UNIVERSITÄT BERN

4. Reflection

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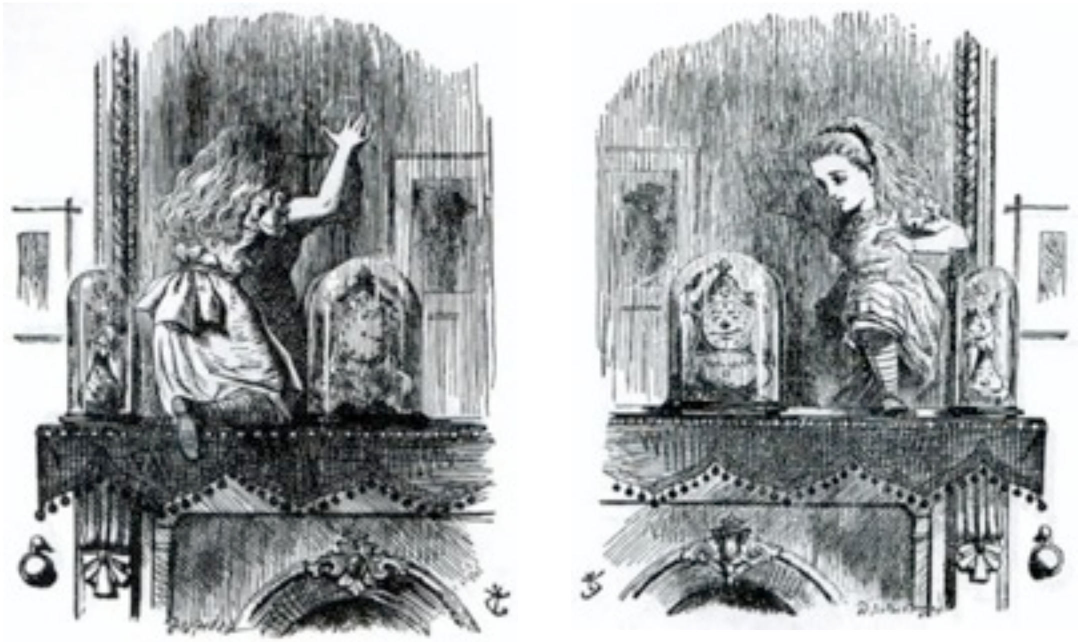
Selected material by Marcus Denker and Stéphane Ducasse

Birds-eye view



Reflection allows you to both *examine* and *alter* the meta-objects of a system.

Using reflection to modify a running system requires some care.

Roadmap

- Reification and reflection
- Reflection in Programming Languages
- Introspection
  - Inspecting objects
  - Querying code
  - Accessing run-time contexts
- Intercession
  - Overriding doesNotUnderstand:
  - Anonymous classes
  - Method wrappers

Roadmap

- **Reification and reflection**
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Why we need reflection

> As a programming language becomes *higher and higher level*, its implementation in terms of underlying machine involves *more and more tradeoffs*, on the part of the implementor, about what cases to optimize at the expense of what other cases. … the *ability to cleanly integrate* something outside of the language’s scope *becomes more and more limited*
>
> Kiczales, in Paepcke 1993

What is are Reflection and Reification?

- *Reflection* is the ability of a program to manipulate as data something representing the state of the program during its own execution.
  - *Introspection* is the ability for a program to observe and therefore reason about its own state.
  - *Intercession* is the ability for a program to modify its own execution state or alter its own interpretation or meaning.

- *Reification* is the mechanism for encoding execution state as data

— Bobrow, Gabriel & White, 1993

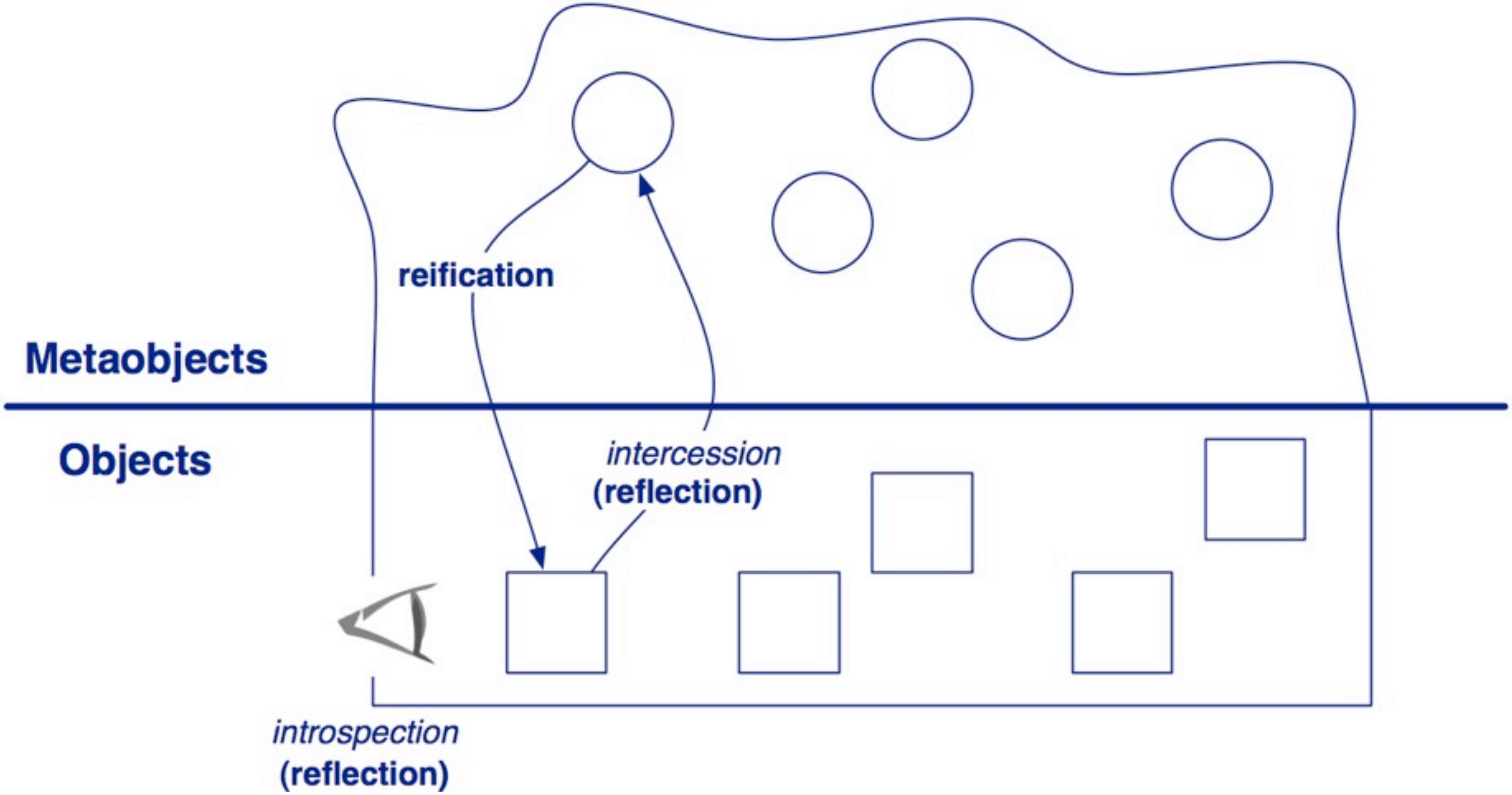
Structural and behavioral reflection

> Structural reflection lets you reify and reflect on
- the *program* currently executed
- its *abstract data types*.

> Behavioral reflection lets you reify and reflect on
- the language *semantics* and *implementation* (processor)
- the data and implementation of the *run-time system*.

Malenfant et al., *A Tutorial on Behavioral Reflection and its Implementation*, 1996

Reflection and Reification



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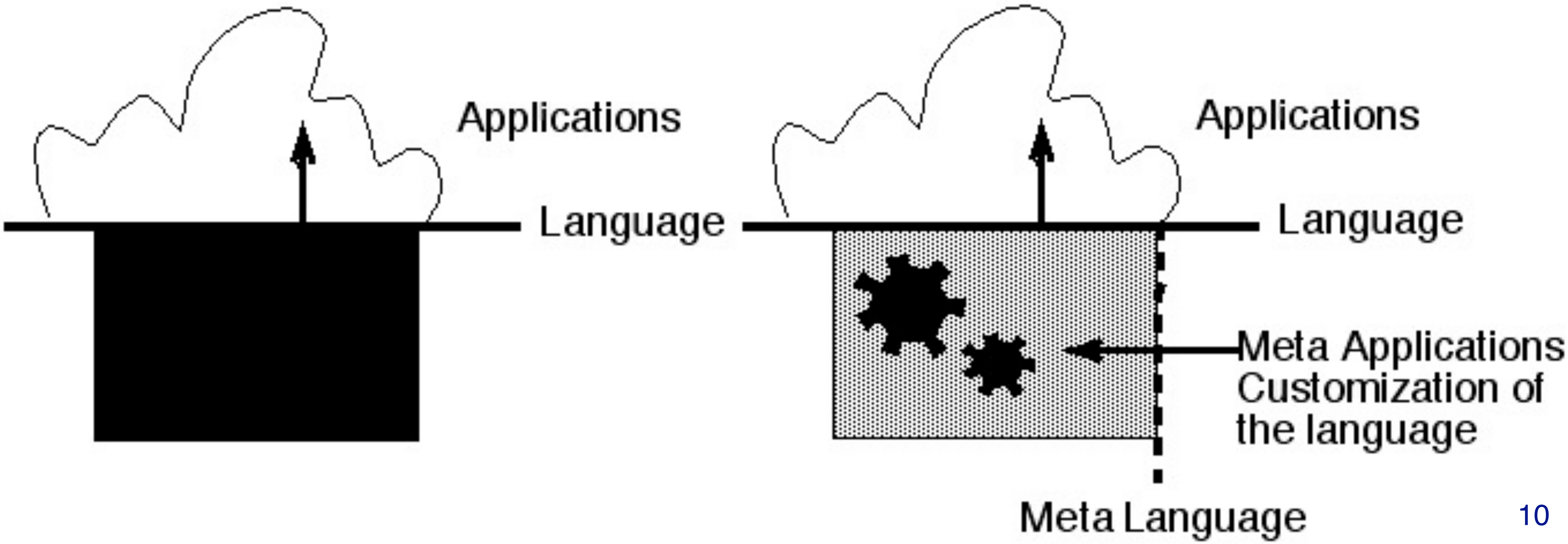
Metaprogramming in Programming Languages

- The meta-language and the language can be different:
  - Scheme and an OO language
- The meta-language and the language can be same:
  - Smalltalk, CLOS
  - In such a case this is a *metacircular architecture*

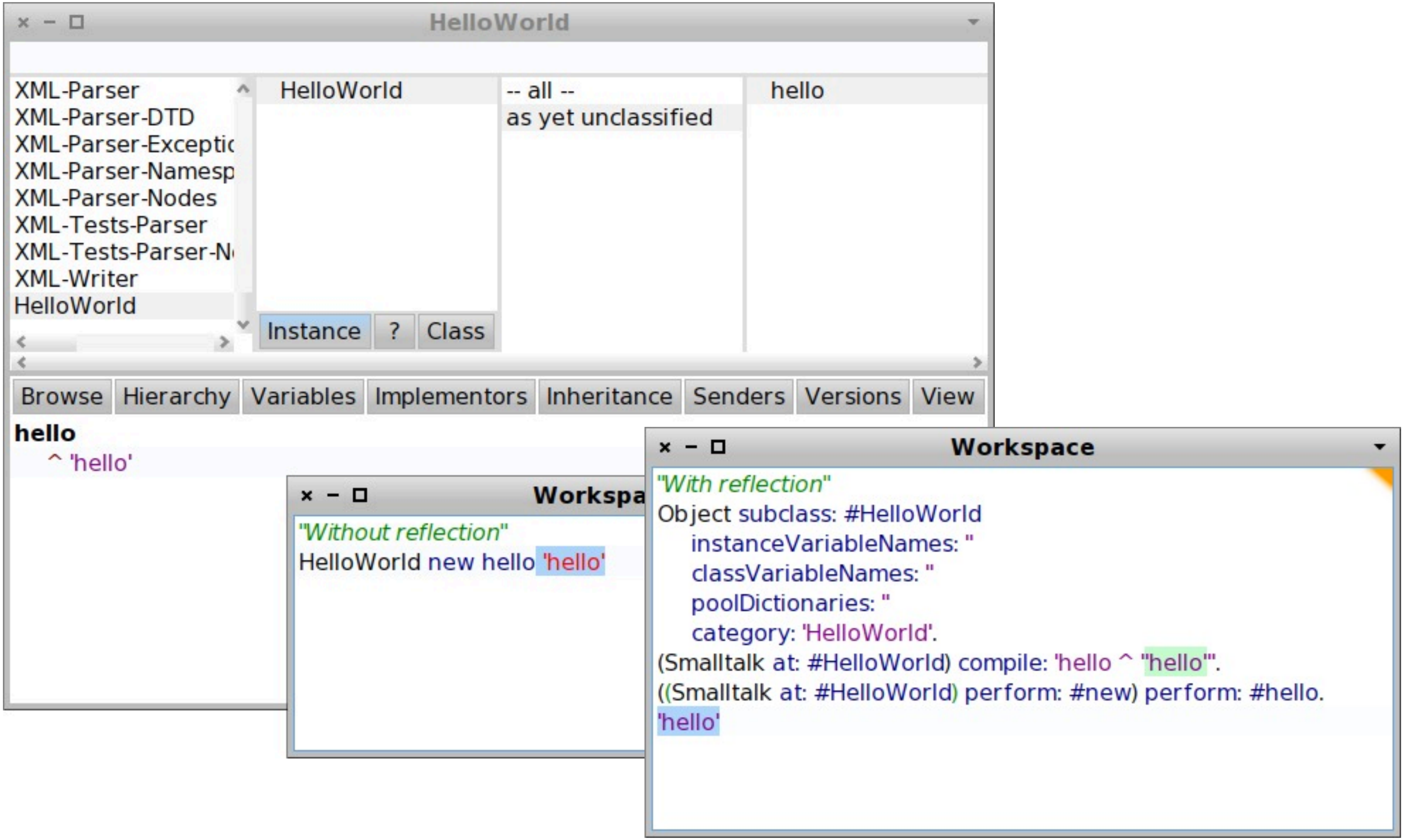


Introspection in Java

```java
// Without introspection
World world = new World();
world.hello();
```

```java
// With introspection
Class cls = Class.forName("World");
Method method = cls.getMethod("hello", null);
method.invoke(cls.newInstance(), null);
```

Reflection in Smalltalk



```
hello
    ^ 'hello'
```

```
"Without reflection"
HelloWorld new hello 'hello'
```

```
"With reflection"
Object subclass: #HelloWorld
    instanceVariableNames: ''
    classVariableNames: ''
    poolDictionaries: ''
    category: 'HelloWorld'.
(Smalltalk at: #HelloWorld) compile: 'hello ^ ''hello'''.
((Smalltalk at: #HelloWorld) perform: #new) perform: #hello.
'hello'
```

Three approaches

1. Tower of meta-circular interpreters
2. Reflective languages
3. Open implementation

1. Tower of meta-circular interpreters

> Each level interprets and controls the next
    — 3-Lisp, Scheme

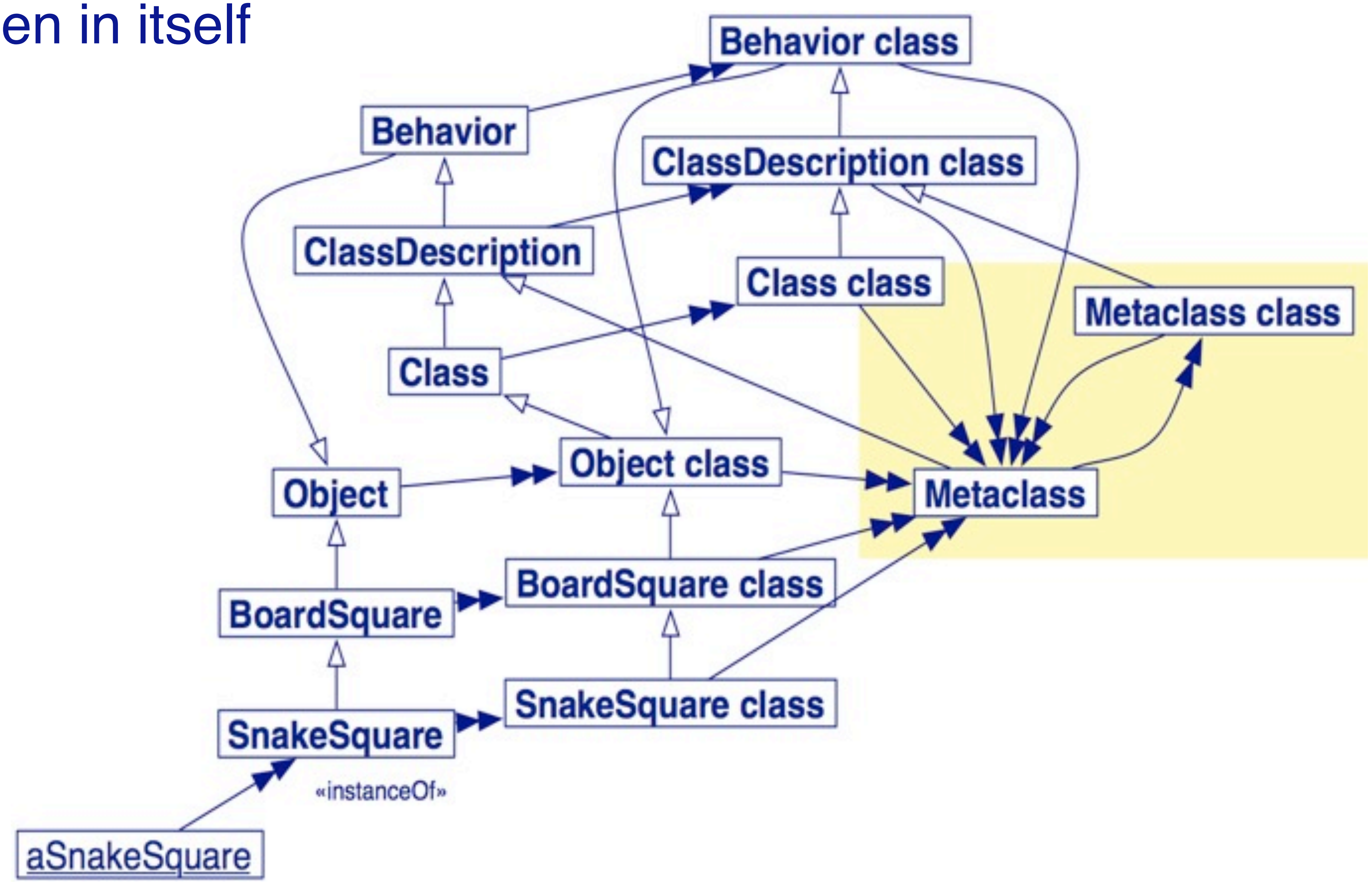
> “Turtles all the way down” [up]
    — In practice, levels are reified on-demand

2. Reflective languages

> Meta-entities control base entities

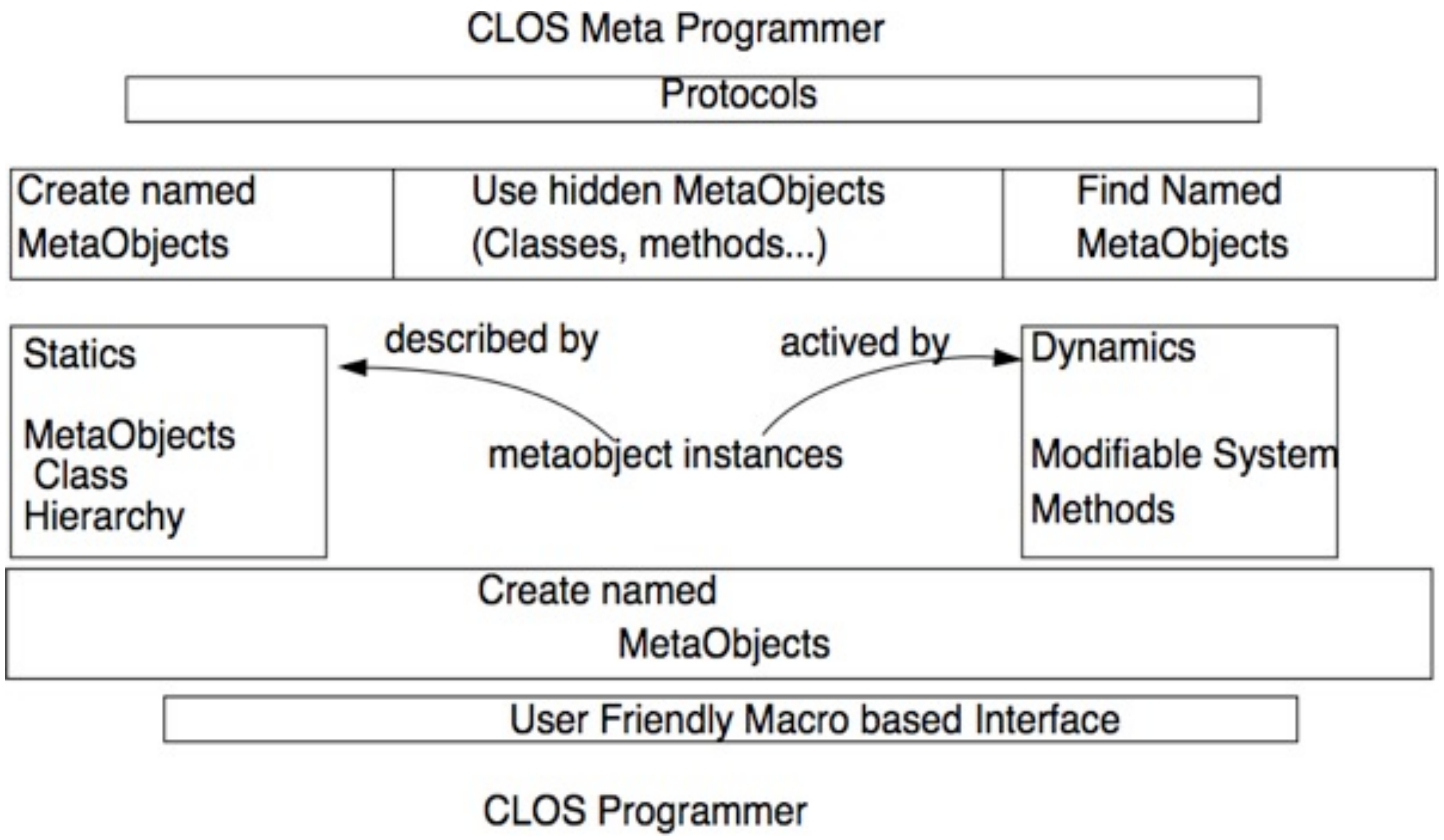
— Smalltalk, Self

— Language is written in itself



3. Open implementation

- Meta-object protocols provide an interface to access and modify the implementation and semantics of a language
  - CLOS
- *More efficient, less expressive than infinite towers*



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The Essence of a Class

1. A format (e.g. a set of instance variables)
2. A superclass
3. A method dictionary

Behavior class>> new

> In Pharo:

```
Behavior class>>new
   | classInstance |
   classInstance := self basicNew.
   classInstance methodDictionary:
      classInstance emptyMethodDictionary.
   classInstance superclass: Object.
   classInstance setFormat: Object format.
   ^ classInstance
```

NB: not to be confused with `Behavior>>new`!

The Essence of an Object

1. Class pointer
2. Values

> Can be special:

- `SmallInteger`
- Indexed rather than pointer values
- Compact classes (`CompiledMethod`, `Array` ...)

Metaobjects vs metaclasses

- Need distinction between metaclass and metaobject!
  - A metaclass is a class whose instances are classes
  - A metaobject is an object that describes or manipulates other objects
    - *Different metaobjects can control different aspects of objects*

Some MetaObjects

- **Structure:**
  - Behavior, ClassDescription, Class, Metaclass, ClassBuilder
- **Semantics:**
  - Compiler, Decompiler, IRBuilder
- **Behavior:**
  - CompiledMethod, BlockContext, Message, Exception
- **ControlState:**
  - BlockContext, Process, ProcessorScheduler
- **Resources:**
  - WeakArray
- **Naming:**
  - SystemDictionary
- **Libraries:**
  - MethodDictionary, ClassOrganizer

Meta-Operations

> “Meta-operations are operations that provide information about an object as opposed to information directly contained by the object ...They permit things to be done that are not normally possible”
>
> *Inside Smalltalk*

Accessing state

- *Object*>>instVarNamed: aString
- *Object*>>instVarNamed: aString put: anObject
- *Object*>>instVarAt: aNumber
- *Object*>>instVarAt: aNumber put: anObject

```
pt := 10@3.
pt instVarNamed: 'x'.
pt instVarNamed: 'x' put: 33.
pt
```

```
10

33@3
```

Accessing meta-information

> *Object*>>class

> *Object*>>identityHash

```
'hello' class
(10@3) class
Smalltalk class
Class class
Class class class
Class class class class

'hello' identityHash
Object identityHash
5 identityHash
```

```
ByteString
Point
SystemDictionary
Class class
Metaclass
Metaclass class

2664
2274
5
```

Changes

- `Object>>primitiveChangeClassTo: anObject`
  - both classes should have the same format, *i.e.*, the same physical structure of their instances
    - *“Not for casual use”*

- `Object>>become: anotherObject`
  - Swap the object pointers of the receiver and the argument.
  - All variables in the entire system that used to point to the receiver now point to the argument, and vice-versa.
  - Fails if either object is a SmallInteger

- `Object>>becomeForward: anotherObject`
  - Like `become:` but only in one direction.

Implementing Instance Specific Methods

```
ReflectionTest>>testPrimitiveChangeClassTo
  | behavior browser |

  behavior := Behavior new. “an anonymous class”
  behavior superclass: Browser.
  behavior setFormat: Browser format.
  browser := Browser new.

  browser primitiveChangeClassTo: behavior new.
  behavior compile: 'thisIsATest ^ 2'.

  self assert: browser thisIsATest = 2.
  self should: [Browser new thisIsATest]
       raise: MessageNotUnderstood.
```

become:

- Swap all the pointers from one object to the other and back (symmetric)

```
ReflectionTest>>testBecome
   | pt1 pt2 pt3 |

   pt1 := 0@0.
   pt2 := pt1.
   pt3 := 100@100.
   pt1 become: pt3.

   self assert: pt1 = (100@100).
   self assert: pt1 == pt2.
   self assert: pt3 = (0@0).
```

becomeForward:

- Swap all the pointers from one object to the other (asymmetric)

```
ReflectionTest>>testBecomeForward
   | pt1 pt2 pt3 |

   pt1 := 0@0.
   pt2 := pt1.
   pt3 := 100@100.
   pt1 becomeForward: pt3.

   self assert: pt1 = (100@100).
   self assert: pt1 == pt2.
   self assert: pt2 == pt3.
```

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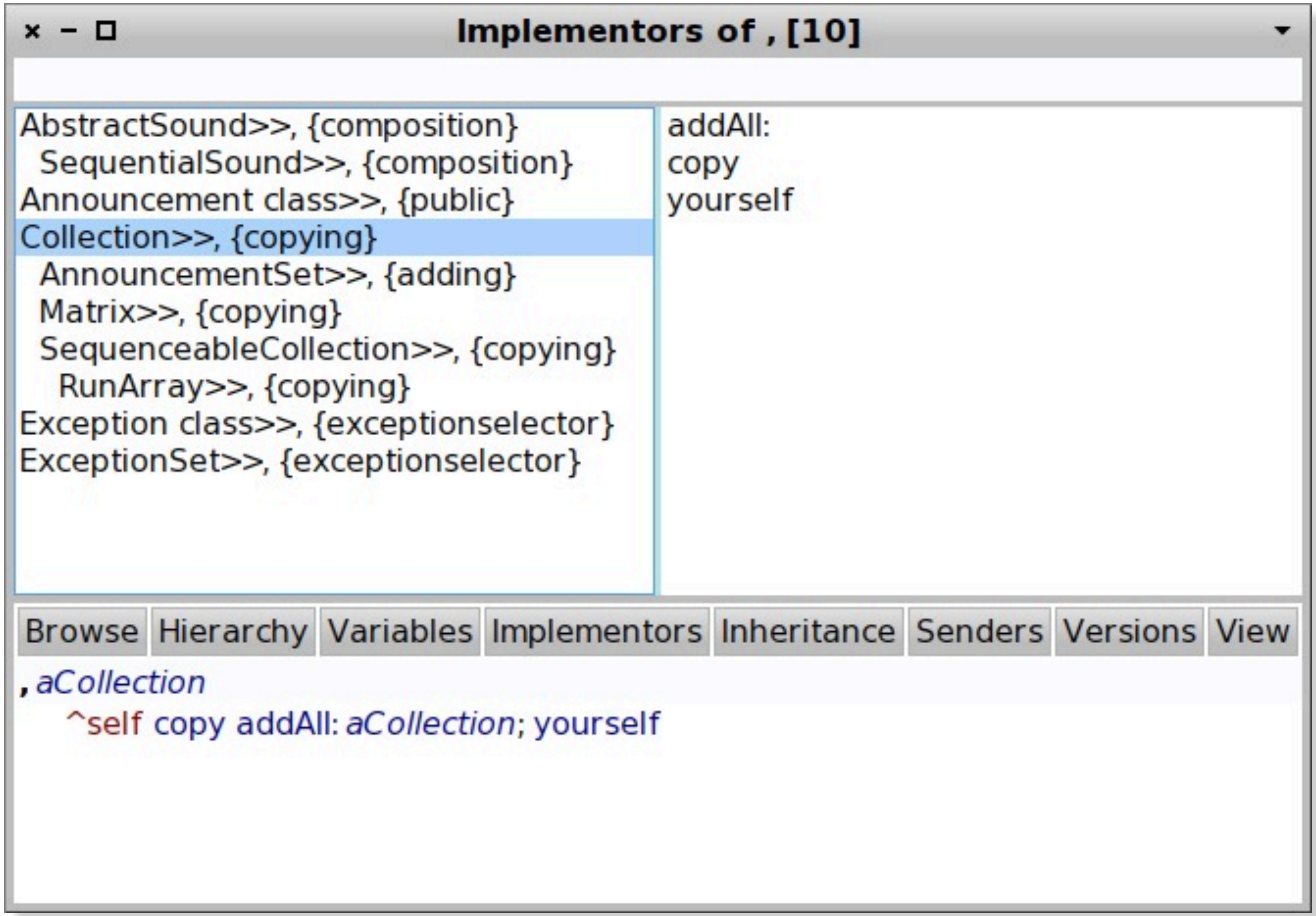
Code metrics

```
Collection allSuperclasses size.
Collection allSelectors size.
Collection allInstVarNames size.
Collection selectors size.
Collection instVarNames size.
Collection subclasses size.
Collection allSubclasses size.
Collection linesOfCode.
```

```
2
610
0
163
0
9
101
864
```

SystemNavigation

```
SystemNavigation default browseAllImplementorsOf: #,
```

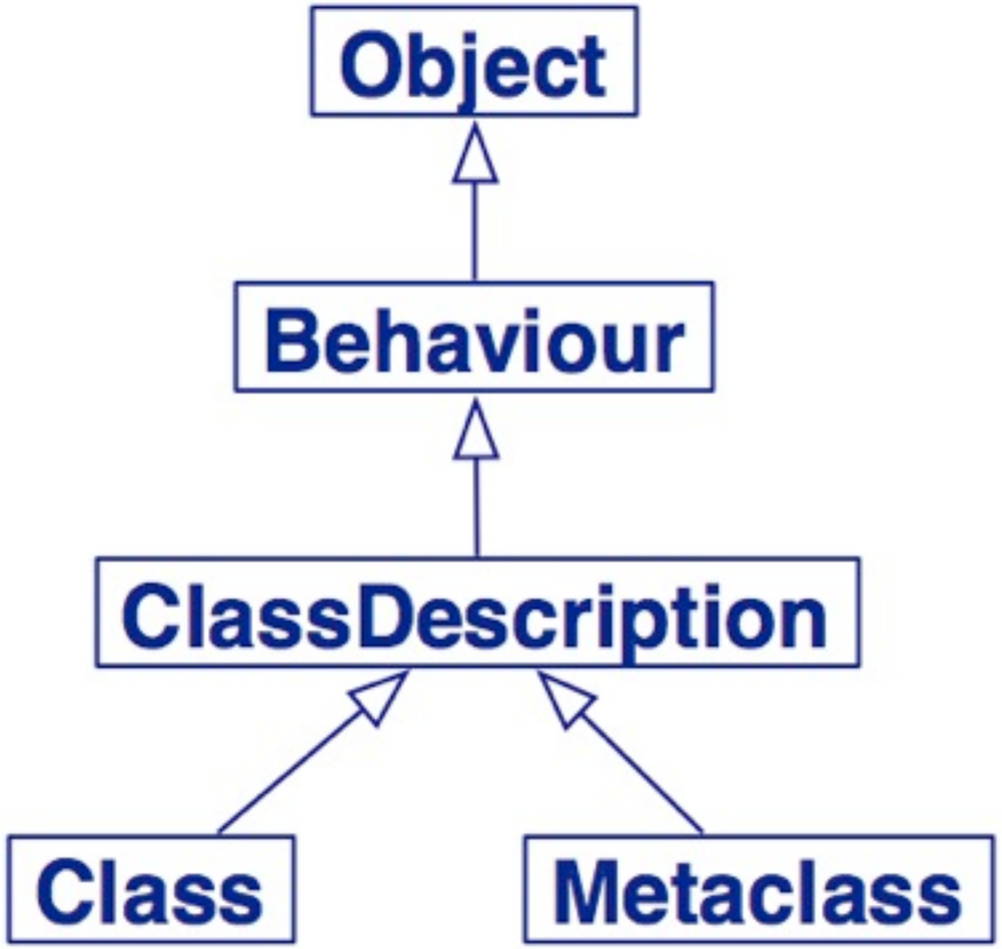


```
AbstractSound>>, {composition}
  SequentialSound>>, {composition}
Announcement class>>, {public}
Collection>>, {copying}
  AnnouncementSet>>, {adding}
  Matrix>>, {copying}
  SequenceableCollection>>, {copying}
    RunArray>>, {copying}
Exception class>>, {exceptionselector}
ExceptionSet>>, {exceptionselector}
```

```
addAll:
copy
yourself
```

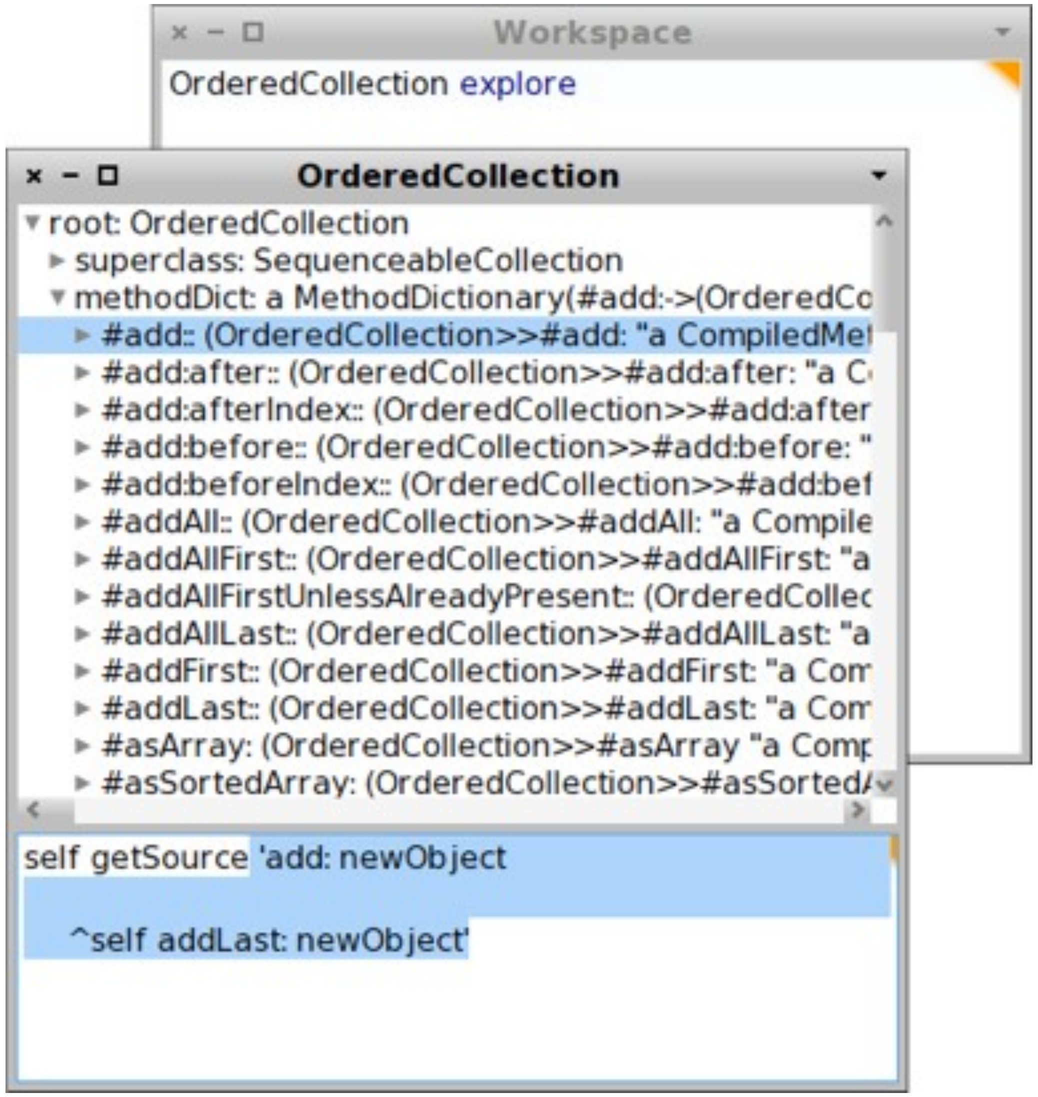
```
, aCollection
	^self copy addAll: aCollection; yourself
```

Recap: Classes are objects too



- Object
  - Root of inheritance
  - Default Behavior
  - Minimal Behavior
- Behavior
  - Essence of a class
  - Anonymous class
  - Format, methodDict, superclass
- ClassDescription
  - Human representation and organization
- Metaclass
  - Sole instance

Classes are Holders of CompiledMethods

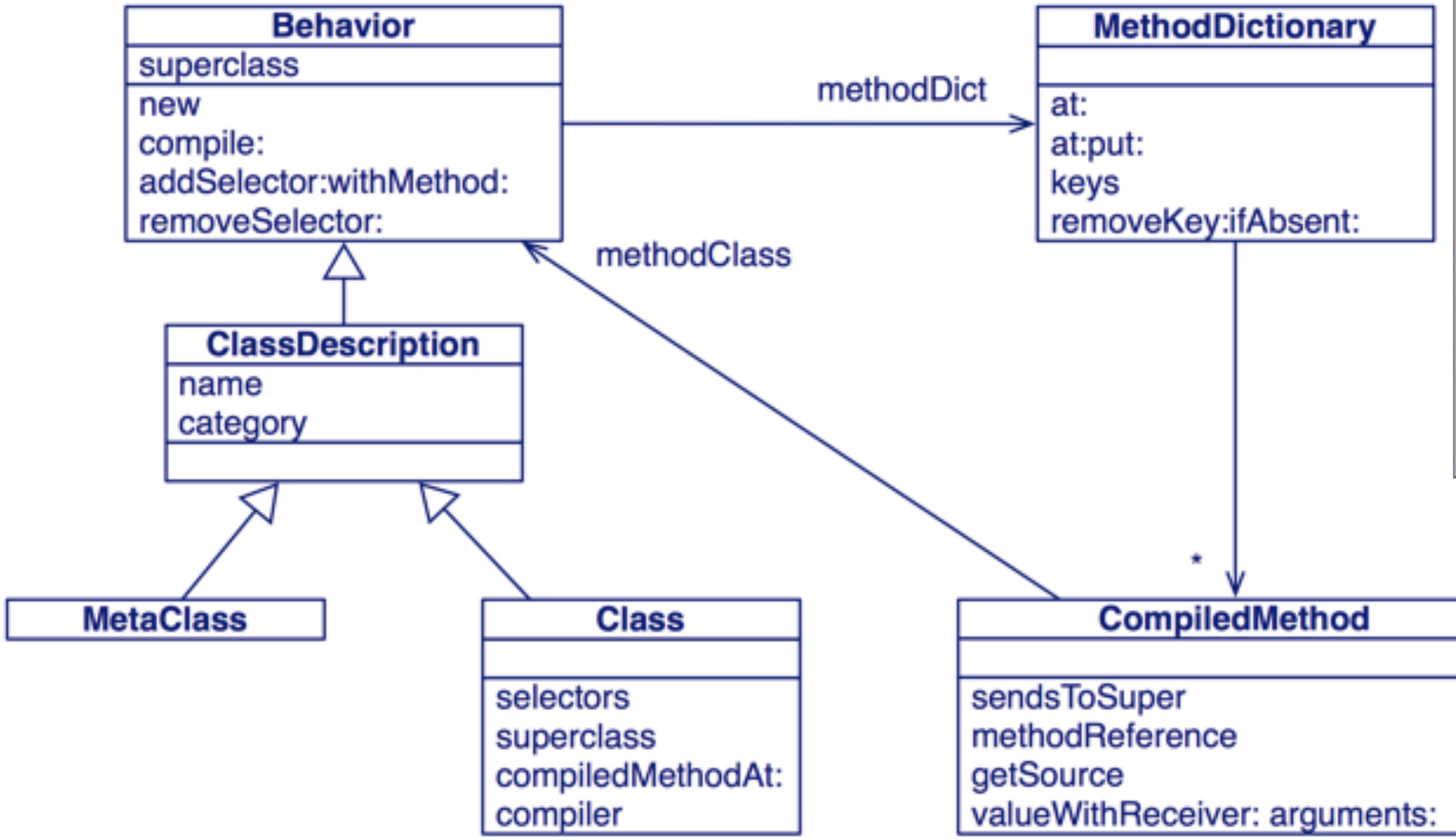


```
OrderedCollection explore
```

```
▾ root: OrderedCollection
  ▸ superclass: SequenceableCollection
  ▾ methodDict: a MethodDictionary(#add:->(OrderedCo
    ▸ #add:: (OrderedCollection>>#add: "a CompiledMet
    ▸ #add:after:: (OrderedCollection>>#add:after: "a C
    ▸ #add:afterIndex:: (OrderedCollection>>#add:after
    ▸ #add:before:: (OrderedCollection>>#add:before: "
    ▸ #add:beforeIndex:: (OrderedCollection>>#add:bef
    ▸ #addAll:: (OrderedCollection>>#addAll: "a Compile
    ▸ #addAllFirst:: (OrderedCollection>>#addAllFirst: "a
    ▸ #addAllFirstUnlessAlreadyPresent:: (OrderedCollec
    ▸ #addAllLast:: (OrderedCollection>>#addAllLast: "a
    ▸ #addFirst:: (OrderedCollection>>#addFirst: "a Com
    ▸ #addLast:: (OrderedCollection>>#addLast: "a Com
    ▸ #asArray: (OrderedCollection>>#asArray "a Comp
    ▸ #asSortedArray: (OrderedCollection>>#asSorted/
```

```
self getSource 'add: newObject

   ^self addLast: newObject'
```



Invoking a message by its name

```
Object>>perform: aSymbol
Object>>perform: aSymbol with: arg
```

- Asks an object to execute a message
  - Normal method lookup is performed

```
5 factorial
5 perform: #factorial
```

```
120
120
```

Executing a compiled method

```
CompiledMethod>>valueWithReceiver:arguments:
```

No lookup is performed!

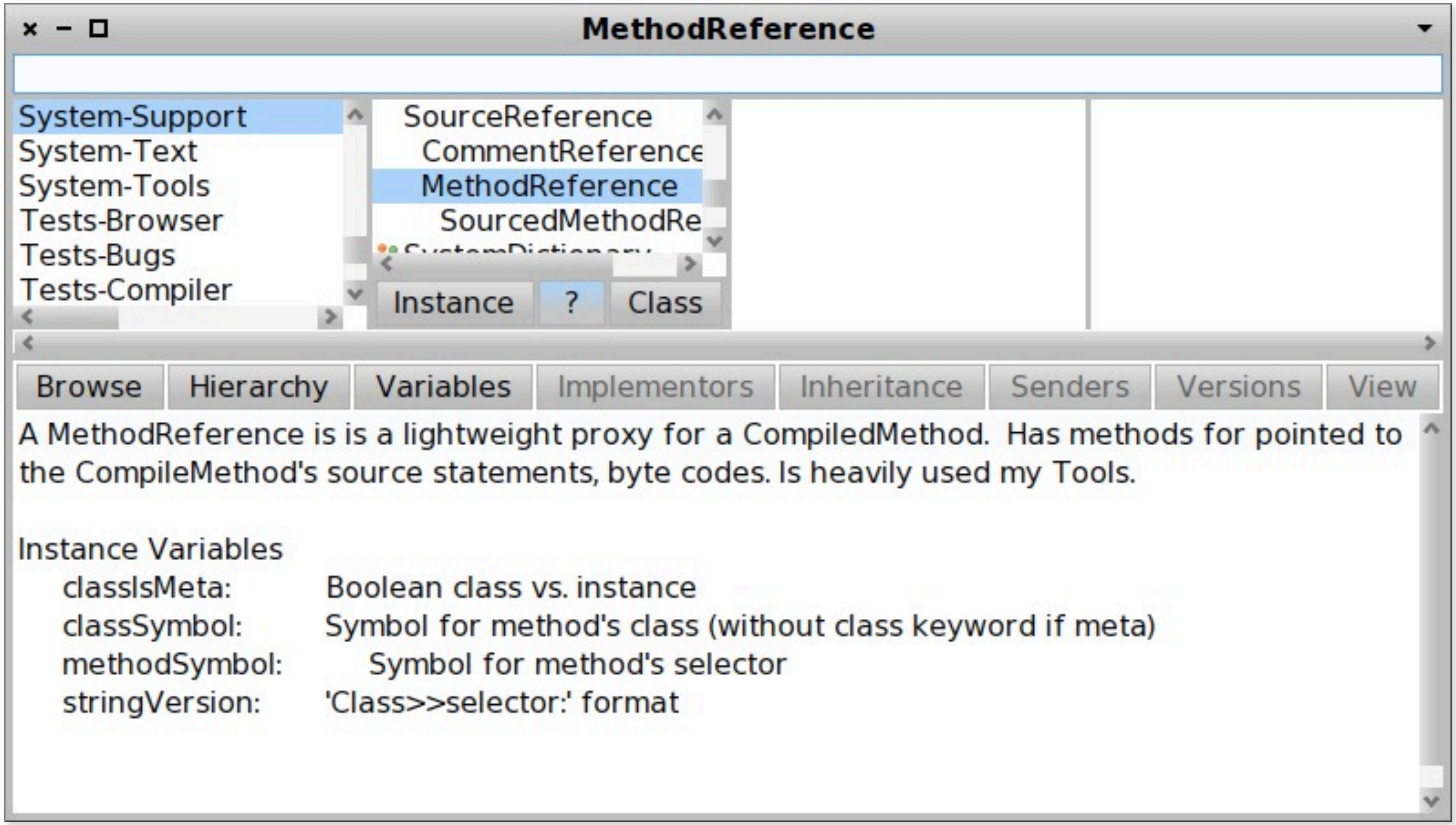
```
(SmallInteger>>#factorial)
   valueWithReceiver: 5
   arguments: #()
```

```
Error: key not found
```

```
(Integer>>#factorial)
   valueWithReceiver: 5
   arguments: #()
```

```
120
```

MethodReference

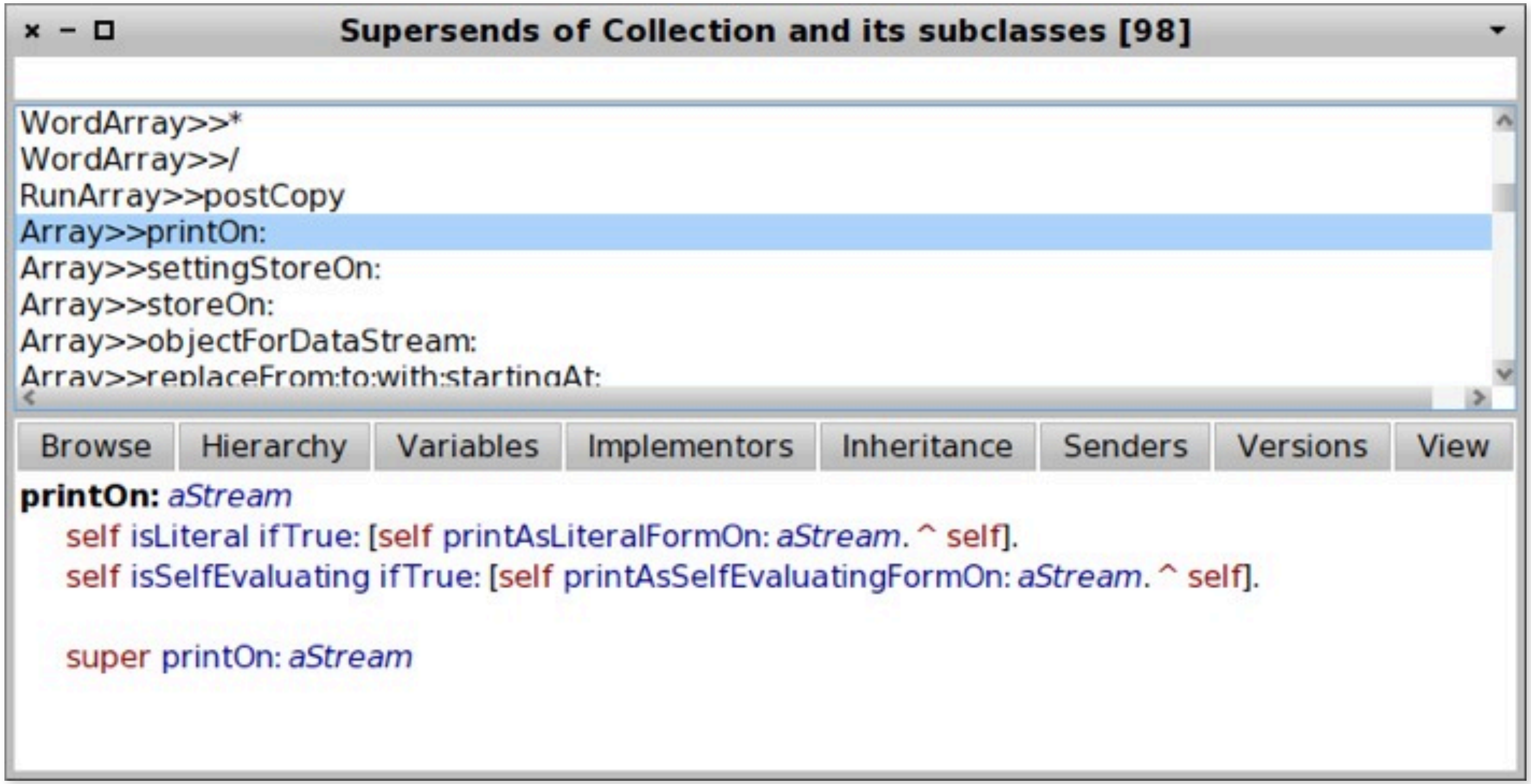


A MethodReference is is a lightweight proxy for a CompiledMethod. Has methods for pointed to the CompileMethod's source statements, byte codes. Is heavily used my Tools.

```
Instance Variables
    classIsMeta:        Boolean class vs. instance
    classSymbol:        Symbol for method's class (without class keyword if meta)
    methodSymbol:           Symbol for method's selector
    stringVersion:      'Class>>selector:' format
```

Finding super-sends within a hierarchy

```
class := Collection.
SystemNavigation default
  browseMessageList: (class withAllSubclasses gather: [:each |
    each methodDict associations
      select: [:assoc | assoc value sendsToSuper]
      thenCollect: [:assoc | MethodReference class: each
                                              selector: assoc key]])
  name: 'Supersends of ' , class name , ' and its subclasses'
```



```
WordArray>>*
WordArray>>/
RunArray>>postCopy
Array>>printOn:
Array>>settingStoreOn:
Array>>storeOn:
Array>>objectForDataStream:
Array>>replaceFrom:to:with:startingAt:
```

```
printOn: aStream
    self isLiteral ifTrue: [self printAsLiteralFormOn: aStream. ^ self].
    self isSelfEvaluating ifTrue: [self printAsSelfEvaluatingFormOn: aStream. ^ self].

    super printOn: aStream
```

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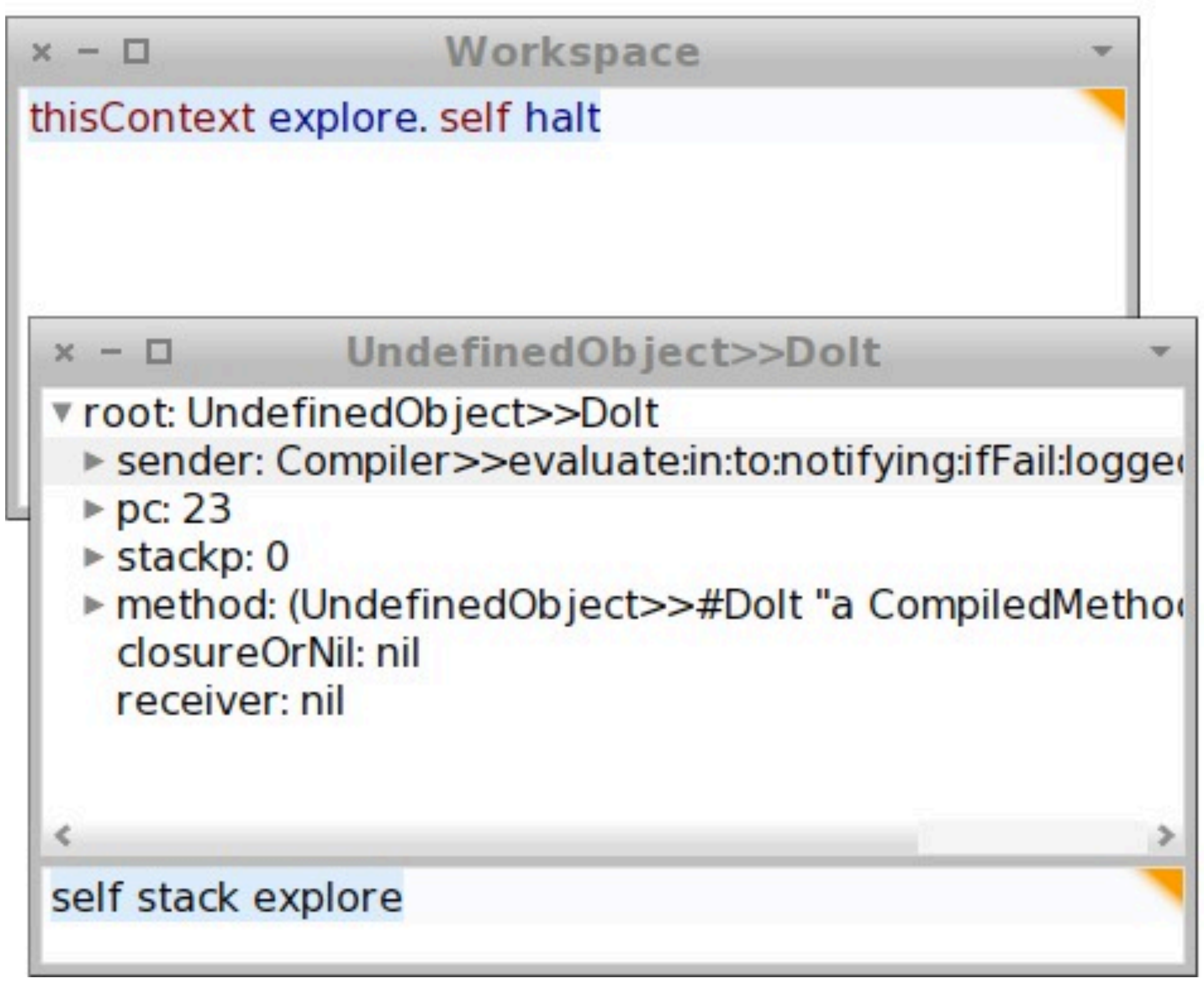
Accessing the run-time stack

> The execution stack can be *reified* and *manipulated* on demand

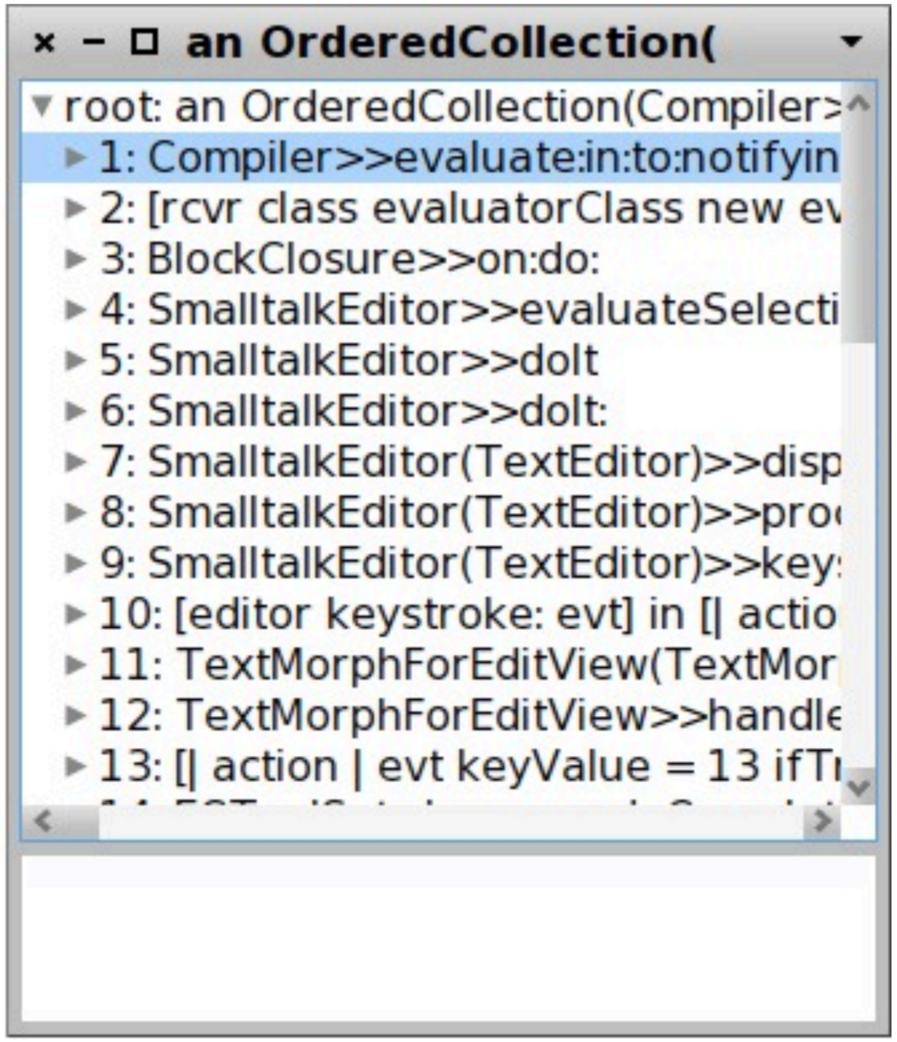
– `thisContext` is a pseudo-variable which gives access to the stack



```
thisContext explore. self halt
```

```
▼ root: UndefinedObject>>DoIt
  ▶ sender: Compiler>>evaluate:in:to:notifying:ifFail:logge
  ▶ pc: 23
  ▶ stackp: 0
  ▶ method: (UndefinedObject>>#DoIt "a CompiledMetho
    closureOrNil: nil
    receiver: nil
```

```
self stack explore
```



```
▼ root: an OrderedCollection(Compiler>
  ▶ 1: Compiler>>evaluate:in:to:notifyin
  ▶ 2: [rcvr class evaluatorClass new ev
  ▶ 3: BlockClosure>>on:do:
  ▶ 4: SmalltalkEditor>>evaluateSelecti
  ▶ 5: SmalltalkEditor>>doIt
  ▶ 6: SmalltalkEditor>>doIt:
  ▶ 7: SmalltalkEditor(TextEditor)>>disp
  ▶ 8: SmalltalkEditor(TextEditor)>>pro
  ▶ 9: SmalltalkEditor(TextEditor)>>key
  ▶ 10: [editor keystroke: evt] in [| actio
  ▶ 11: TextMorphForEditView(TextMor
  ▶ 12: TextMorphForEditView>>handle
  ▶ 13: [| action | evt keyValue = 13 ifTr
```

What happens when a method is executed?

- > We need space for:
  - — The temporary variables
  - — Remembering where to return to
- > Everything is an Object!
  - — So: we model this space with objects
  - — Class MethodContext

```
ContextPart variableSubclass: #MethodContext
   instanceVariableNames: 'method closureOrNil receiver'
   classVariableNames: ''
   poolDictionaries: ''
   category: 'Kernel-Methods'
```

MethodContext

- MethodContext holds all state associated with the execution of a CompiledMethod
  - Program Counter (pc, from ContextPart)
  - the Method itself (method)
  - Receiver (receiver) and the Sender (sender)

- The sender is the previous MethodContext
  - (or BlockContext)
  - The *chain of senders* is a stack
  - It grows and shrinks on activation and return

Contextual halting

> You can’t put a halt in methods that are called often

— e.g., `OrderedCollection>>add:`

— *Idea:* only halt if called from a method with a certain name

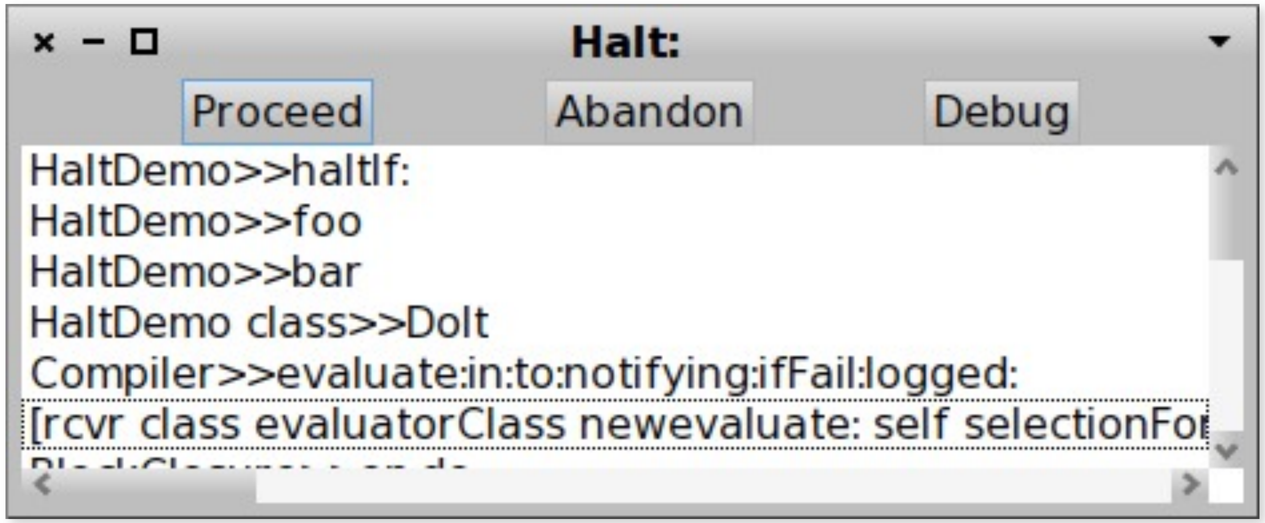
```
HaltDemo>>haltIf: aSelector
   | context |
   context := thisContext.
   [context sender isNil]
      whileFalse:
         [context := context sender.
         (context selector = aSelector)
         ifTrue: [ Halt signal ] ].
```

NB: Object>>haltIf: in Pharo is similar

HaltDemo

```
HaltDemo>>foo
   self haltIf: #bar.
   ^ 'foo'

HaltDemo>>bar
   ^ (self foo), 'bar'
```



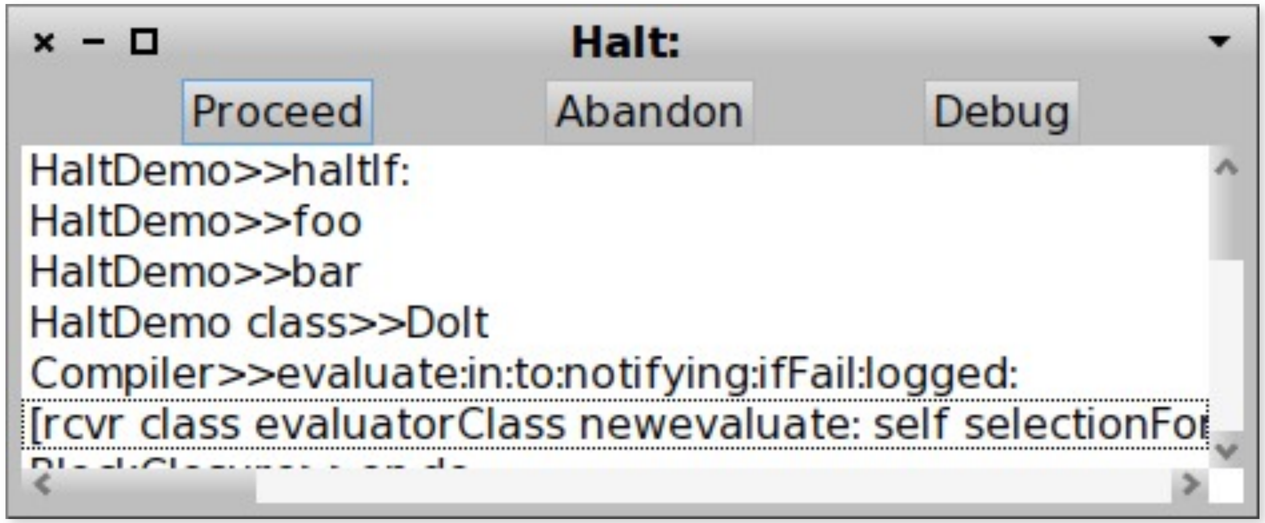
```
HaltDemo>>haltIf:
HaltDemo>>foo
HaltDemo>>bar
HaltDemo class>>DoIt
Compiler>>evaluate:in:to:notifying:ifFail:logged:
[rcvr class evaluatorClass newevaluate: self selectionFor
```

HaltDemo

```
HaltDemo>>foo
   self haltIf: #bar.
   ^ 'foo'

HaltDemo>>bar
   ^ (self foo), 'bar'
```

```
HaltDemo new foo
```



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HaltDemo>>foo
HaltDemo>>bar
HaltDemo class>>DoIt
Compiler>>evaluate:in:to:notifying:ifFail:logged:
[rcvr class evaluatorClass newevaluate: self selectionFor
BlockClosure>>on:do:
```

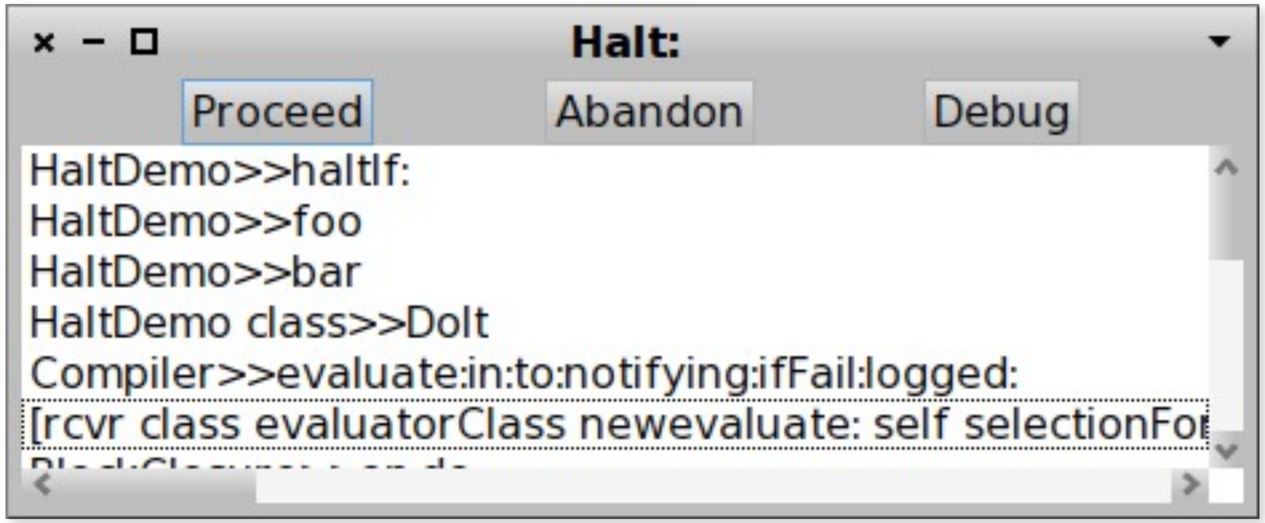
HaltDemo

```
HaltDemo>>foo
   self haltIf: #bar.
   ^ 'foo'

HaltDemo>>bar
   ^ (self foo), 'bar'
```

```
HaltDemo new foo
```

```
'foo'
```



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```

HaltDemo

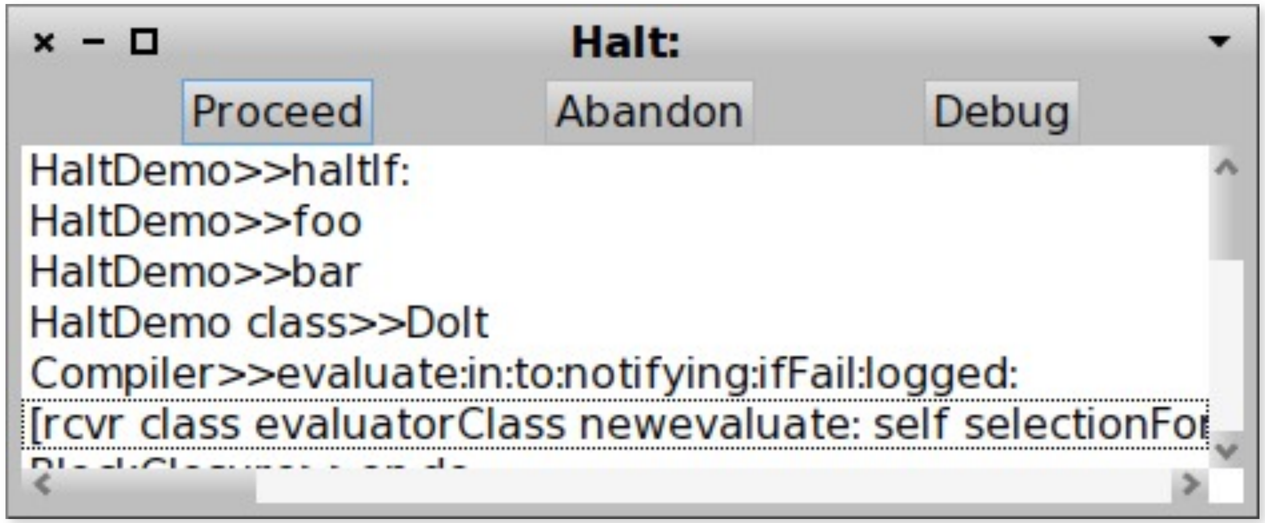
```
HaltDemo>>foo
   self haltIf: #bar.
   ^ 'foo'

HaltDemo>>bar
   ^ (self foo), 'bar'
```

```
HaltDemo new foo
```

'foo'

```
HaltDemo new bar
```



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HaltDemo class>>DoIt
Compiler>>evaluate:in:to:notifying:ifFail:logged:
[rcvr class evaluatorClass newevaluate: self selectionFor
```

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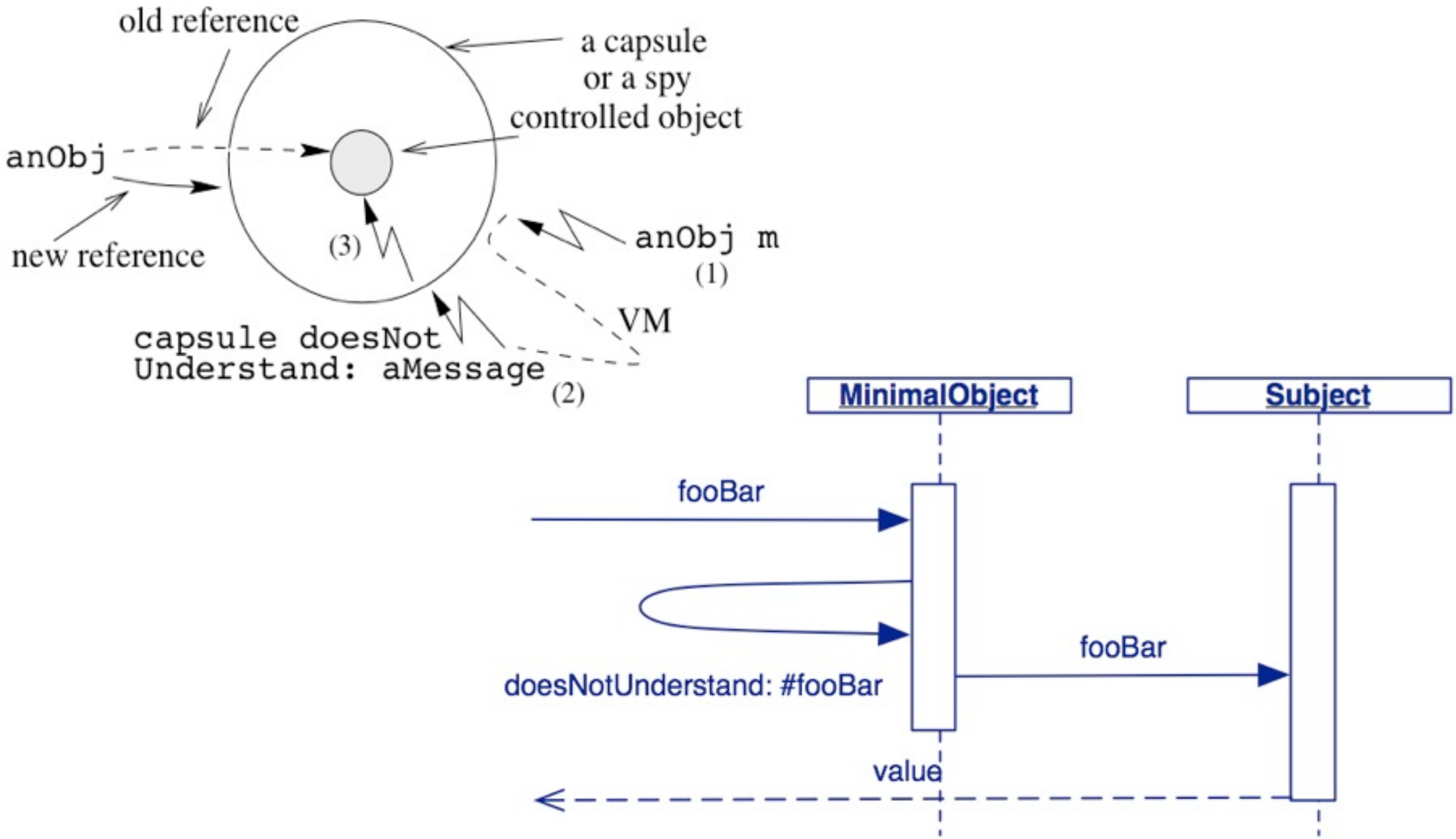
Overriding doesNotUnderstand:

> Introduce a *Minimal Object*
  - Wraps a normal object
  - Does not understand very much
  - Redefines `doesNotUnderstand:`
  - Superclass is `nil` or `ProtoObject`
  - Uses `becomeForward:` to substitute the object to control

Minimal Object at Work



Logging message sends with a minimal object

```
ProtoObject subclass: #LoggingProxy
   instanceVariableNames: 'subject invocationCount'
   classVariableNames: ''
   poolDictionaries: ''
   category: 'PBE-Reflection'
```

```
LoggingProxy>>initialize
   invocationCount := 0.
   subject := self.
```

```
LoggingProxy>>doesNotUnderstand: aMessage
   Transcript show: 'performing ', aMessage printString; cr.
   invocationCount := invocationCount + 1.
   ^ aMessage sendTo: subject
```

```
Message>>sendTo: receiver
   ^ receiver perform: selector withArguments: args
```

Using become: to install a proxy

```
testDelegation
   | point |
   point := 1@2.
   LoggingProxy new become: point.
   self assert: point invocationCount = 0.
   self assert: point + (3@4) = (4@6).
   self assert: point invocationCount = 1.
```

NB: `become:` will swap the `subject` variable of the proxy

Limitations

- self problem
  - Messages sent by the object to itself are not trapped!
- Class control is impossible
  - Can’t swap classes
- Interpretation of minimal protocol
  - What to do with messages that are understood by both the MinimalObject and its subject?

Using minimal objects to dynamically generate code

```
DynamicAccessors>>doesNotUnderstand: aMessage
  | messageName |
  messageName := aMessage selector asString.
  (self class instVarNames includes: messageName)
    ifTrue: [self class compile:
              messageName , String cr , ' ^ '
                          , messageName.
       ^ aMessage sendTo: self].
  super doesNotUnderstand: aMessage
```

A minimal object can be used to dynamically generate or lazily load code that does not yet exist.

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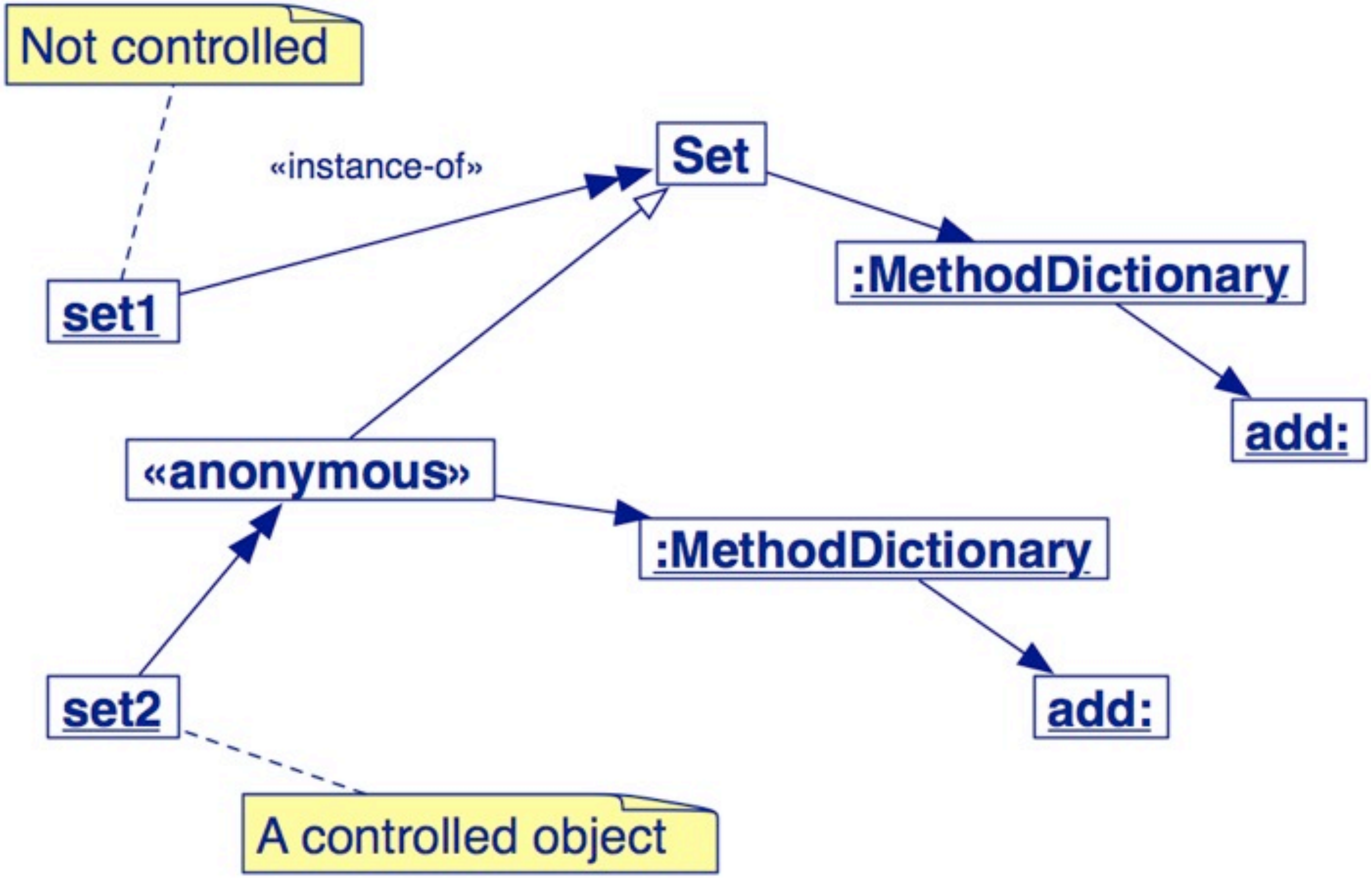
Message control with anonymous classes

> Create an *anonymous class*
  - Instance of Behavior
  - Define controlling methods
  - Interpose it between the instance and its class

Selective control



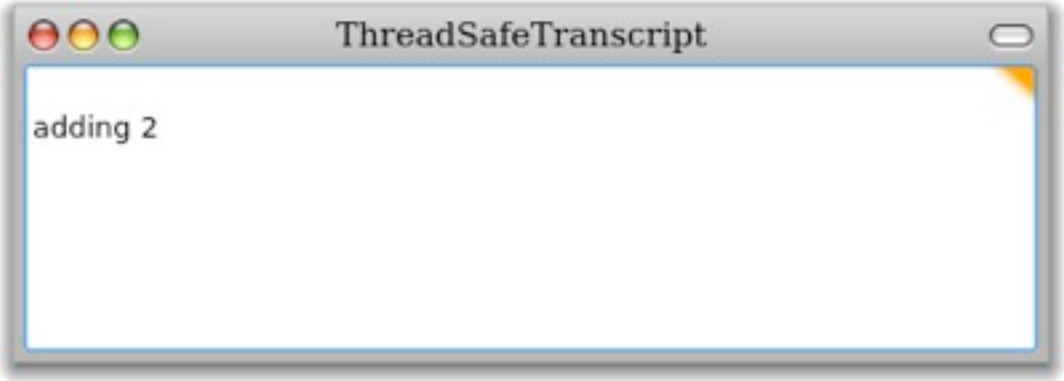
Anonymous class in Pharo

```
| anonClass set |
anonClass := Behavior new.
anonClass superclass: Set;
   setFormat: Set format.

anonClass compile:
   'add: anObject
      Transcript show: ''adding '', anObject printString; cr.
      ^ super add: anObject'.

set := Set new.
set add: 1.

set primitiveChangeClassTo: anonClass basicNew.
set add: 2.
```



```
adding 2
```

Evaluation

- Either instance-based or group-based
- Selective control
- No self-send problem
- Good performance
- Transparent to the user
- Requires a bit of compilation
  - (could be avoided using clone as in Method Wrapper)

Roadmap

- > Reification and reflection
- > Reflection in Programming Languages
- > Introspection
  - — Inspecting objects
  - — Querying code
  - — Accessing run-time contexts
- > **Intercession**
  - — Overriding doesNotUnderstand:
  - — Anonymous classes
  - — **Method wrappers**

Method Substitution

First approach:

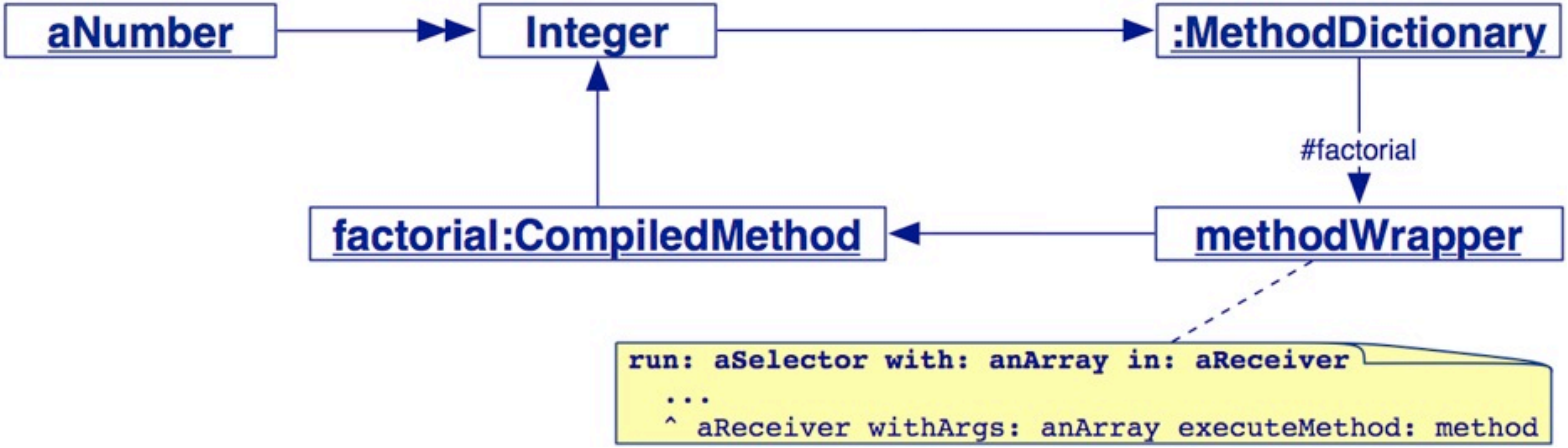
> Add methods with mangled names
- — but the user can see them

Second approach:

> Wrap the methods without polluting the interface
- — replace the method by an object that implements run:with:in:

MethodWrapper before and after methods

A MethodWrapper replaces an original CompiledMethod in the method dictionary of a class and wraps it by performing some before and after actions.



```
run: aSelector with: anArray in: aReceiver
  ...
  ^ aReceiver withArgs: anArray executeMethod: method
```

A LoggingMethodWrapper

```
LoggingMethodWrapper>>initializeOn: aCompiledMethod
   method := aCompiledMethod.
   reference := aCompiledMethod methodReference.
   invocationCount := 0
```

```
LoggingMethodWrapper>>install
   reference actualClass methodDictionary
      at: reference methodSymbol
      put: self
```

`uninstall` is similar …

```
LoggingMethodWrapper>>run: aSelector with: anArray in: aReceiver
   invocationCount := invocationCount + 1.
   ^ aReceiver withArgs: anArray executeMethod: method
```

NB: Duck-typing also requires (empty) `flushCache`, `methodClass:`, and `selector:` methods

Installing a LoggingMethodWrapper

```
logger := LoggingMethodWrapper on:
Integer>>#factorial.

logger invocationCount.     0
5 factorial.
logger invocationCount.     0

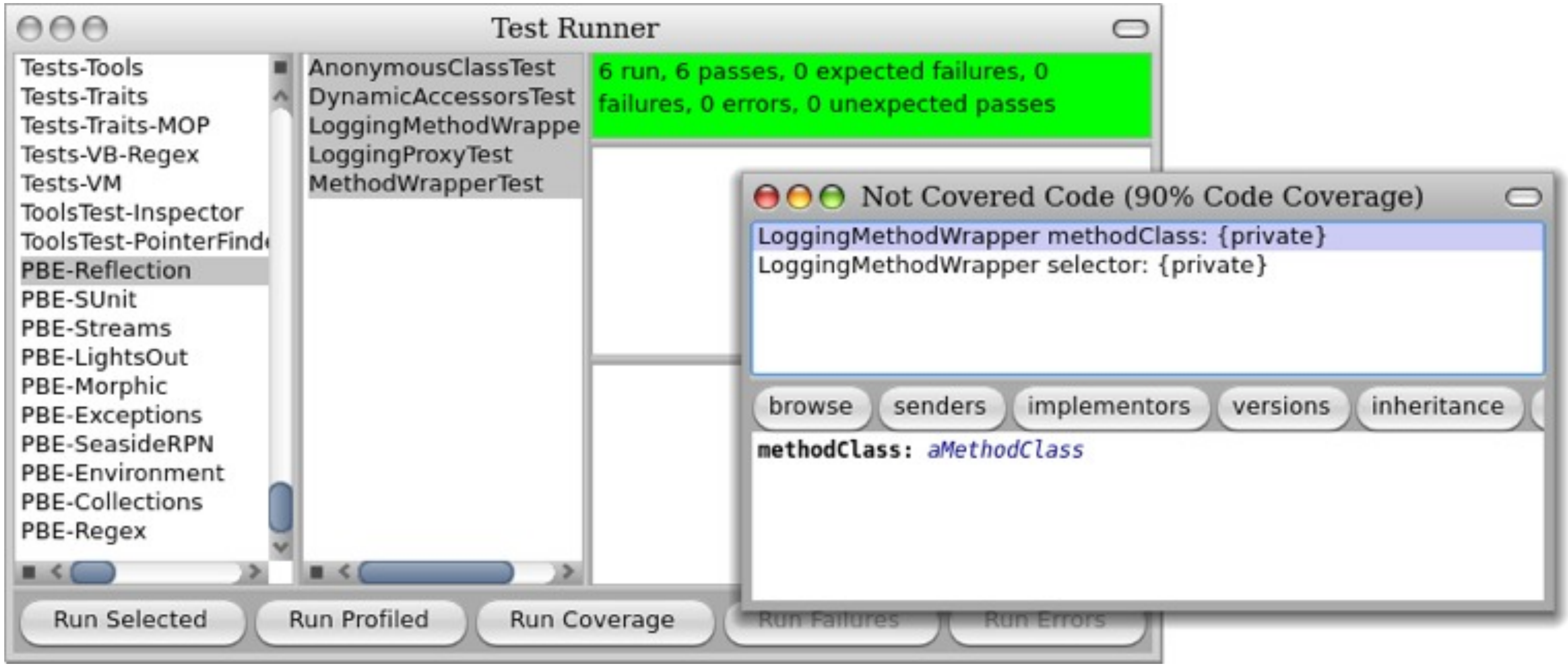
logger install.
[ 5 factorial ] ensure: [logger uninstall].
logger invocationCount.     6

10 factorial.
logger invocationCount.     6
```

Checking Test Coverage

```
TestCoverage>>run: aSelector with: anArray in: aReceiver
   self mark; uninstall.
   ^ aReceiver withArgs: anArray executeMethod: method
```

```
TestCoverage>>mark
   hasRun := true
```



6 run, 6 passes, 0 expected failures, 0 failures, 0 errors, 0 unexpected passes

LoggingMethodWrapper methodClass: {private}
LoggingMethodWrapper selector: {private}

```
methodClass: aMethodClass
```

Evaluation

> Class based:
  - all instances are controlled

> Only known messages intercepted

> A single method can be controlled

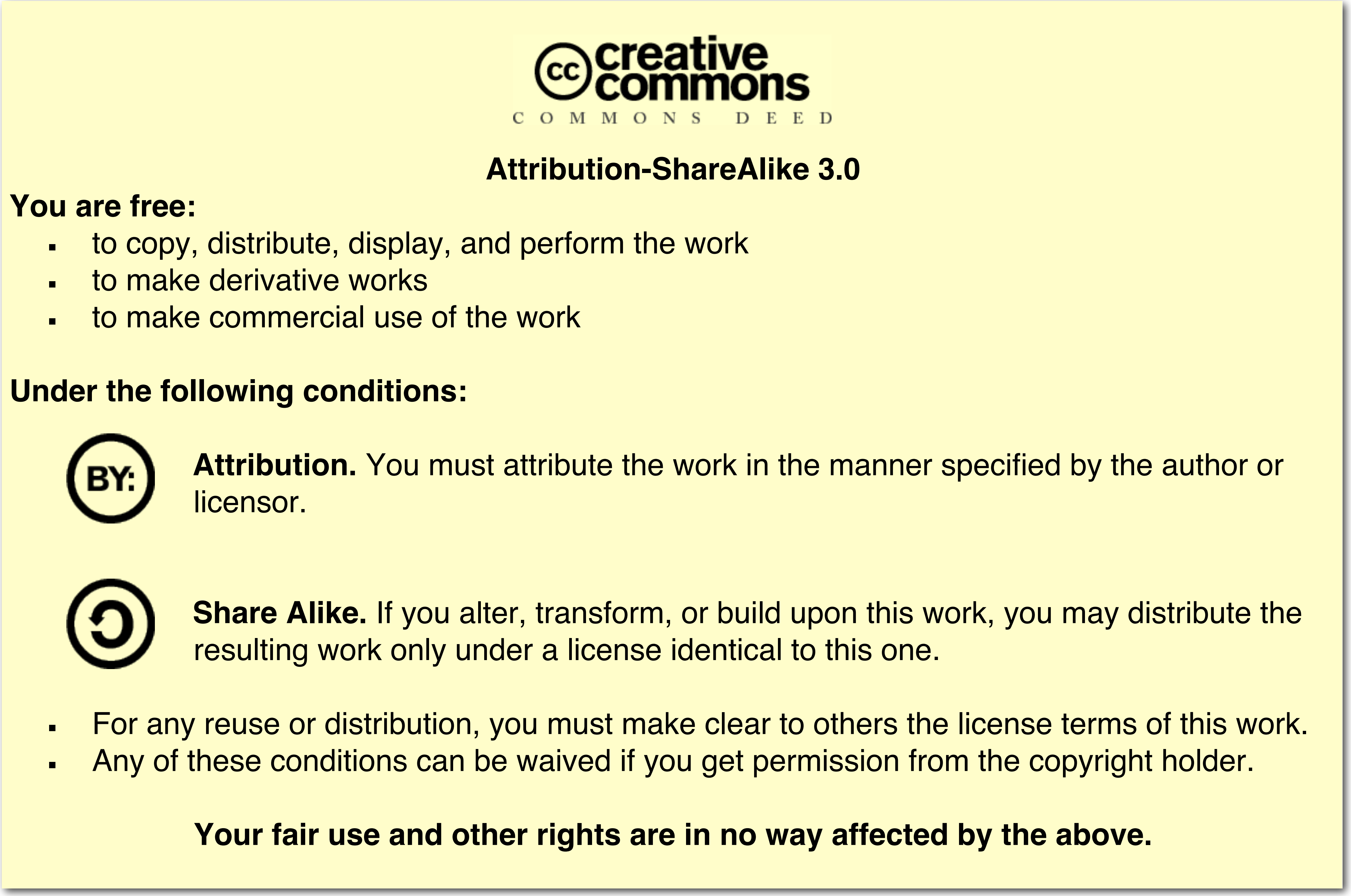
> Does not require compilation for installation/removal

What you should know!

- What is the difference between introspection and intercession?
- What is the difference between structural and Behavioral reflection?
- What is an object? What is a class?
- What is the difference between performing a message send and simply evaluating a method looked up in a MethodDictionary?
- In what way does thisContext represent the run-time stack?
- What different techniques can you use to intercept and control message sends?

Can you answer these questions?

- What form of “reflection” is supported by Java?
- What can you do with a metacircular architecture?
- Why are Behavior and Class different classes?
- What is the class ProtoObject good for?
- Why is it not possible to become: a SmallInteger?
- What happens to the stack returned by thisContext if you proceed from the self halt?
- What is the metaclass of an anonymous class?



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