Source:

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add
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Stack Machine Architectures

Typical instructions:

```
push
pop
add
call
return
jump
```

Example Source:

```
x := 4 + y * z;
```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

Example Source:

```
x := 4 + (a do: b+c) * z;
```

Compiler produces:

```
push 4
push a
push b
push c
add
call foo
push z
mult
add
pop x
```

Stack Machine Architectures

Typical instructions:

```
push
pop
add
~~call~~  send
return
jump
```

Example Source:

```
x := 4 + y * z;
```

Compiler produces:

```
push 4
push y
push z
mult
add
pop x
```

Example Source:

```
x := 4 + (a do: b+c) * z;
```

Compiler produces:

```
push 4
push a
push b
push c
add
~~call foo~~  send #do:
push z
mult
add
pop x
```

The Virtual Machine

Typical instructions:

```
push x
pop x
sendMessage #xxx
returnTop
jump x
```
... etc ...

Each is encoded into 8-bit bytecode:

```
00   push receiver's 1st instance variable
01   push receiver's 2nd instance variable
60   pop into 1st instance variable
61   pop into 2nd instance variable
76   push constant 1
C0   send #at:
B1   send #-
7C   return top
```
... etc ...

The Virtual Machine

Typical instructions:

```
push x
pop x
sendMessage #xxx
returnTop
jump x
```
... etc ...

Each is encoded into 8-bit bytecode:

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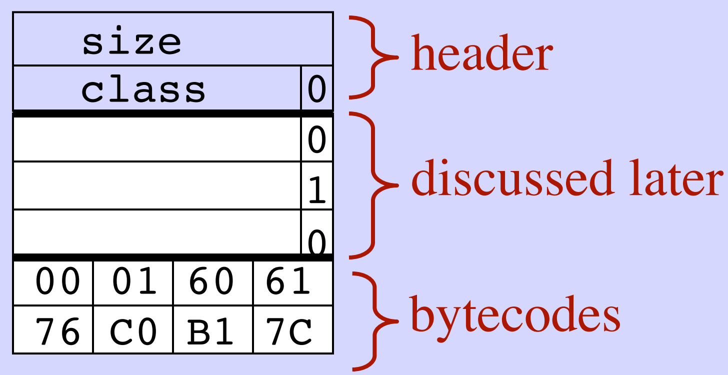
```
... etc ...

As Stored in the Object:



An Example Method

Method:

```
popLifo
    | myTemp |
    myTemp ← lifoArray at: lifoTop.
    lifoTop ← lifoTop - 1.
    ^ myTemp
```

Class:
Lifo

Instance Variables:
lifoArray (1st inst var)
lifoTop (2nd inst var)

Compiled Bytecodes:

An Example Method

Method:

```
popLifo
    | myTemp |
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```

Class:

Lifo

Instance Variables:

lifoArray (1st inst var)

lifoTop (2nd inst var)

Compiled Bytecodes:

```
00    Push receiver’s 1st instance variable (lifoArray)
01    Push receiver's 2nd instance variable (lifoTop)
C0    Send binary message #at:
68    Pop stack into 1st temp variable (myTemp)
01    Push receiver’s 2nd instance variable (lifoTop)
76    Push constant 1
B1    Send binary message #-
61    Pop stack into receiver’s 2nd instance variable (lifoTop)
10    Push 1st temp variable (myTemp)
7C    Return stack top
```

Bytecodes Can Refer to Operands

Directly:

The **receiver** (self)

The **arguments** to the method

The receiver's **instance variables**

The **temporary variables** (i.e., "local" variables)

Some common **constants**:

```
nil, true, false, -1, 0, 1, 2
```

32 common **message selectors**:

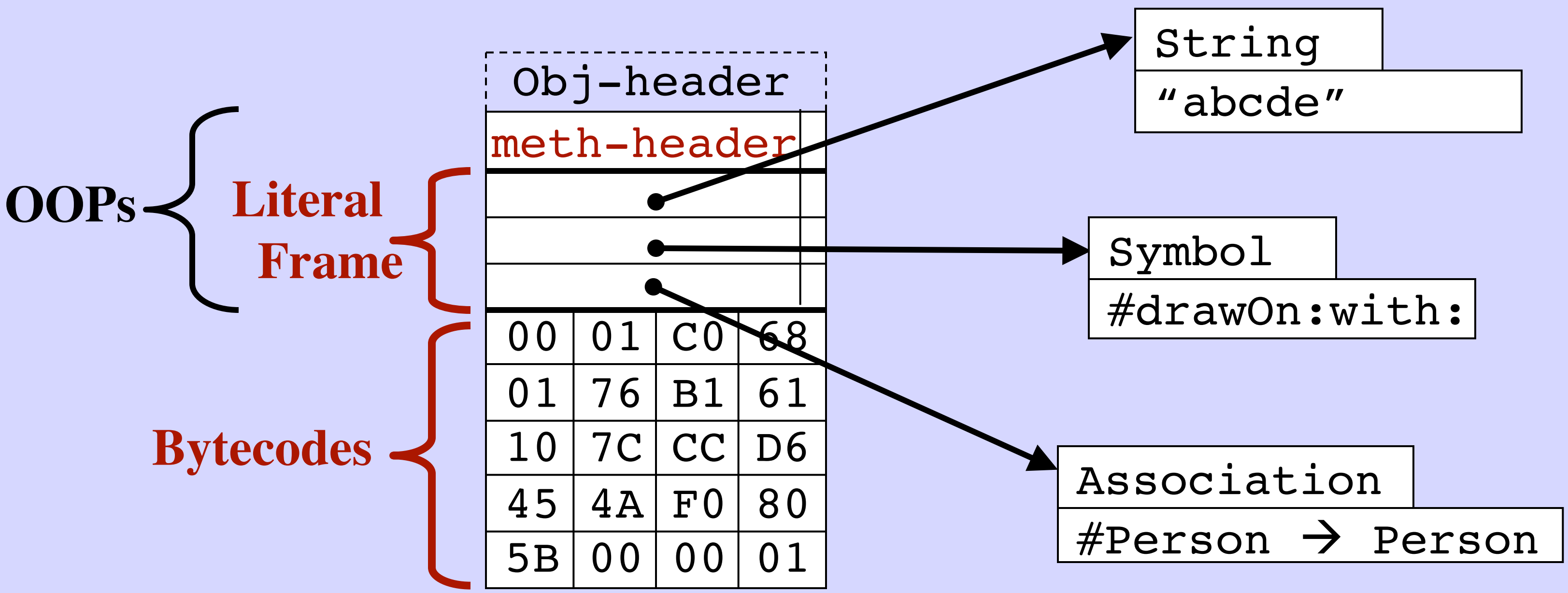
```
+   -   <   =   at:   at:put:   @   x   y …
```

Indirectly:

Thru the "literal frame":

- **Constants** occurring within the method (e.g., 57, $a, 'abc')
- All other **message selectors**
- **Global variables** (e.g., class names)

The Format of *CompiledMethod* Objects



The *CompiledMethod* Header

- The size of the activation record (i.e., the “stack frame”)
- The number of temporary variables for this method
- Number of literals (i.e., where to find 1st bytecode)
- Additional flags:
    - Just return self
    - Just return instance variable k (where k = 0 .. 31)
    - Is this a “normal” method?
        - Number of arguments? 0 .. 4
    - An extension header word is used for all other cases
        - Number of arguments? (0 .. 31)
        - Is this a primitive method? (0 .. 255)

Message Selectors

From the bytecode, the interpreter can get

the message selector

the number of arguments

32 commonly used selectors are handled specially

```
+   -   <   =   @   do:   at:   at:put:   class ...
```

Two versions of the "send-message" bytecode

- Optimized encoding for the 32 common selectors

```
1 0 1 - - - - -
```

- The more general version

  Longer than 1 byte

The number of arguments

32 common selectors → Implicit

"general" send-message bytecode → Encoded into the instruction

All Other Selectors

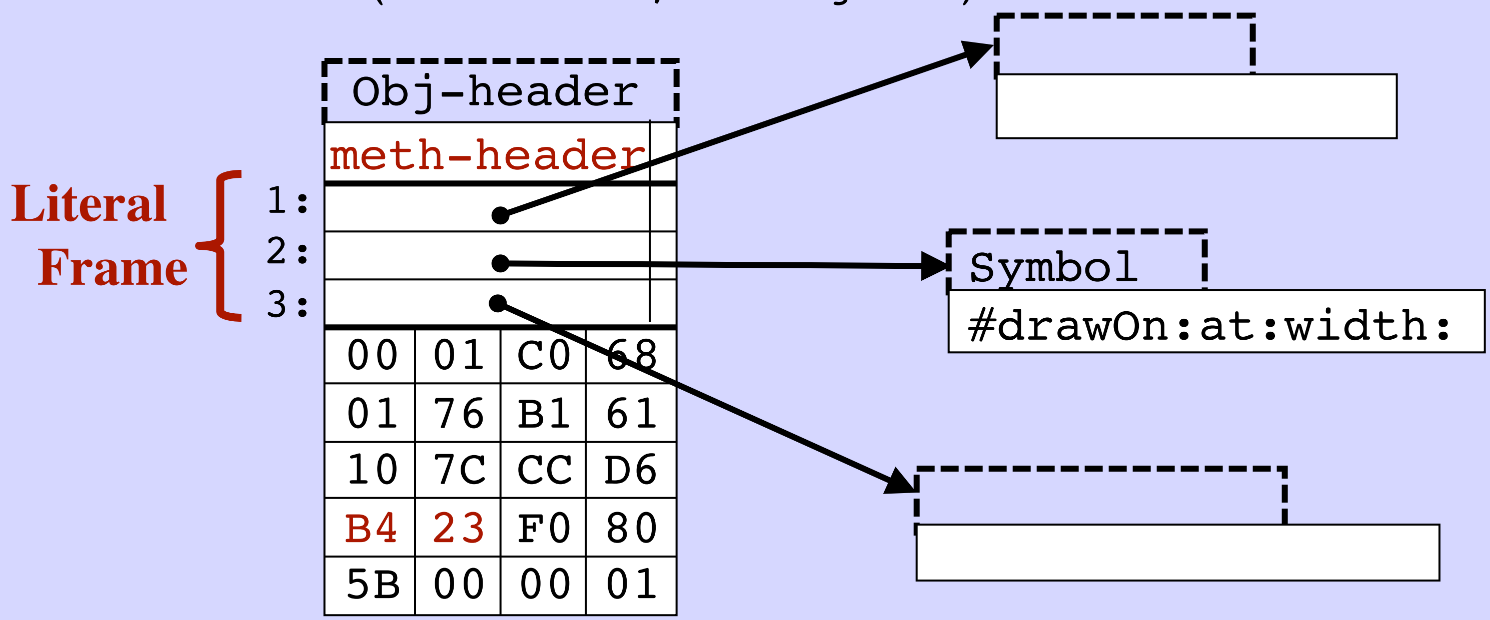
The remaining selectors are stored in the literal area

The bytecode for a "general" send includes:

- Which literal field points to the selector
- Number of arguments

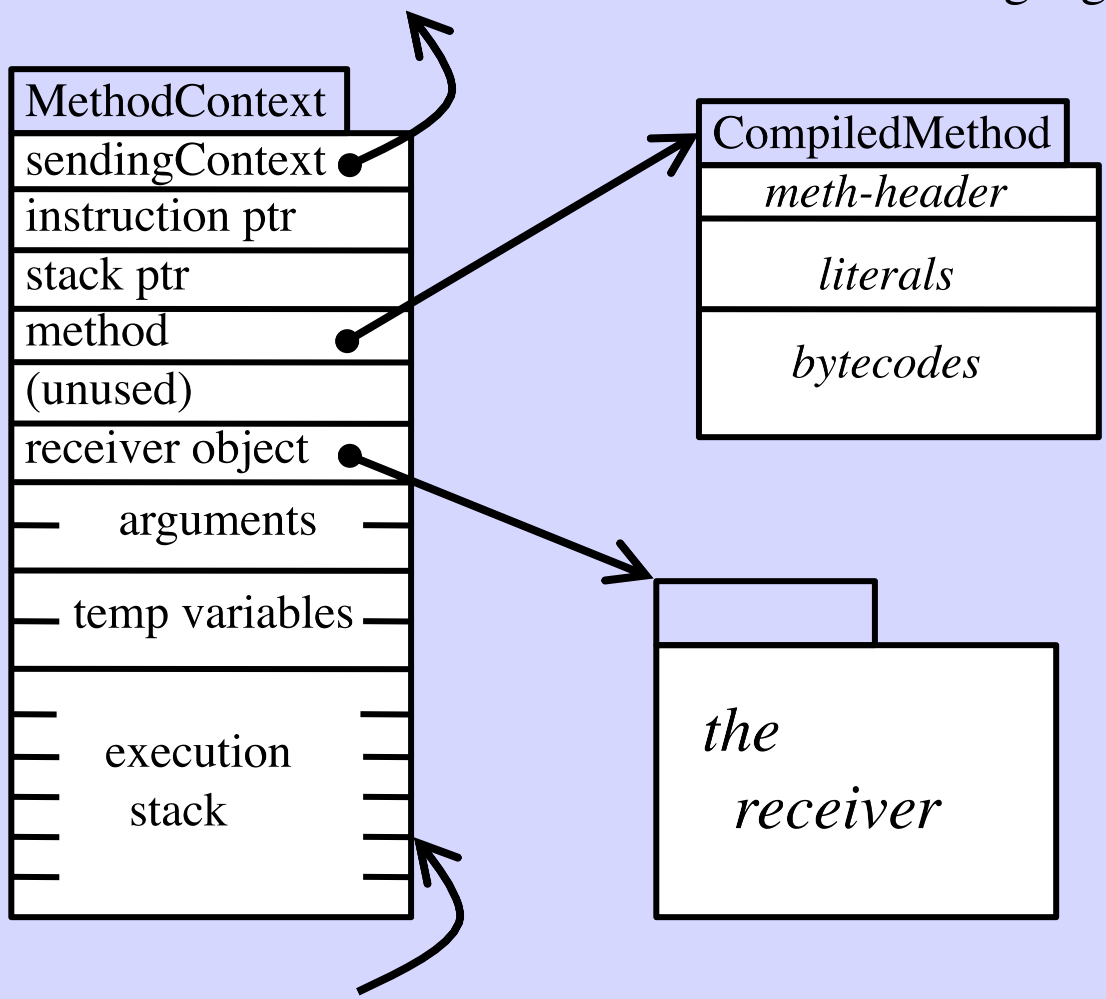
Bytecode:

```
B4 23  Send (literal: 2; numArgs: 3)
```



Activation Records

- When a method is called, a *MethodContext* is created.
- Like an "Activation Record" or "Frame" in traditional language



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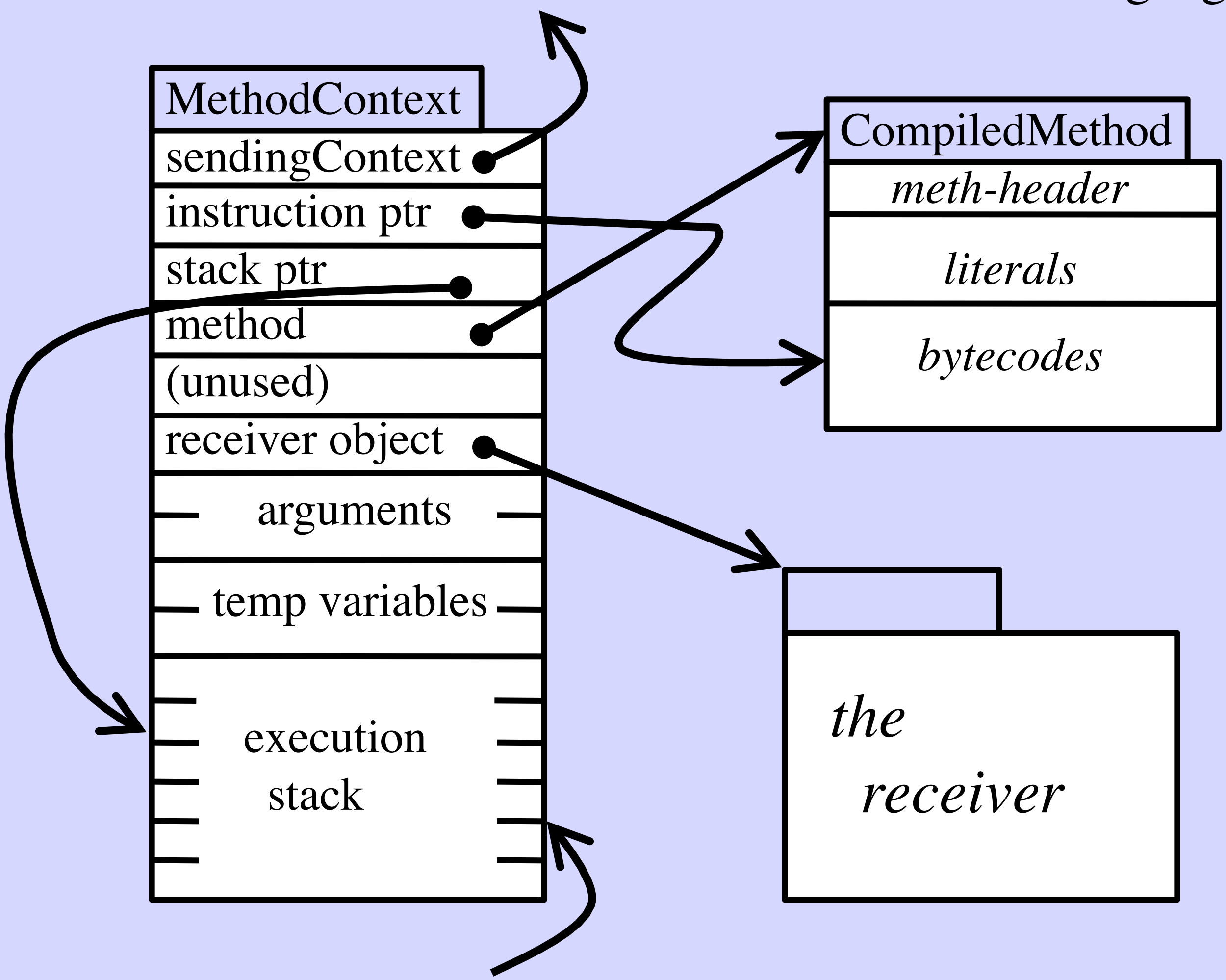

What Happens When a Message is Sent?

x at: y put: z

```
    00    push x onto the stack
    00    push y onto the stack
    00    push z onto the stack
    00    send #at:put: message (numArgs: 2)
```

(Pops recvr and args. Leave result on top of sender's stack.)

- Find the receiver buried underneath the args
- Do method lookup to obtain the *CompiledMethod* object
- Allocate a new *MethodContext*
  (The *CompiledMethod* tells how big the *MethodContext* should be)
- Initialize the *MethodContext*
  - Pointer to receiver
  - Instruction pointer
  - Pointer to the *CompiledMethod* object
  - Pointer to the top of the stack
  - Pointer to the sending context
- Pop the message arguments and store into the new *MethodContext*
- Begin executing bytecodes in the new method, using the new *MethodContext*

MethodContexts are Objects!

Advantages

- *MethodContexts* live in the object heap

  Running code can be saved in the "image" file
- ***Debugger can access them easily***

  Debugging tools can be written in Smalltalk
- Blocks are represented as objects, too!

  A *BlockContext* object can be passed around, stored, etc.

  You can send messages to blocks (e.g., `#value`)

Disadvantages

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Disadvantages

- Creation overhead!
- Very short lifetimes!
  → Big strain on the garbage collector

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- Very short lifetimes!
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***Conclusion*:**
A worthwhile abstraction
… but special optimizations are mandatory!
(A stack is really used)

PrimitiveMethods

- Some methods are implemented directly in the VM.
  SmallInteger arithmetic, I/O, performance critical code, etc.
- The VM executes a native “C” function.
  Normal bytecode execution does not happen.
- Primitive operations may “fail”.
  e.g., the “C” code cannot handle some special cases.

The native code terminates
The method is executed, as normal.

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  The native code terminates

  The method is executed, as normal.

Example from SmallInteger:

```
/ aNumber
  <primitive: 10>
  aNumber isZero
      ifTrue: [^(ZeroDivide dividend: self) signal].
  (aNumber isMemberOf: SmallInteger)
      ifTrue: [^(Fraction numerator: self
                          denominator: aNumber) reduced]
      ifFalse: [^super / aNumber]
```

The “backup” method

PrimitiveMethods – Implementation

A flag in the header of the *CompiledMethod*
- Does this method have a “primitive” implementation?
- Header includes the primitive number (0 .. 255)

The *MethodContext* is not created

Instead, a native routine in the VM is called.

The native routine manipulates values on the sender’s stack
- Pop arguments off the stack
- Leave the result on the stack

Problems while executing a primitive?

Primitives execution “fails”

Undo any partial execution

Execute the backup method

Create a *MethodContext*

Execute the *CompiledMethod*’s bytecodes

Blocks

Every block is an object

```
...
b4 := [ :x :y | stmt. stmt. stmt. x+y ].
...
```

```
...
z := b4 value: a value: b.
...
```

Blocks

Every block is an object

```
...
b4 := [ :x :y | stmt. stmt. stmt. x+y ].
...
```

```
...
z := b4 value: a value: b.
...
```

BlockContext

When encountered in execution, a ***BlockContext*** is created.
When evaluated, it's like invoking a method.

After execution, the block returns

… to the caller

```
[ :x :y | stmt. stmt. stmt. x+y ]
```

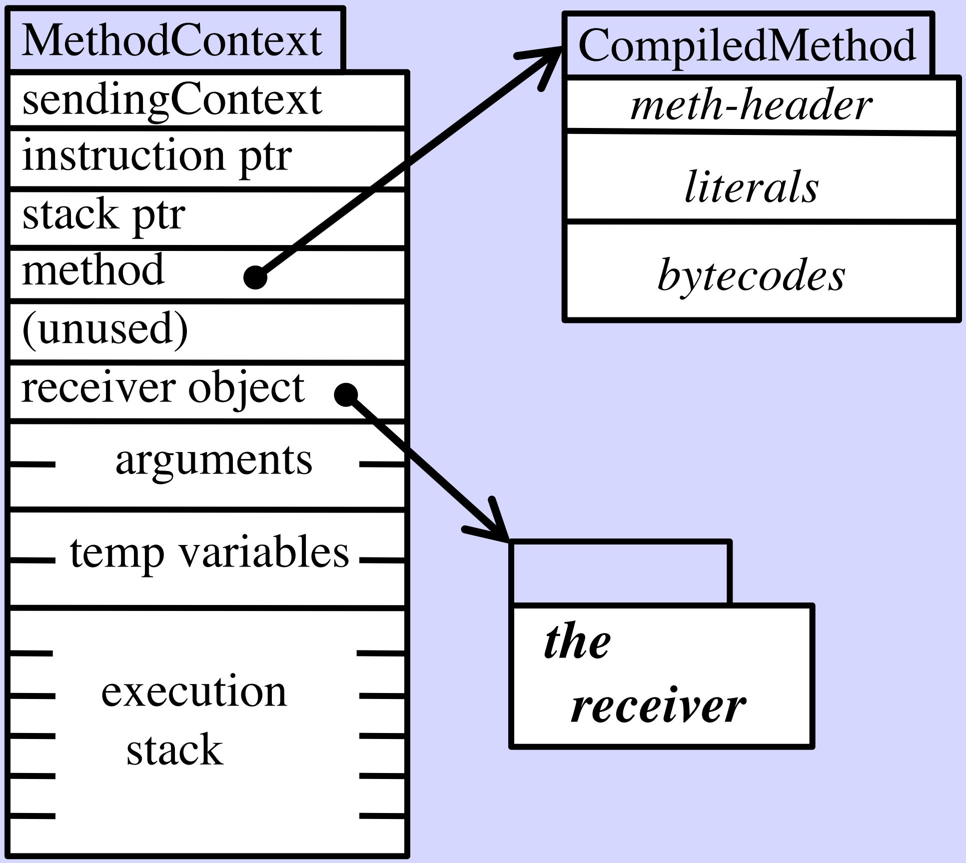
… from the method where it was created

```
[ :x :y | stmt. stmt. stmt. ^x+y ]
```

The *BlockContext* object will be garbage collected

when no longer needed (i.e., not reachable)

How are Blocks Represented?



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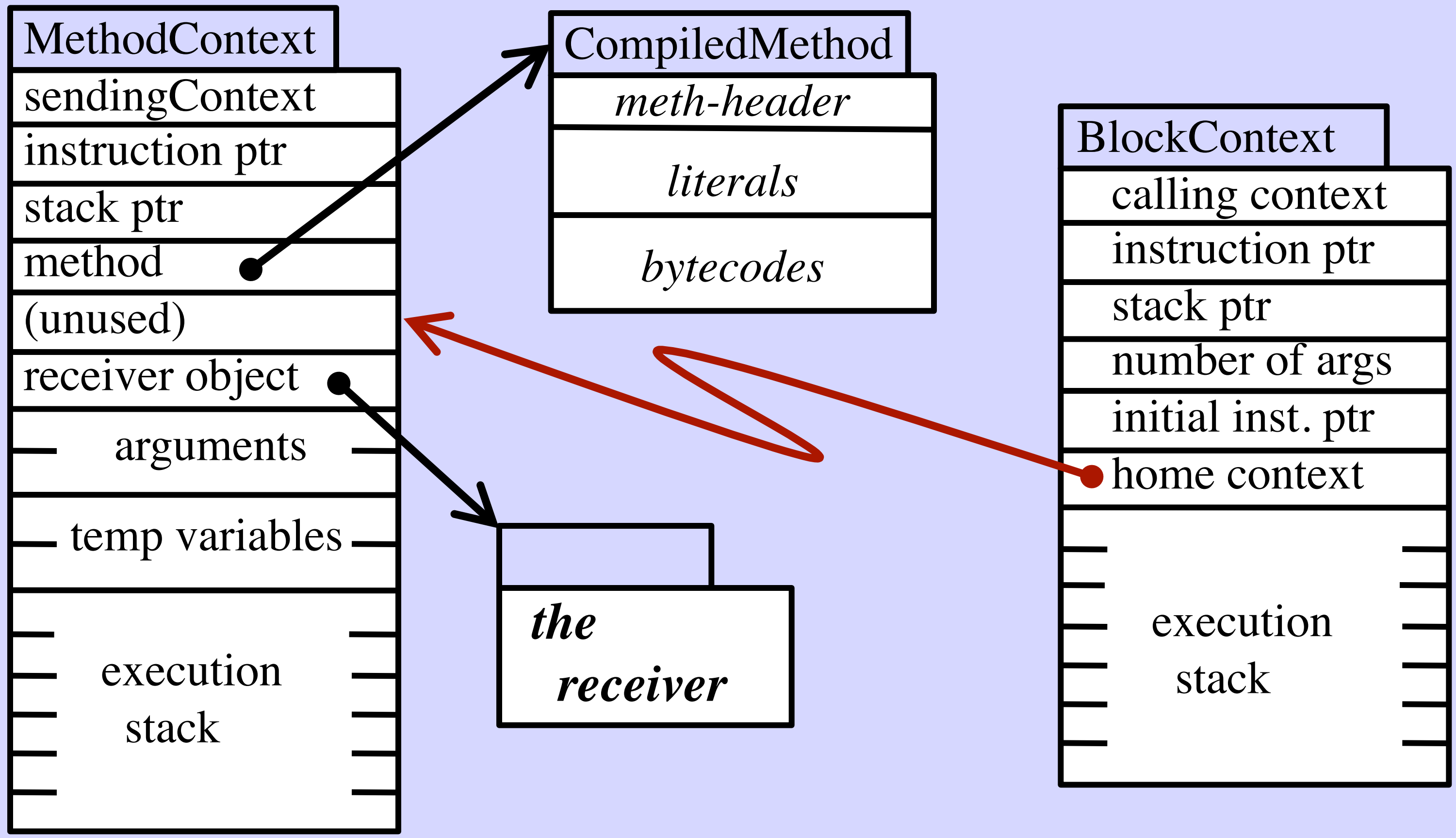

When created, the ***BlockContext*** has a pointer back to its ***"home context"***.

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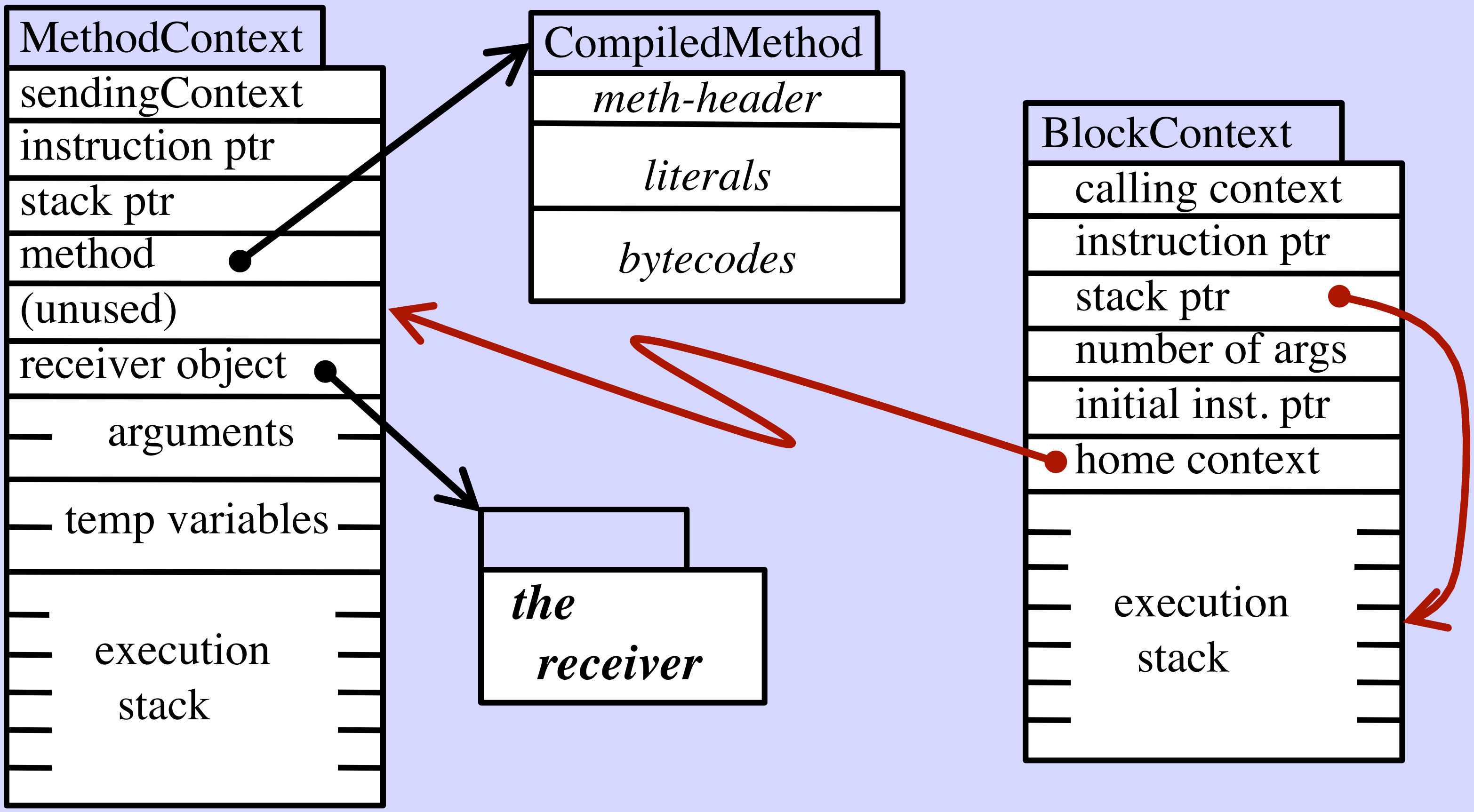

The BlockContext has its own ***execution stack***

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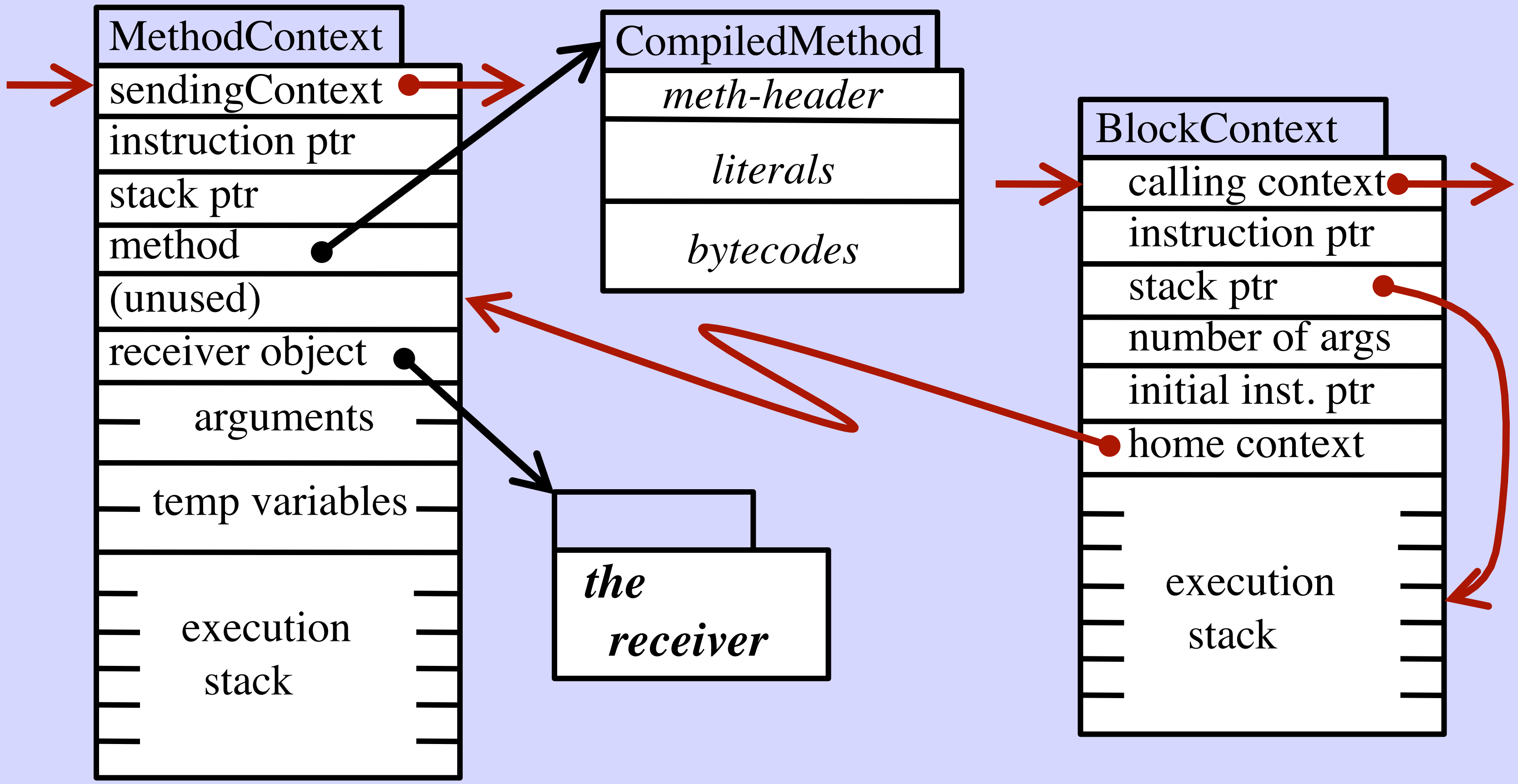
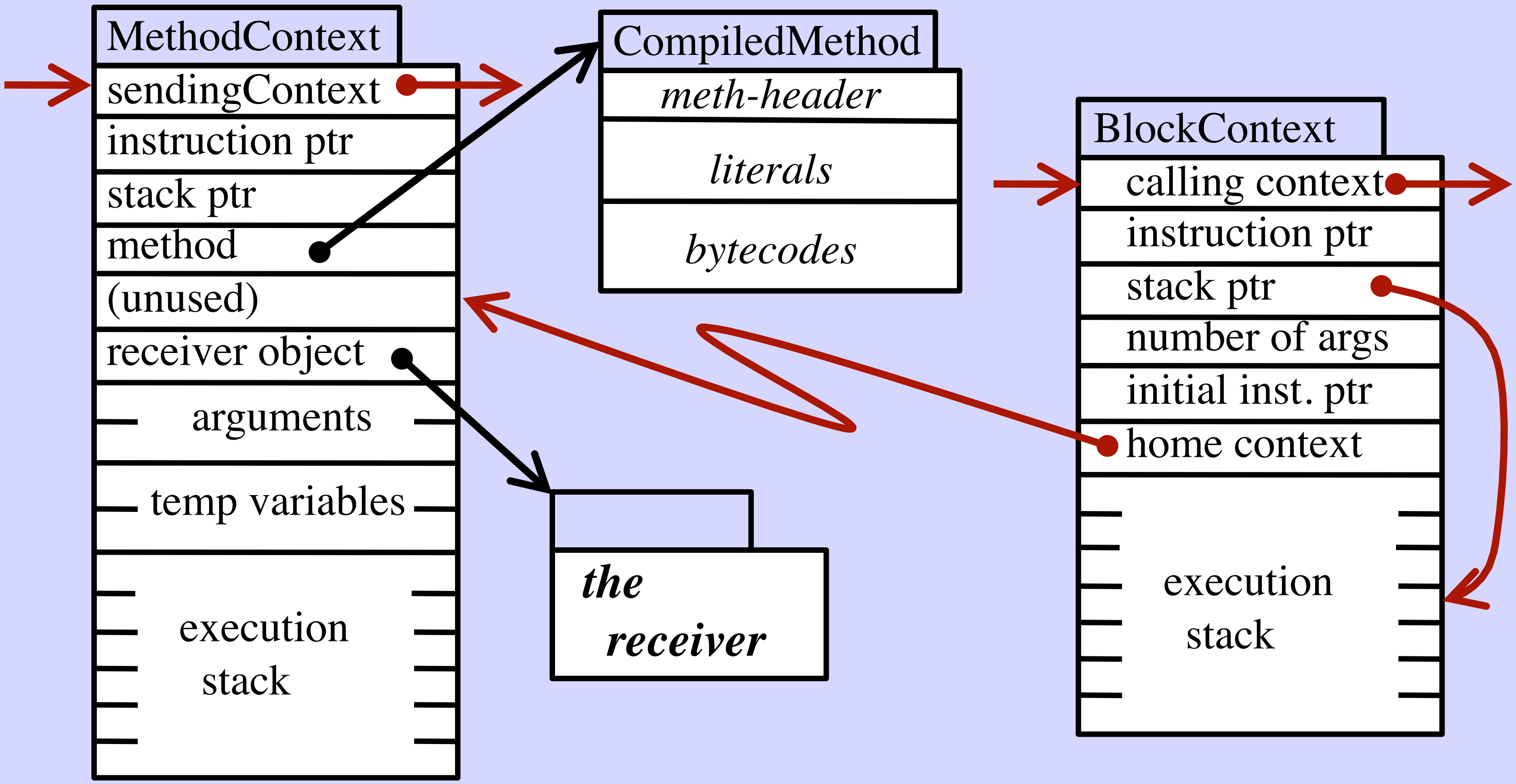


When evaluated (i.e., when invoked / called)…
the ***BlockContext*** is added to the ***"calling stack"*** of frames.

How are Blocks Represented?



NOTE: The block keeps it temps and arguments in the home context.
Only one invocation active at one time; NO RECURSION!

The `blockCopy:` primitive

Will create a block object.
Will push a ptr to it onto stack.

The `blockCopy:` primitive

```
incrAll
    ^ self do: [ :x | x incr ]
```

Will create a block object.
Will push a ptr to it onto stack

CompiledMethod:

Header:

Literals:

Bytecodes:

The `blockCopy:` primitive

```
incrAll
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Will create a block object.
Will push a ptr to it onto stack

CompiledMethod:

Header: *1 temp variable needed (x)*

Literals: `#incr`

Bytecodes:

```
70      Push receiver (self) onto stack
```

[redacted]

```
CB      Send #do:
7C      Return stack top
```

The `blockCopy:` primitive

```
incrAll
    ^ self do: [ :x | x incr ]
```

Will create a block object.
Will push a ptr to it onto stack

CompiledMethod:

Header: *1 temp variable needed (x)*

Literals: `#incr`

Bytecodes:

```
70      Push receiver (self) onto stack
89      Push the active context onto the stack
76      Push 1 onto the stack (num args to block)
C8      Send #blockCopy:
A4 04   Jump around next 4 bytes
68      Pop stack into 1st temp variable (x)
10      Push 1st temp var (x) onto the stack
D0      Send #incr
7D      Block Return (return stack top as block's result)
CB      Send #do:
7C      Return stack top
```

blockCopy:

Skip this slide

- A primitive method
  - Passed the number of arguments
  - Sent to the current context
    - (The "home context")
- Creates a new ***BlockContext*** object
  - Initializes its "HomeContext" field
  - Initializes its "InitialInstructionPointer" field
    - Based on the current instruction pointer + 2
  - Pushes an OOP to the new ***BlockContext*** onto the current stack
- Storage for arguments to the block…
  - The block's arguments must be allocated space somewhere.
  - They are allocated in the home context (as temp variables)
  - A block begins by popping its arguments into the home context
    - What if the method that created the block has already returned?
    - No problem; the space still exists.
      - Why will the home context not get garbage collected?

Blocks have two ways of returning

```
(x < y)
   ifTrue: [ stmt.  stmt.  stmt.  43 ]
   ifFalse: [ stmt.  stmt.  stmt.  ^43 ]
```

Normal Return

Return from enclosing method

How does a block return?

Pop a value off of the current stack.
Push it (the return value) onto the caller's stack.
Resume executing caller's instructions.

Normal return from a block:

Push result onto Calling Context's stack.
Resume execution using Calling Context's instruction pointer.

Return from enclosing method:

Look at the Home Context.
    Look at its Sending Context
Push result onto that context's stack.
Resume execution using that context.

Blocks in Smalltalk are not "Closures"

```
| fact |
fact ← [ :n |
  (n < 1)
    ifTrue: [1]
    ifFalse: [ n * (fact value: (n - 1)) ]
  ].

fact value: 4 → ???
```

The block invokes itself recursively.

This code will not work correctly!

In Smalltalk / Squeak:

Blocks may not be entered recursively.

Only one ***BlockContext*** is created.

Storage for only one copy of "n"

The interpreter will catch this.

"Attempt to evaluate a block that is already being evaluated"

Pharo Implements Blocks Differently

```
incrAll
  ^ self do: [ :x | x incr ]
```

CompiledMethod:

Header: *numArgs=0, numTemps=0, isPrimitive=No,*

Literals: `#incr`

Bytecodes:

```
70   Push receiver (self) onto stack
8F
01   closureNumCopied: 0, numArgs=1, next 3 bytes
00
03
10   pushTemp: 0
D0   send: #incr
7D   Block Return (return stack top as block's result)
CB   Send #do:
7C   Return stack top
```

Message Sending in C++

Skip these slides

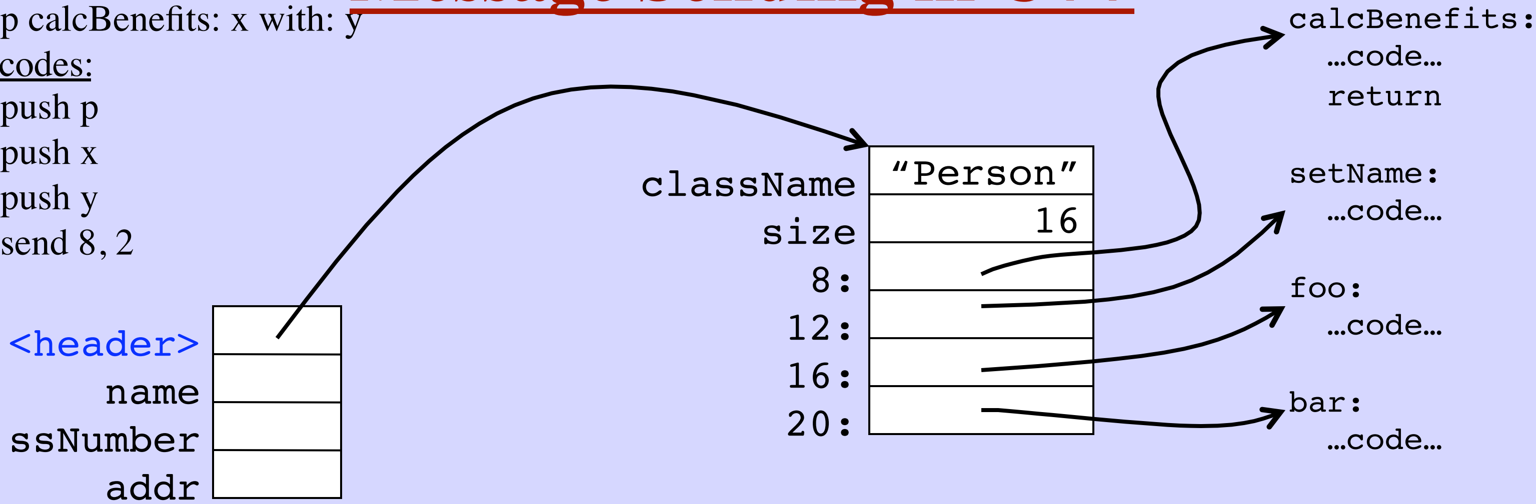
Message Sending in C++

Source:

p calcBenefits: x with: y

Bytecodes:

push p
push x
push y
send 8, 2



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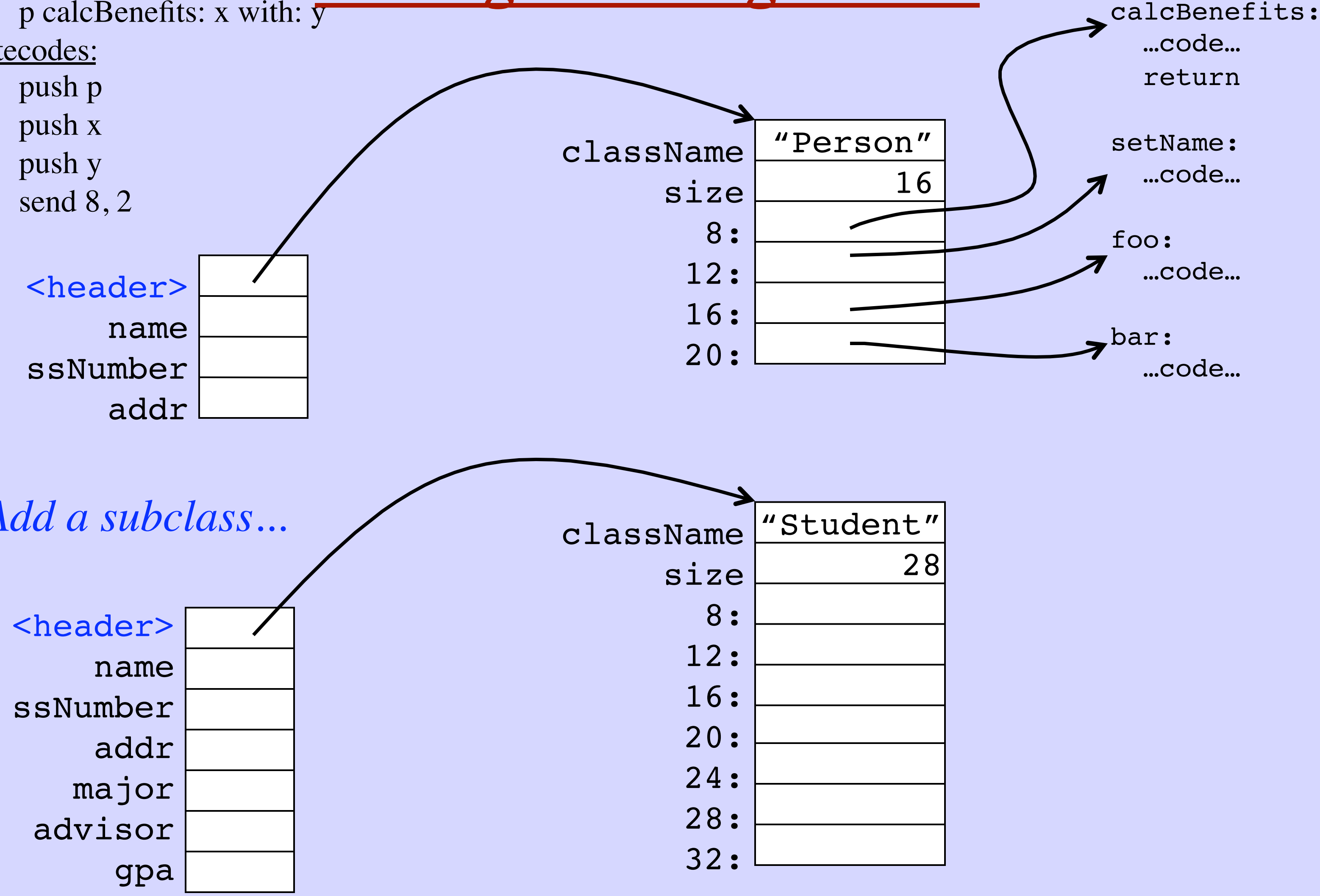

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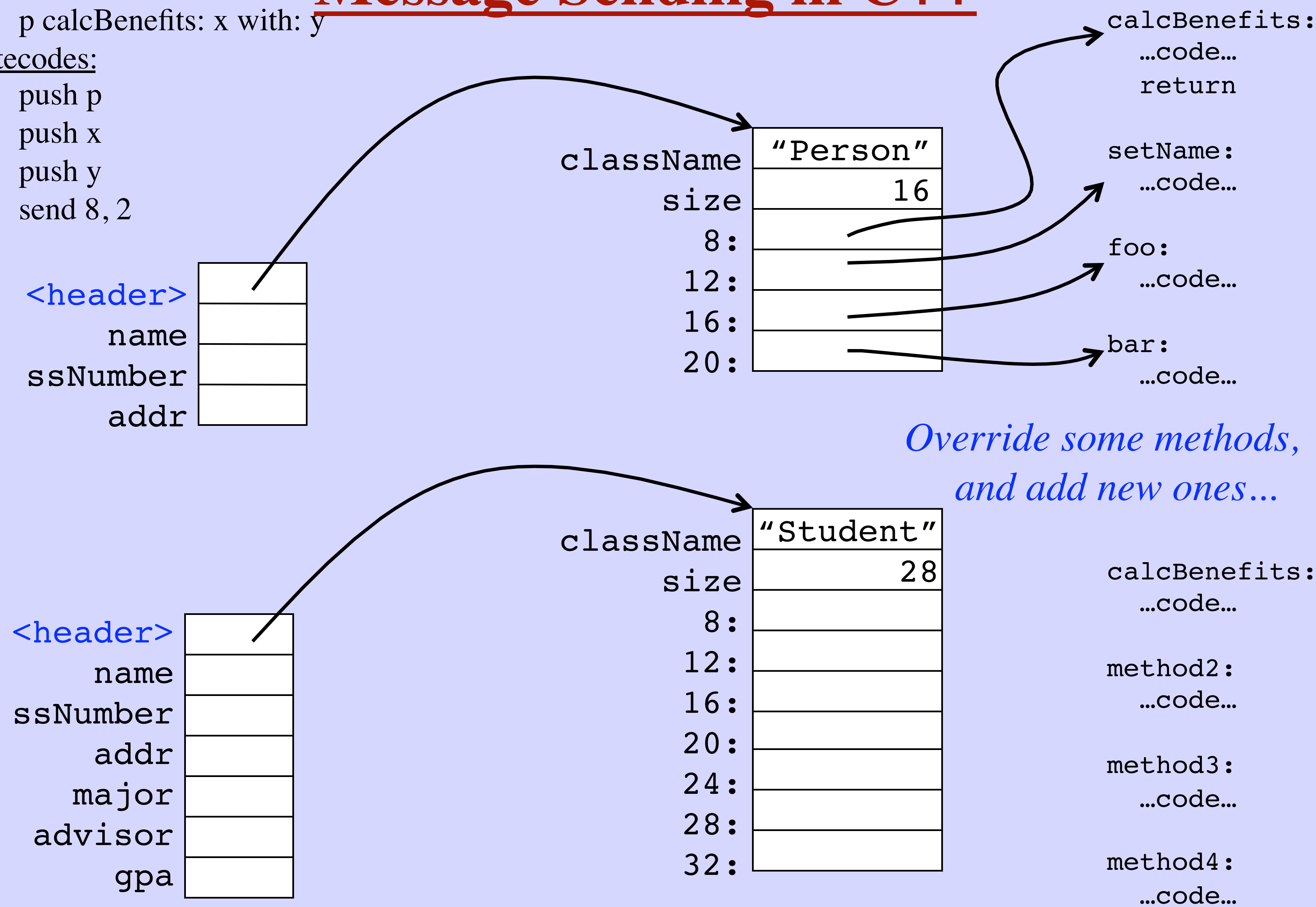

Override some methods, and add new ones…

Message Sending in C++

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Bytecodes:

push p
push x
push y
send 8, 2