# 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.

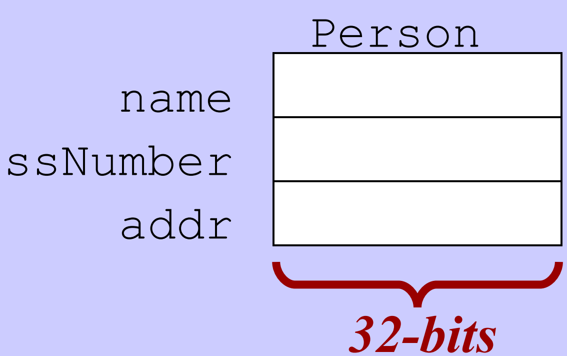
• Architecture of SOAR: Smalltalk on a RISC, by Ungar, Blau, Foley, Samples, Patterson, 11th Annual Symposium on Computer Architecture, Ann Arbor, MI, 1984.

• 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

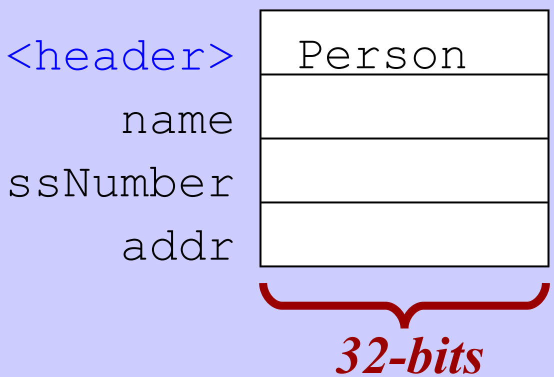
Object = Block of memory (i.e., “struct”, “record”)

Field = Offset into record (“instance variable”)

***Header***

A “hidden” field, included in every object.

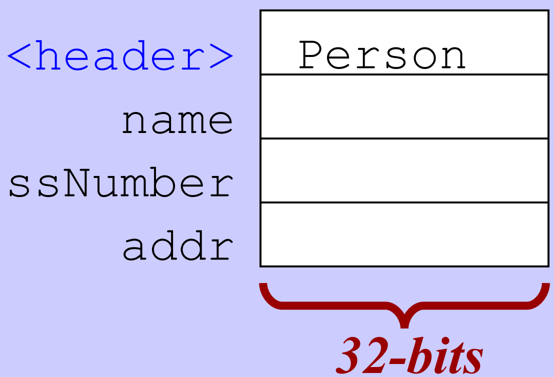
Tells the class of the object (and other stuff).

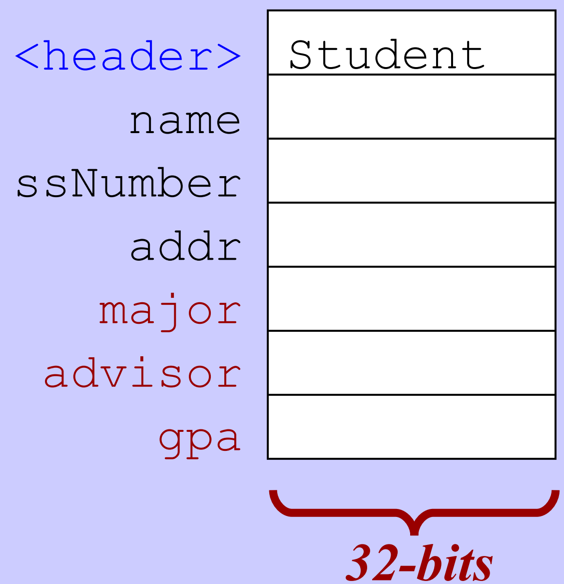


# Representing Objects

Subclassing:
- Existing fields in the same locations
- New fields added to end of record

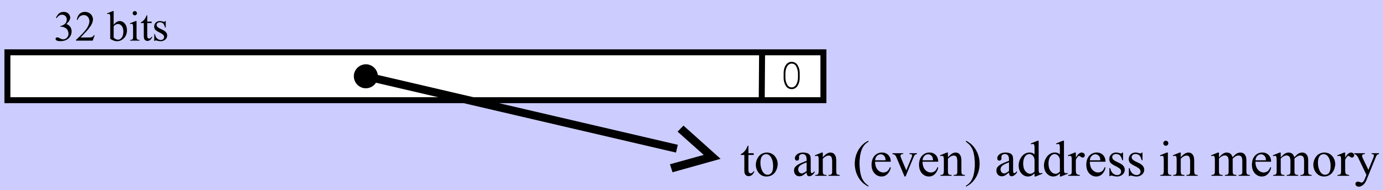
*Example: Student is a subclass of Person*



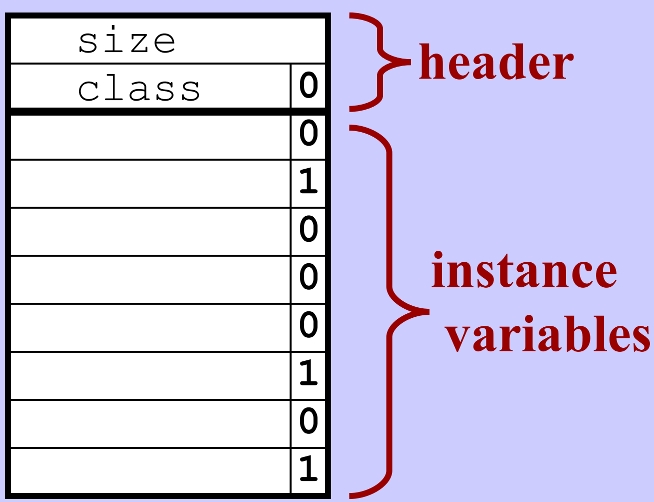
# Tagged Values

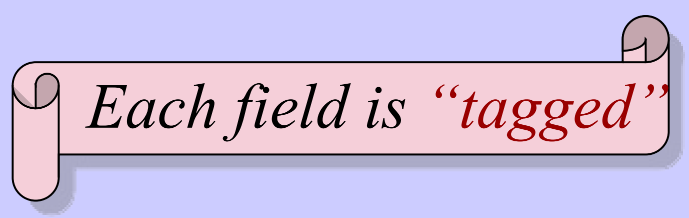
## Object-Oriented Pointers (OOPs)



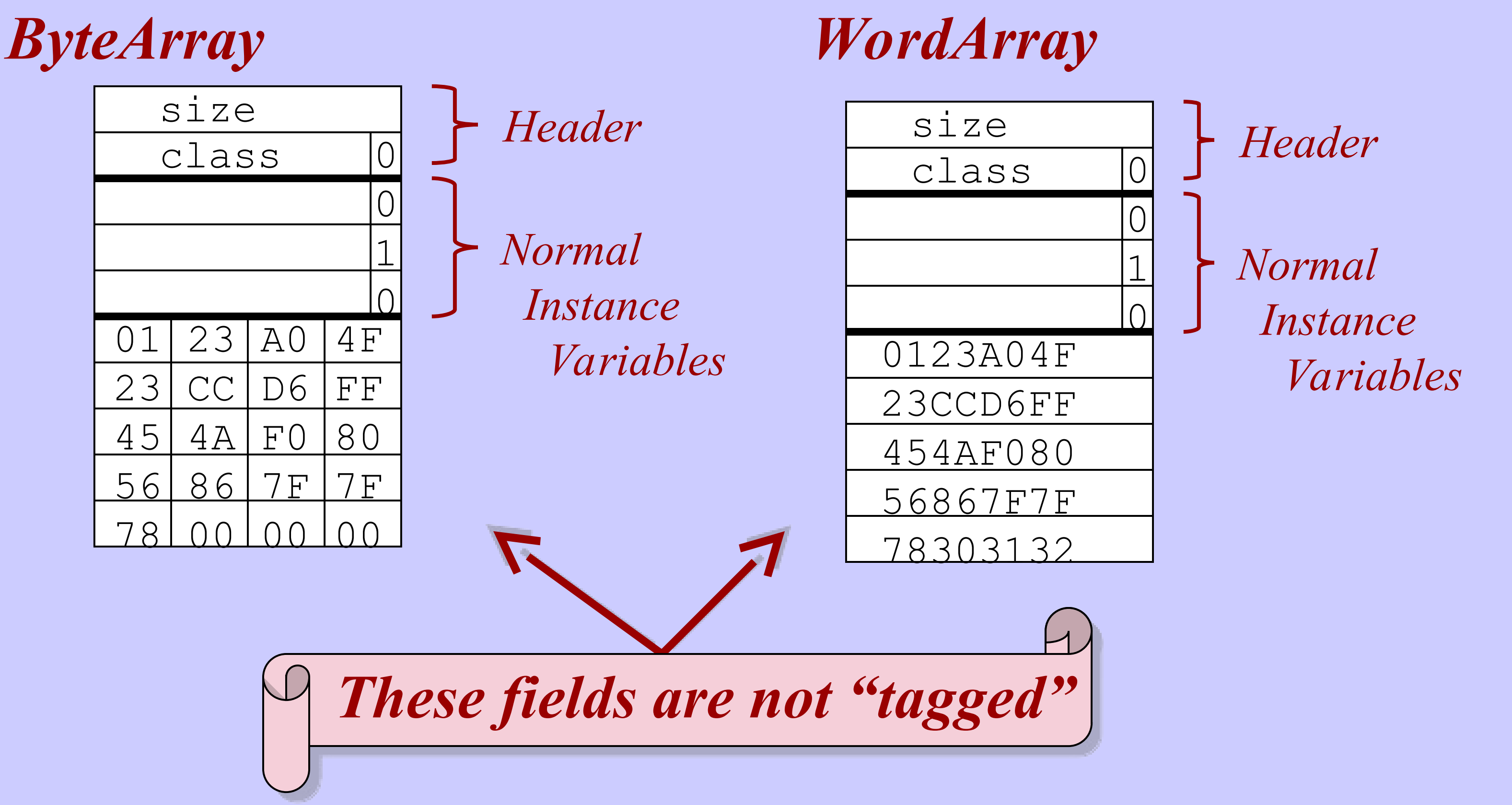

## SmallIntegers (-1,073,741,824 .. 1,073,741,823)


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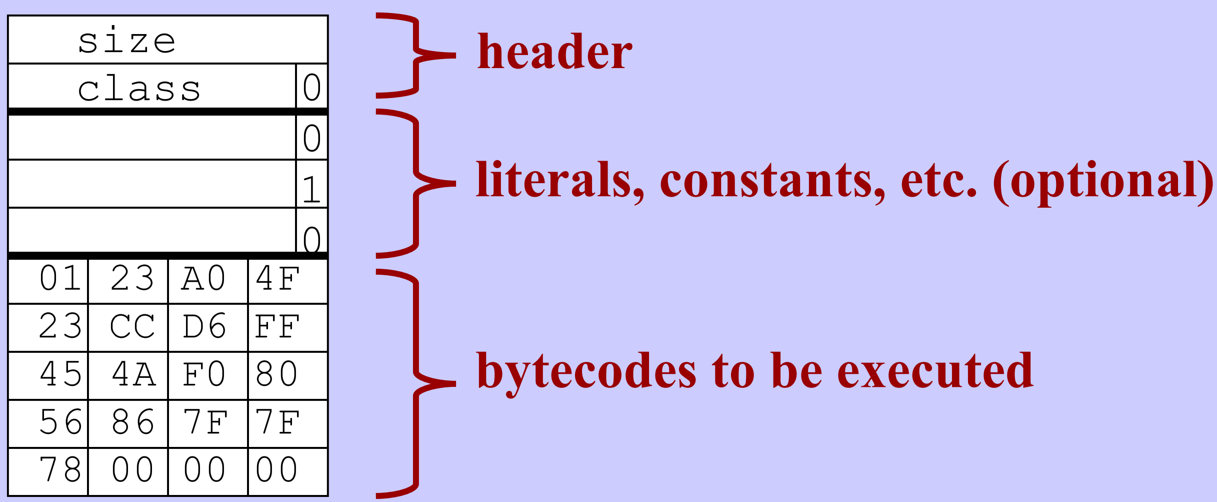
Translates methods (i.e., Strings) into instances of a class called

***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:
```

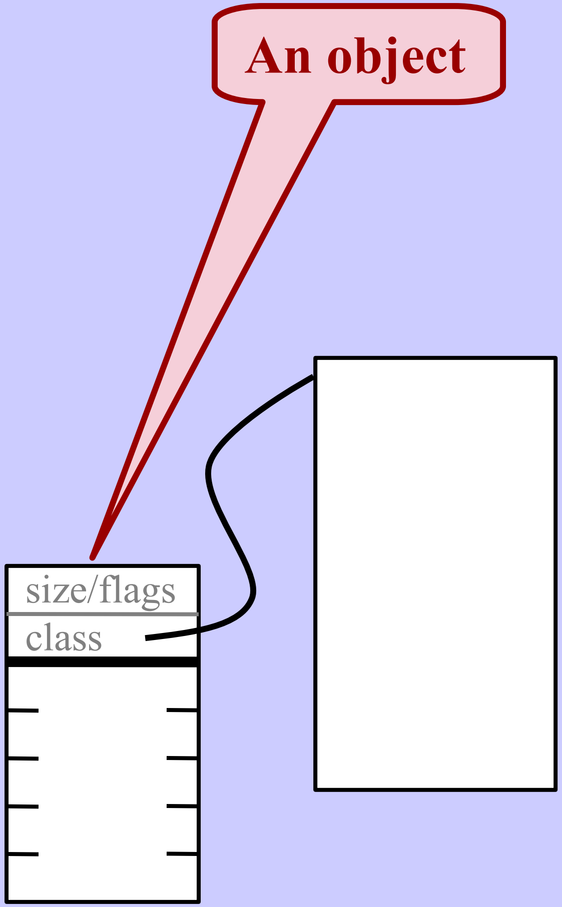
Like the class ***String***.
***Symbol*** is a subclass of ***String***.

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



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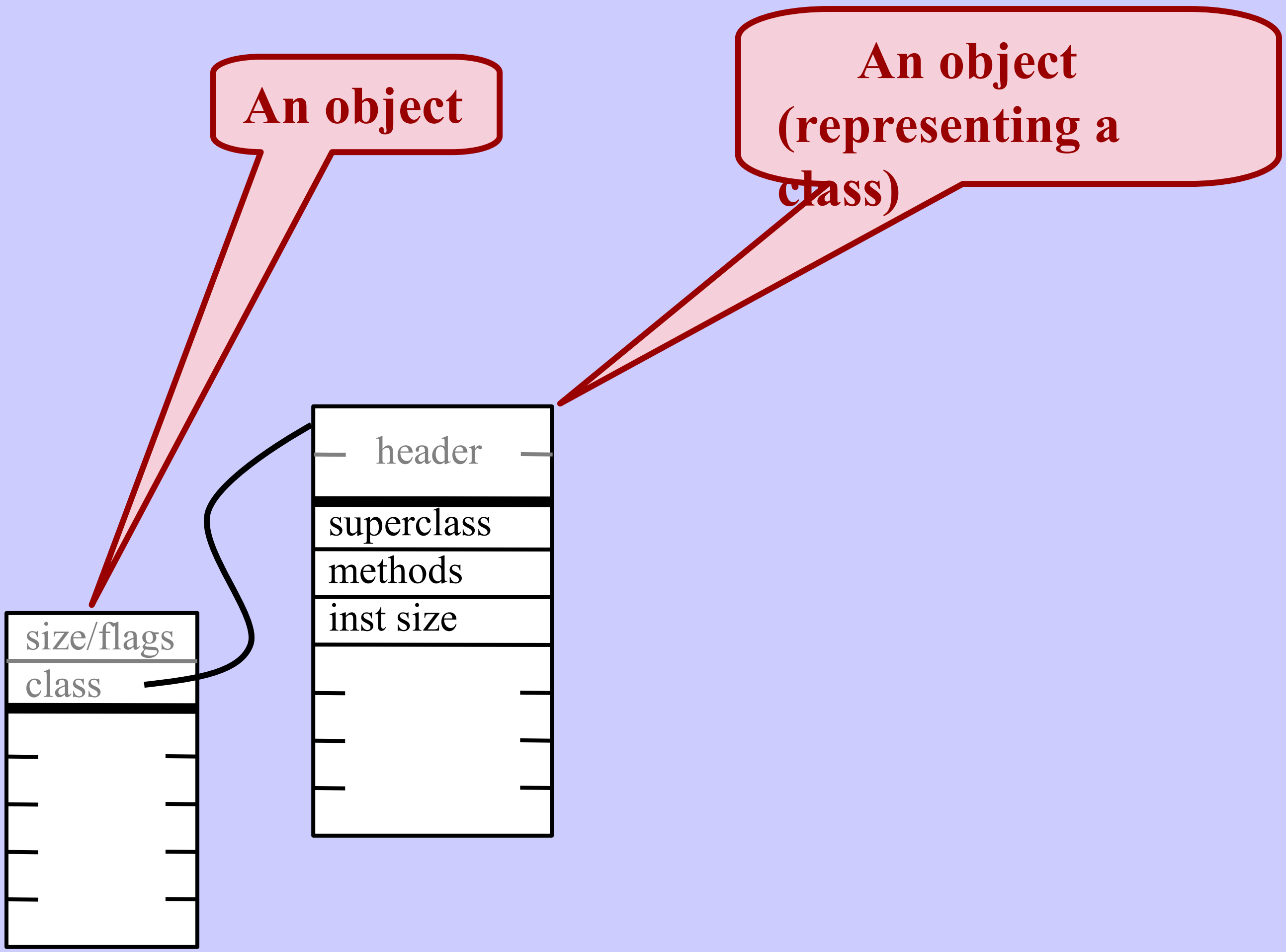

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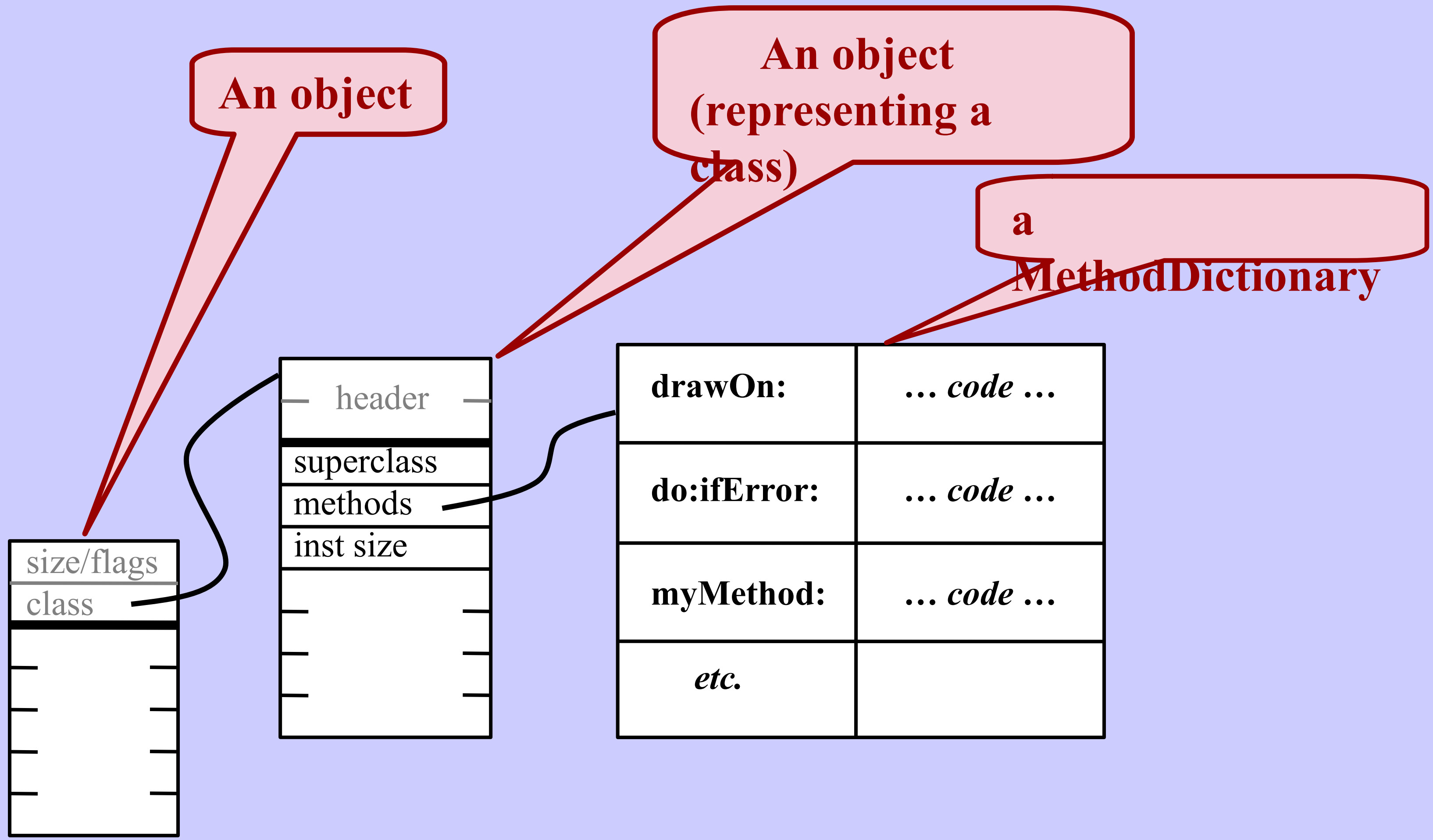

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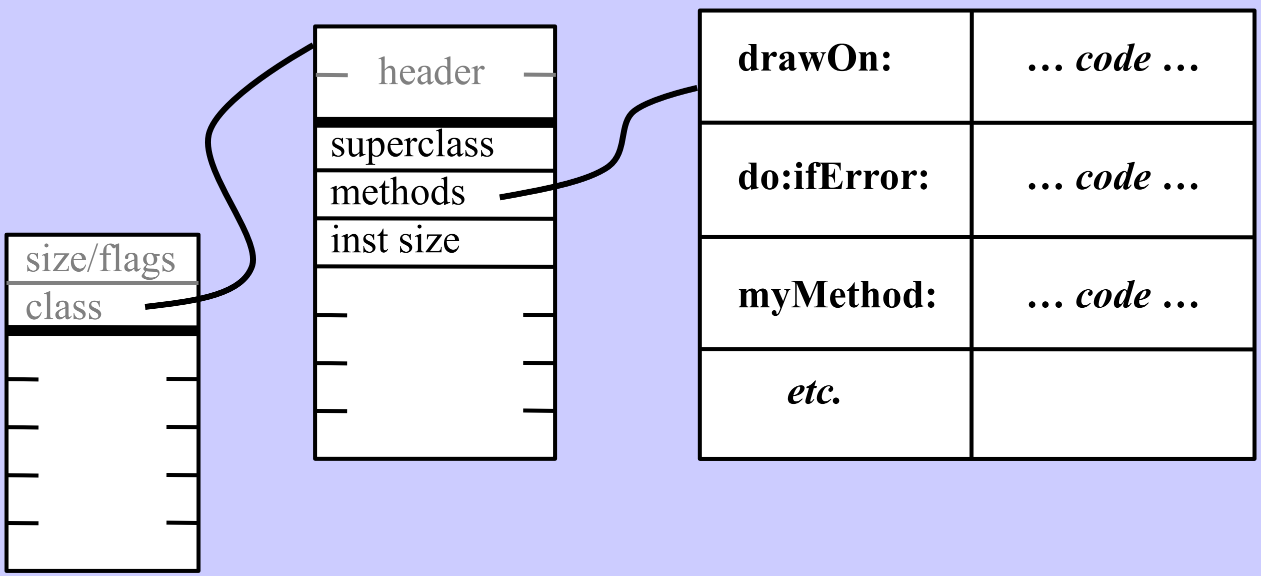

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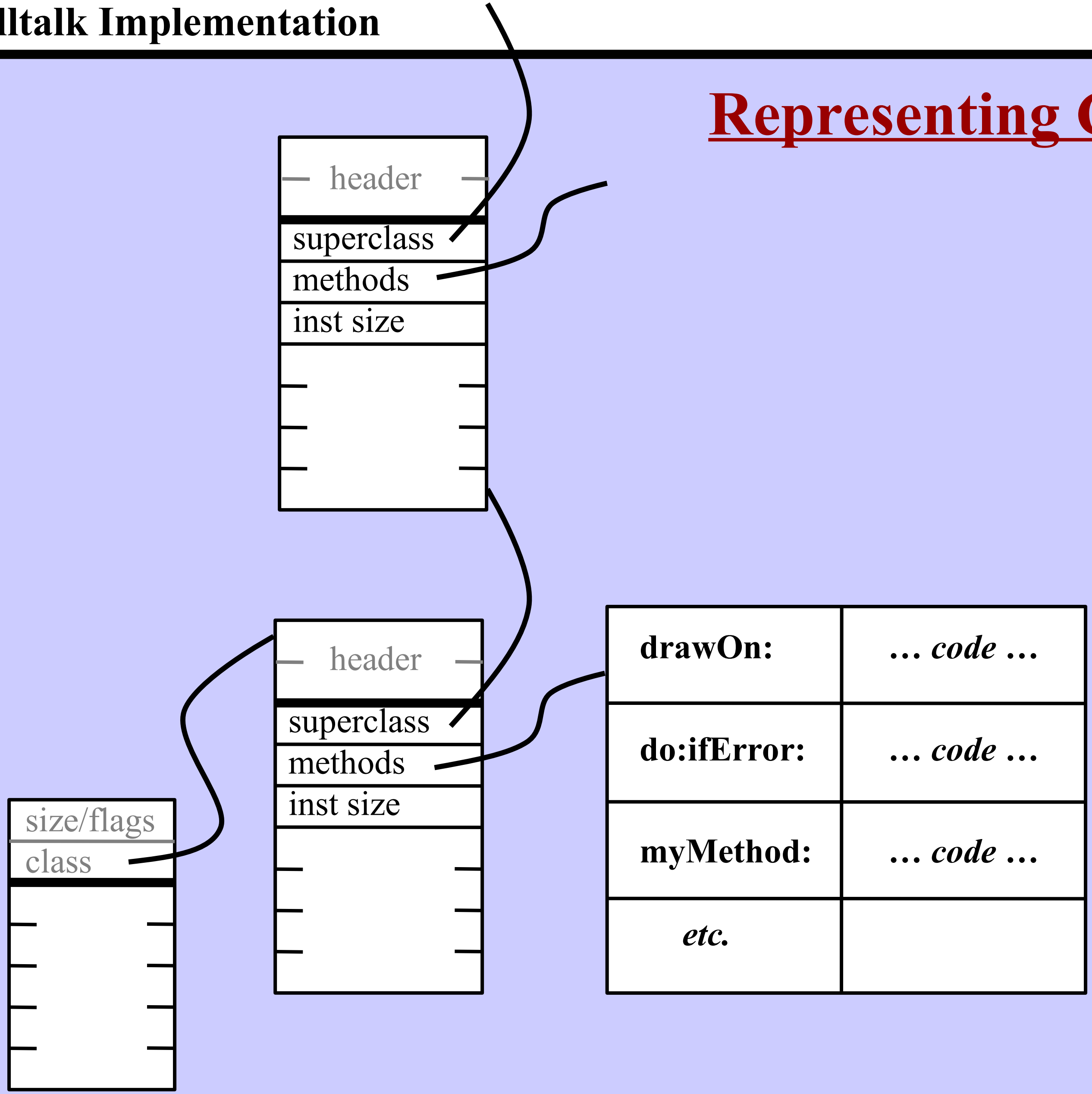

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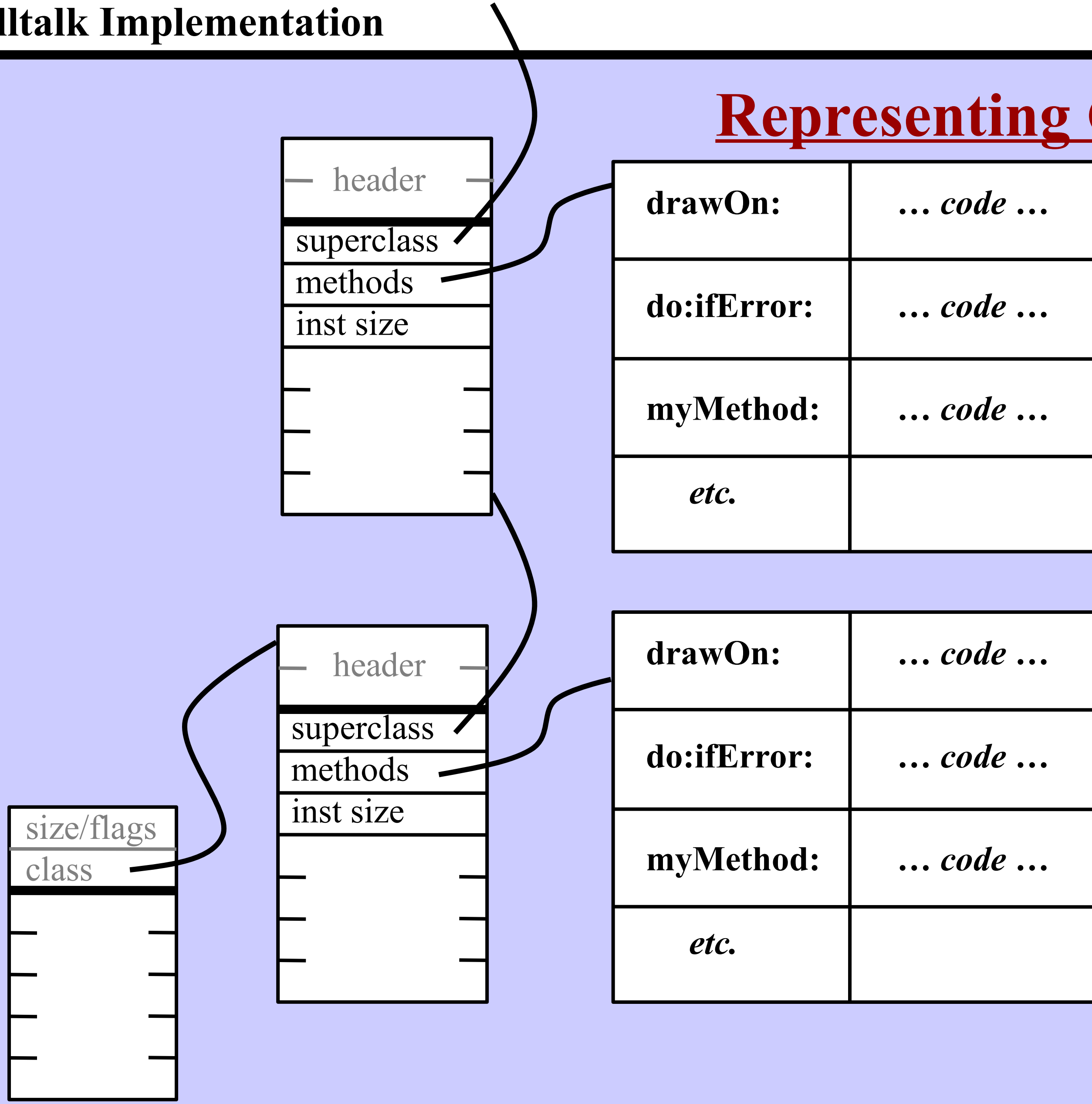

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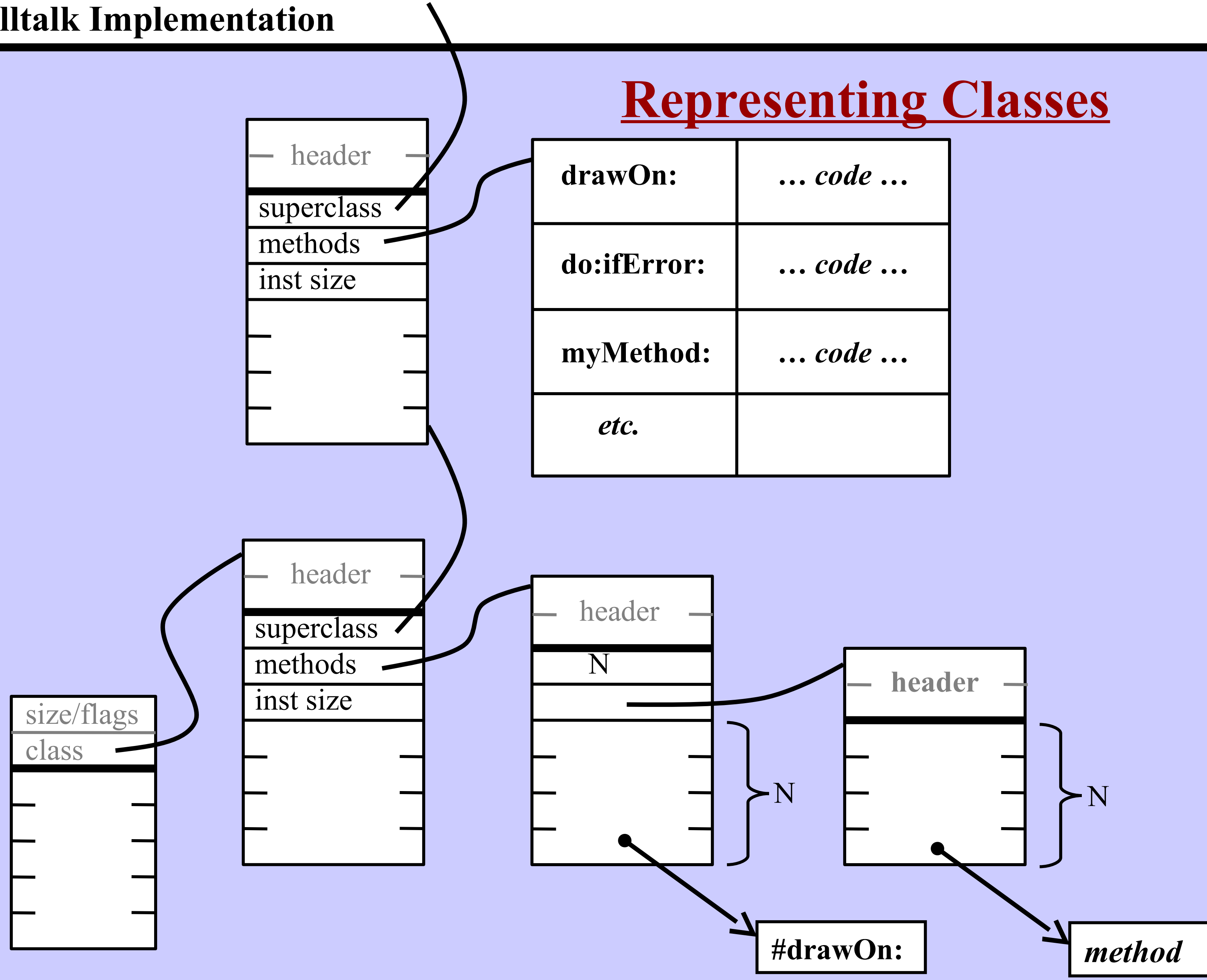

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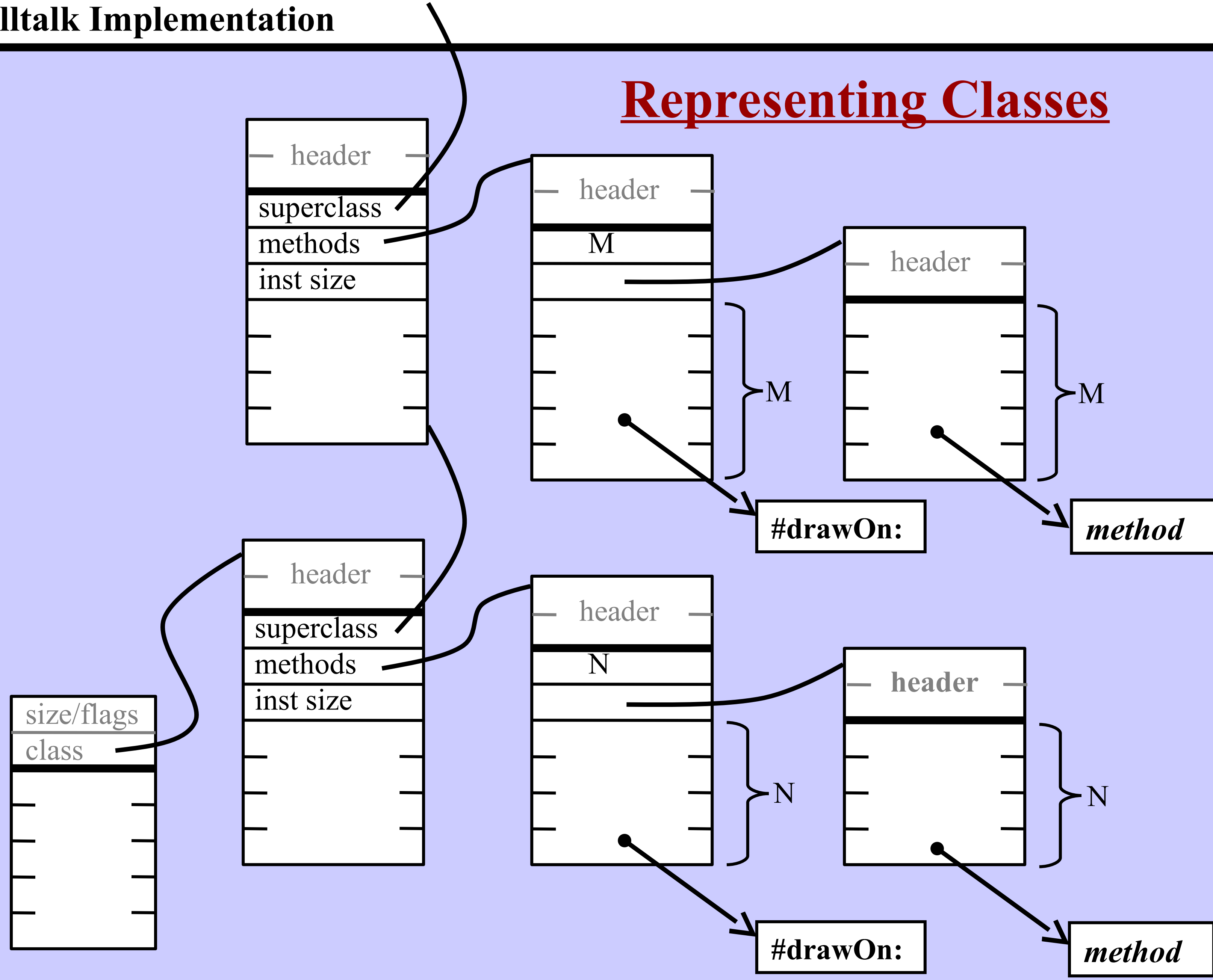

# Stack Machine Architectures

*Typical instructions:*

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

***Example Source:***

***Compiler produces:***

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*Typical instructions:*

```
push
pop
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call
return
jump
```

***Example Source:***

```
     4 + y
```

***Compiler produces:***

```
push 4
push y
add
```

# Stack Machine Architectures

*Typical instructions:*

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pop
add
call
return
jump
```

***Example Source:***

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

***Compiler produces:***

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

# Stack Machine Architectures

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***Example Source:***

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

***Compiler produces:***

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push 4
push y
add
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```

# Stack Machine Architectures

*Typical instructions:*

```
push
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add
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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:*

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pop
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jump
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***Example Source:***

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x := 4 + y * z;
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```
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
mult
add
pop x
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# Stack Machine Architectures

*Typical instructions:*

```
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*Example Source:*

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push 4
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add
pop x
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*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:*

```
push
pop
add
call
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jump
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*Example Source:*

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call foo
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mult
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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 + (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* ...

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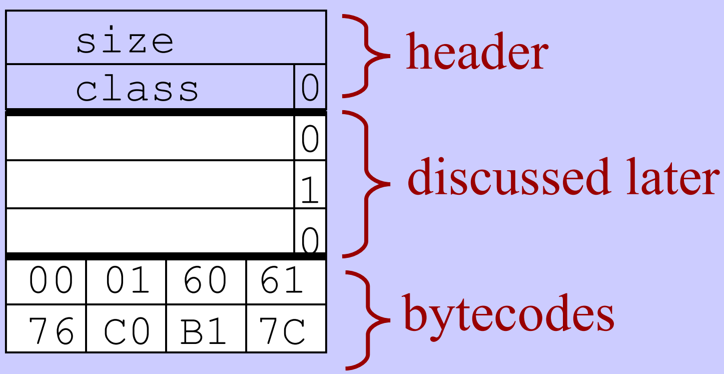
```

... *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:

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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**:

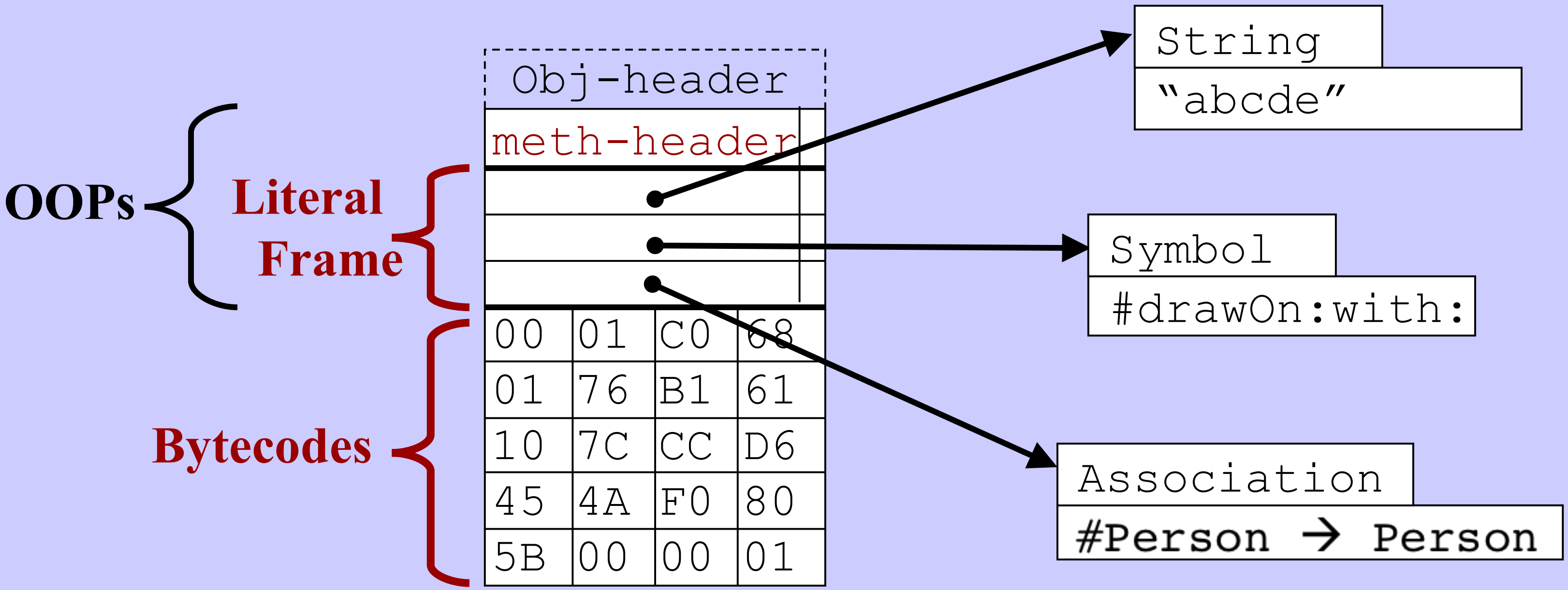
```
+   -   <   =   at:   at:put:   @   x   y ...
```

***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

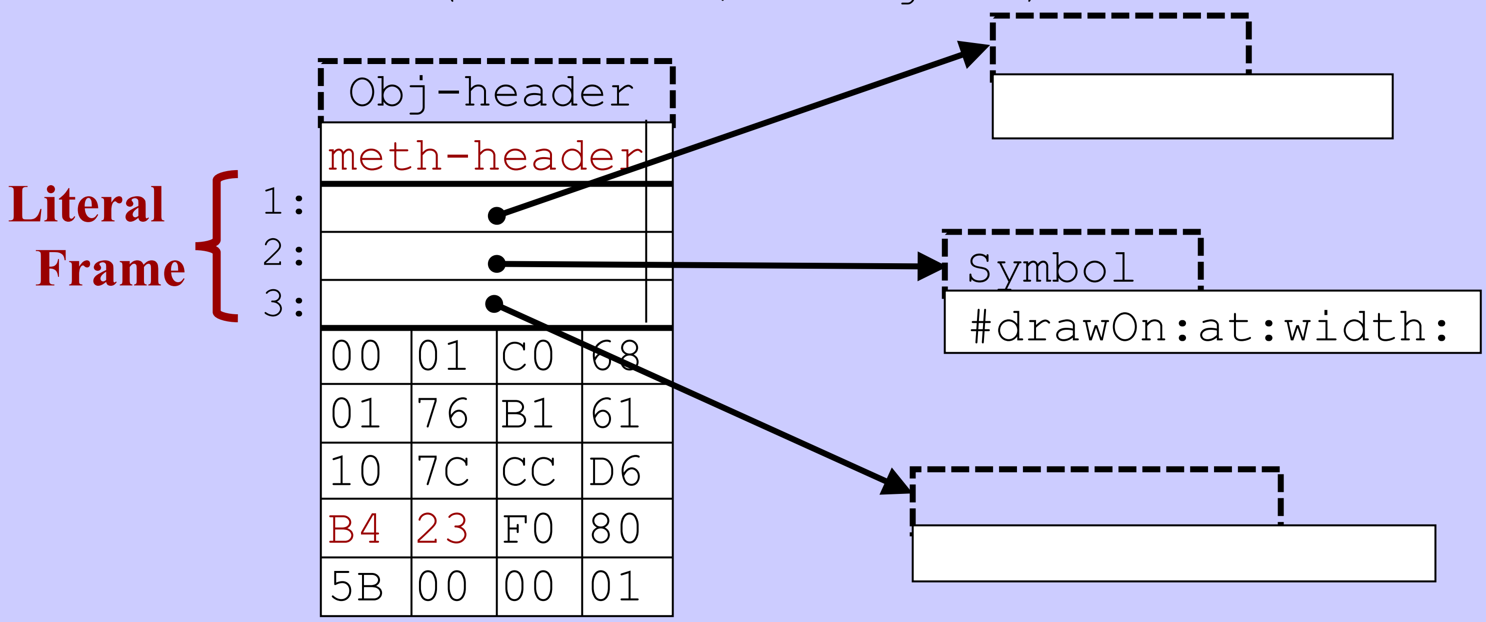
The remaining selectors are stored in the literal area

The bytecode for a "general" send includes:

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

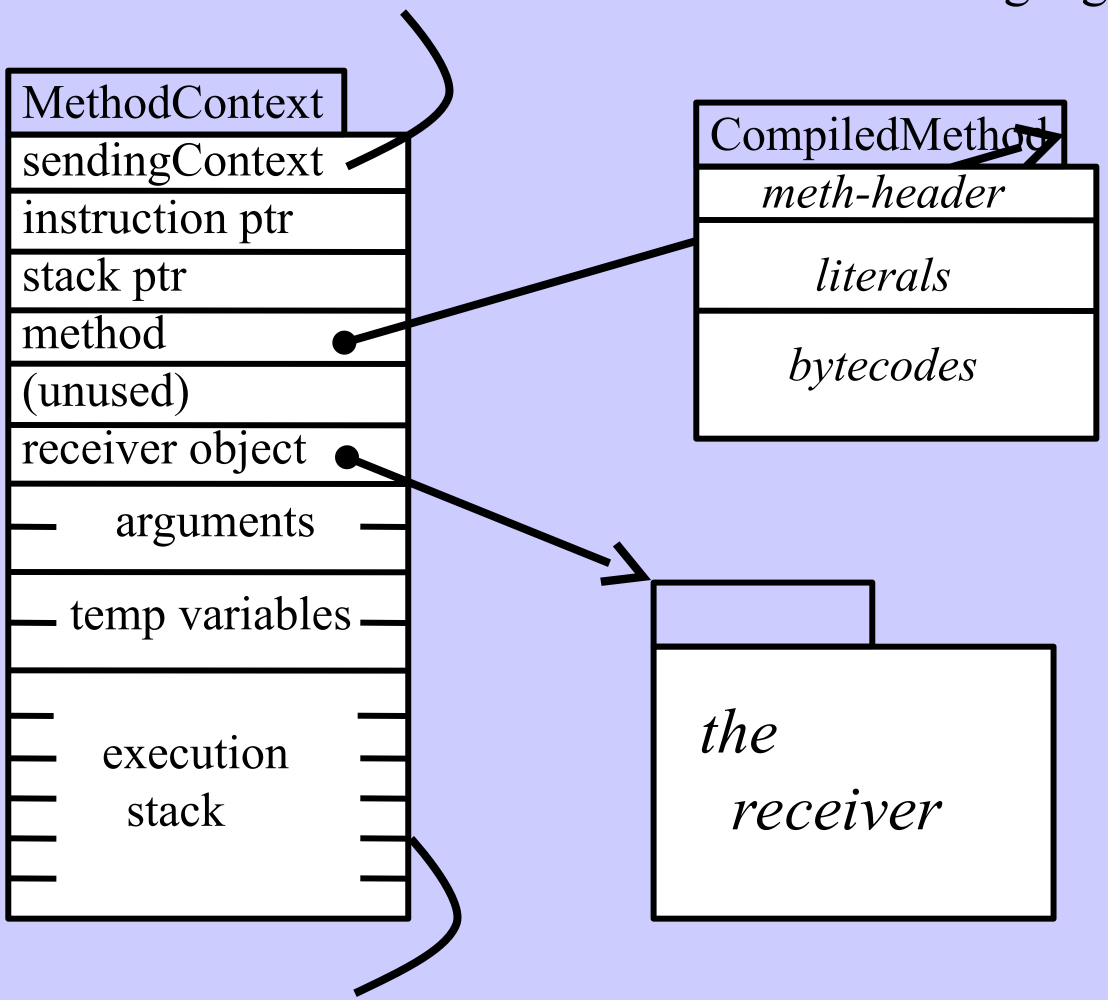
Bytecode:

```
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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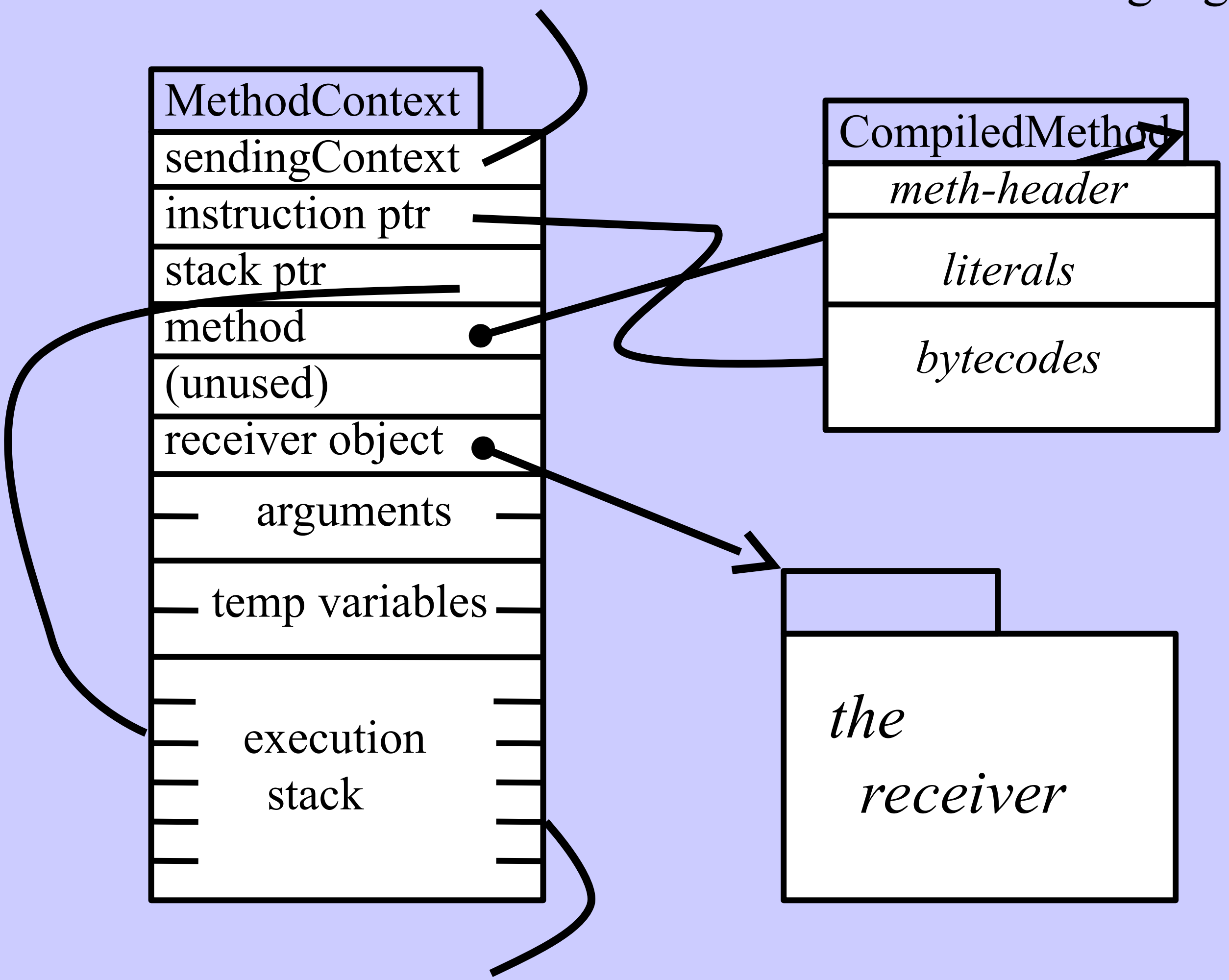

# What Happens When a Message is Sent?

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

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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 ]
```

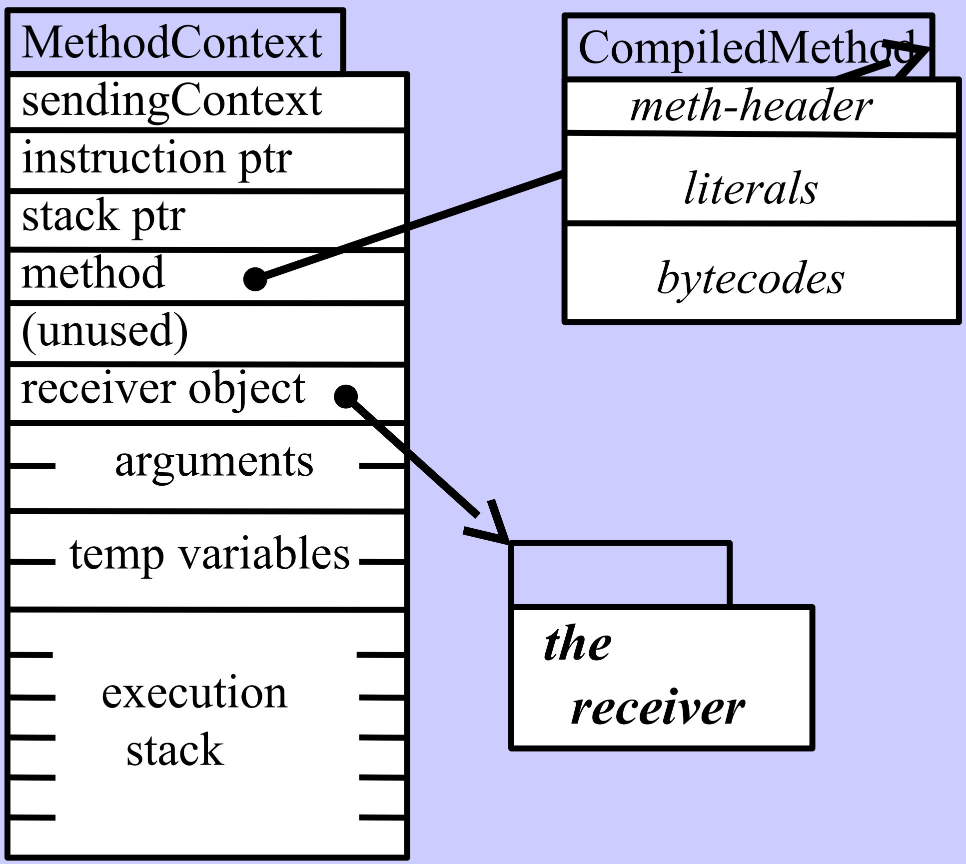
***… from the method where it was created***

```
[ :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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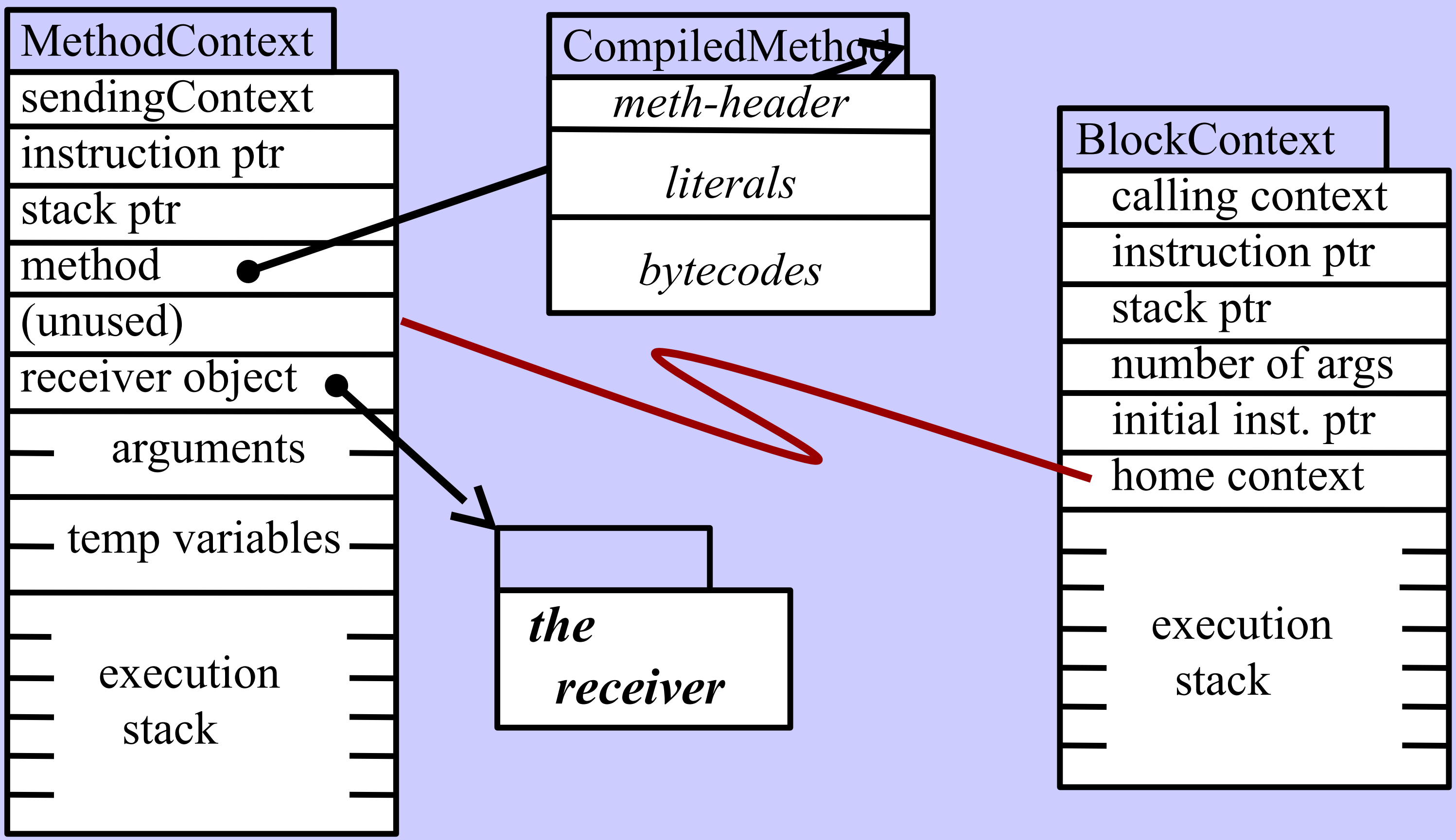


When created, the ***BlockContext*** has a pointer back to its ***"home context"***.

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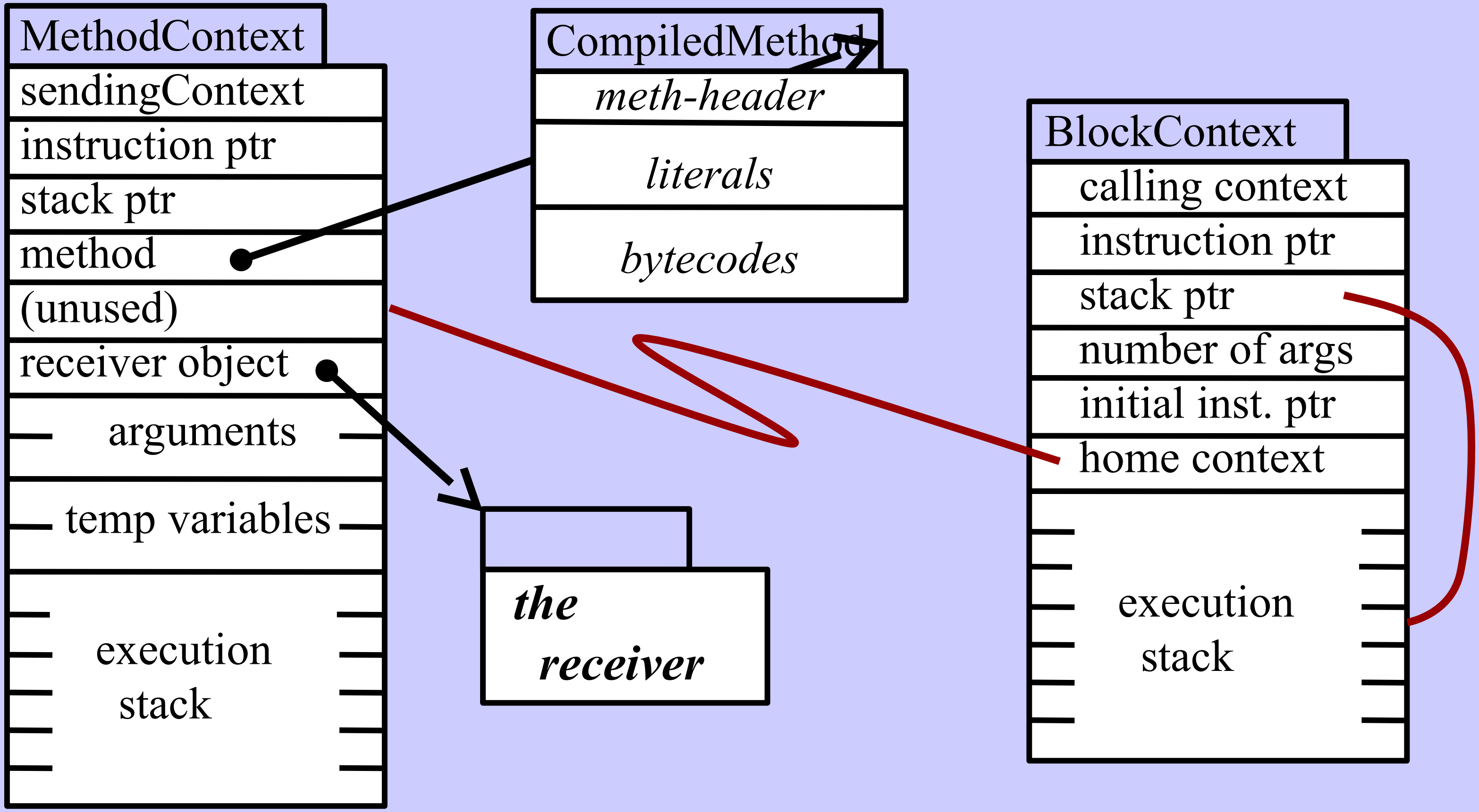
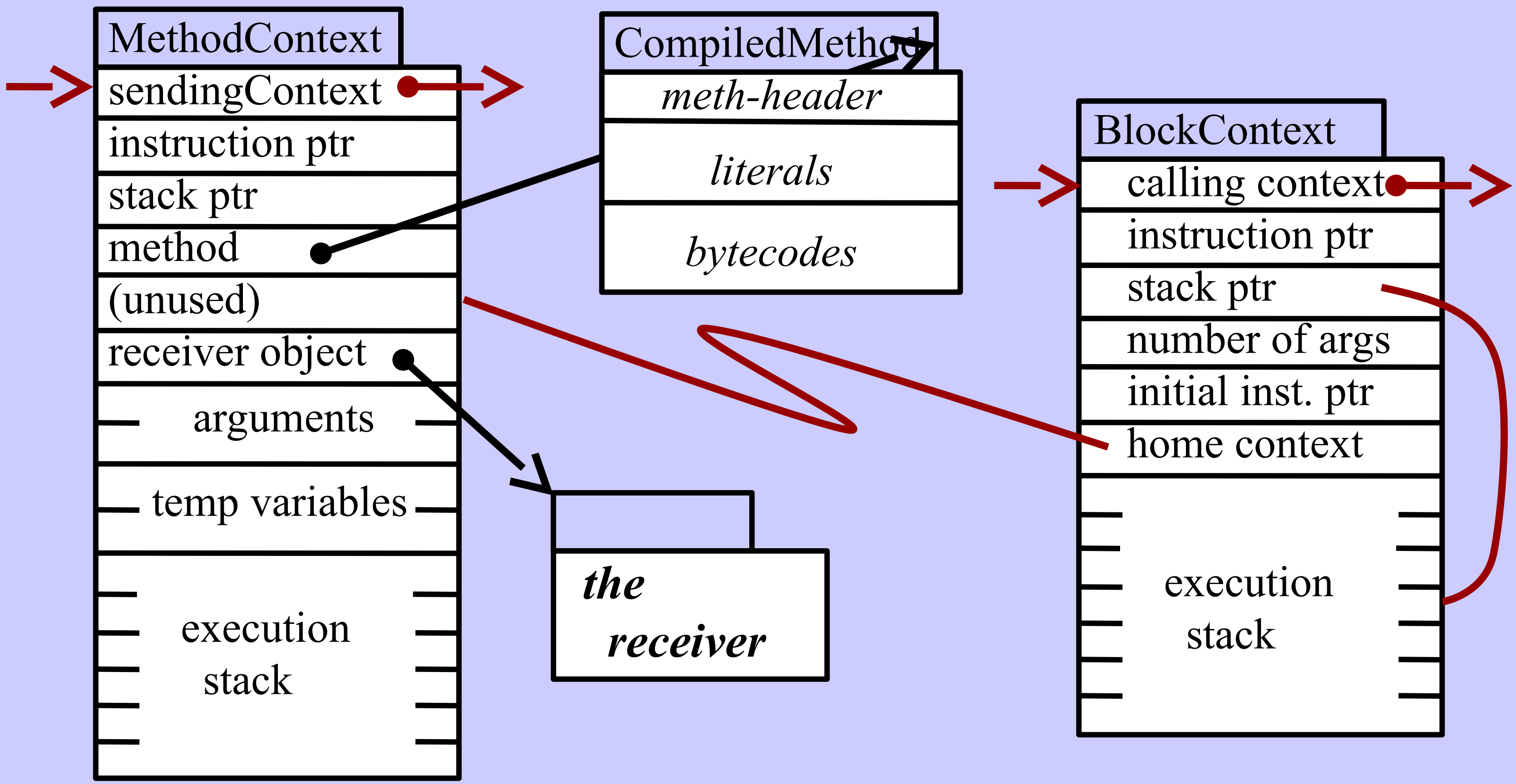


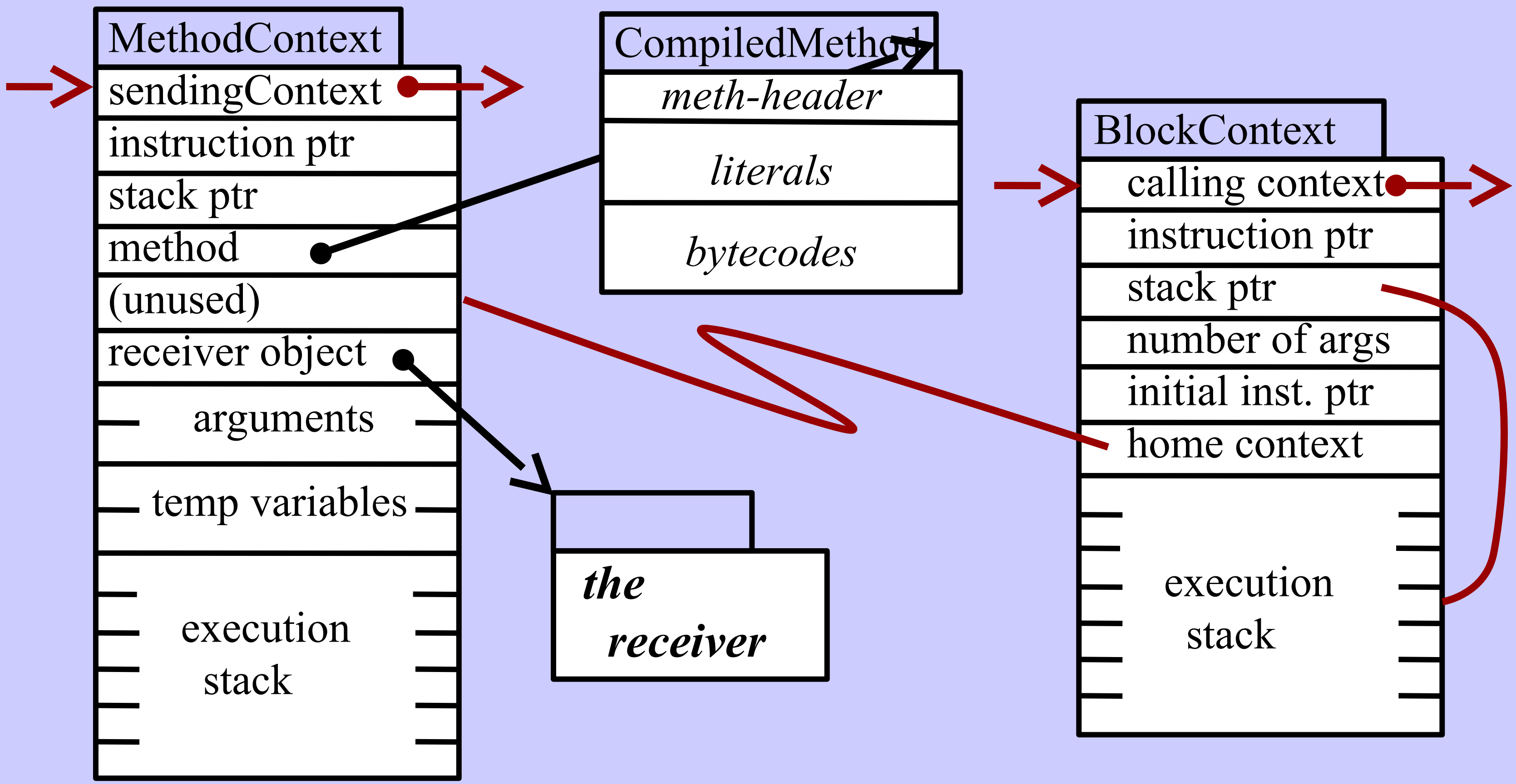

The BlockContext has its own ***execution stack***

# How are Blocks Represented?




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
    ^ 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
```

[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.**

On 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
00   closureNumCopied: 0, numArgs=1, next 3 bytes
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*

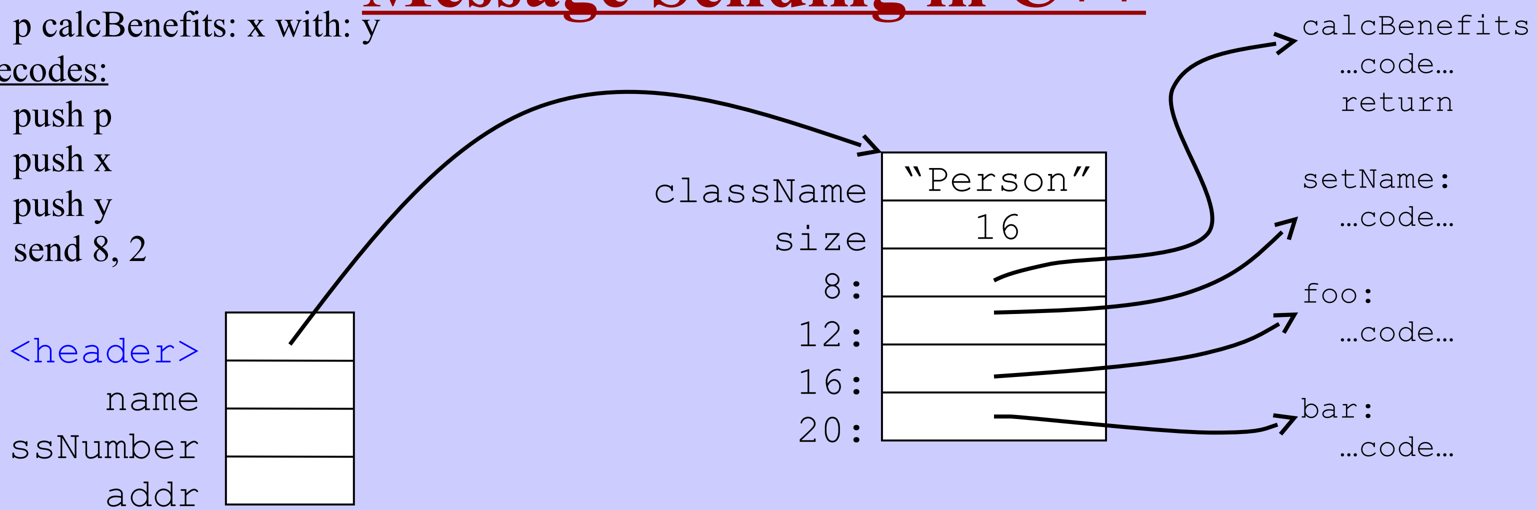
# Message Sending in C++

Source:

p calcBenefits: x with: y

Bytecodes:

push p
push x
push y
send 8, 2



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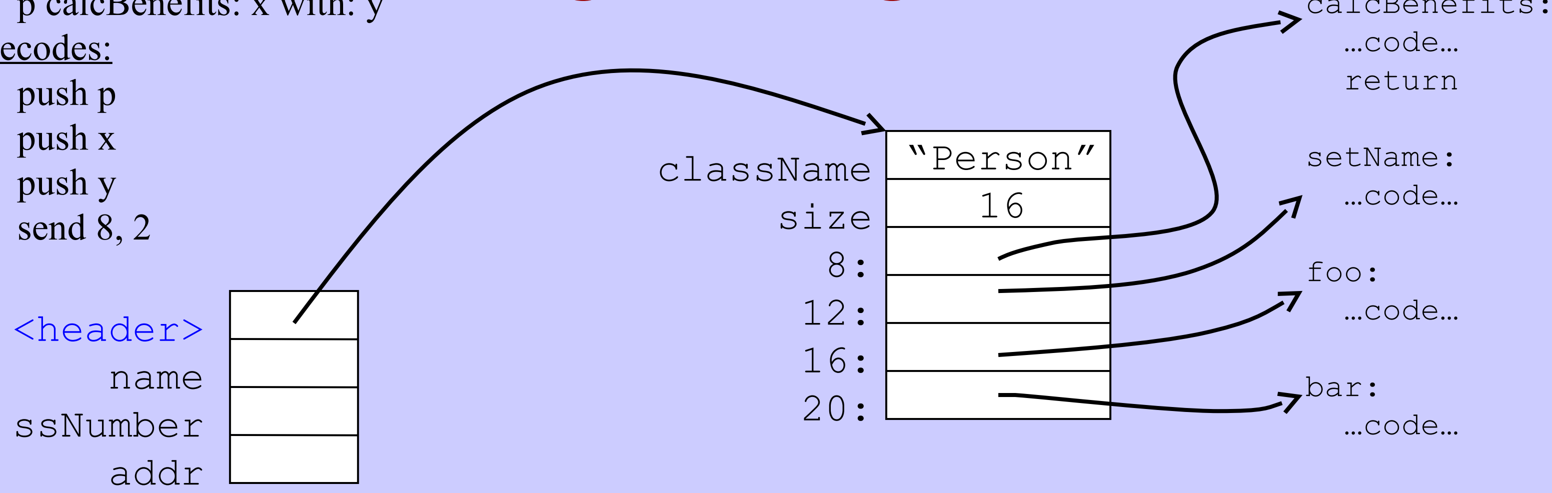
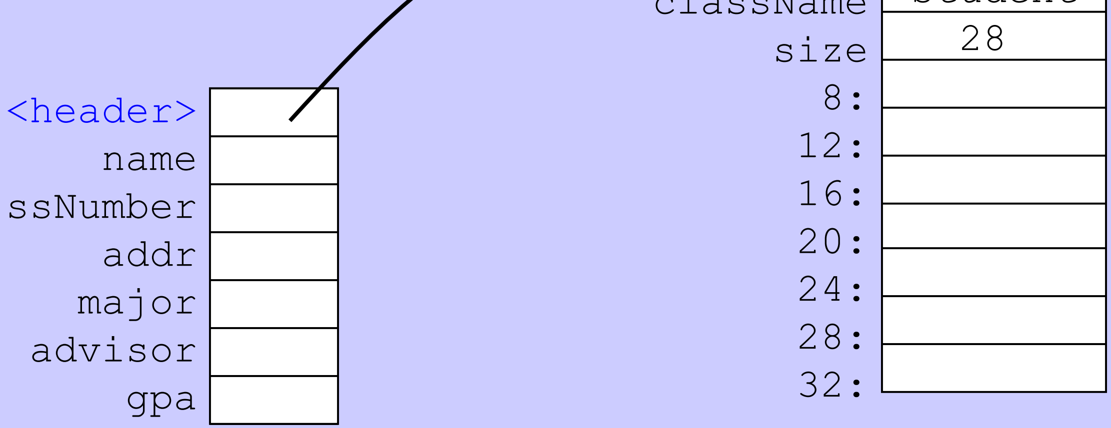



*Add a subclass...*



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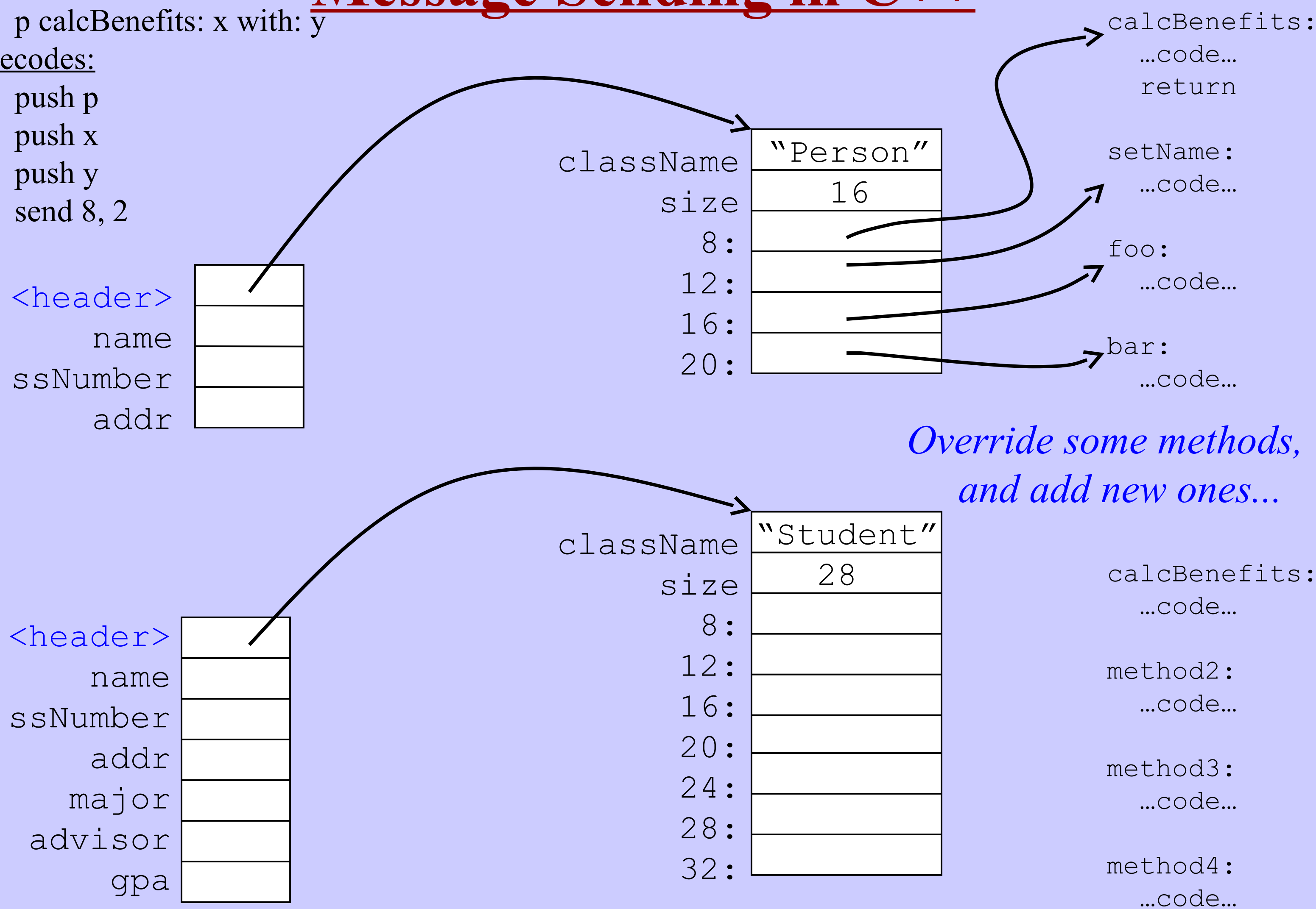


*Override some methods,*
*and add new ones...*

# Message Sending in C++

Source:

p calcBenefits: x with: y

Bytecodes:

push p
push x
push y
send 8, 2