Computational Reflection and Context-Oriented Programming

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Invited lecture at

Advanced Development Techniques

PhD School in Computer Science
University of Milan

3–9 July 2012

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Main Schedule

1. **Reflection**
   a. Principles — day 1
   b. In Smalltalk — day 2

2. Context-Oriented Programming
   a. Infrastructure — day 3
   b. Adaptation
   c. Composition — day 4
   d. Resolution

Course Schedule

Day	Theory	Practice
Tuesday July 3	Course introduction	
	Basics of reflection	
	Introduction to Smalltalk	
Wednesday July 4	Reflection in Smalltalk	
Thursday July 5	Context-oriented programming Why? What? How?	Infrastructure
		Adaptation
Monday July 9		Composition
		Resolution

Reflection in Smalltalk

* partly based on slides by Roel Wuyts

Reflection (revisited)

- Reflection is the ability of a program to examine and control its own implementation
- Computational reflection is good for
  - extending a language
  - building programming environments
  - advanced software development tools
  - ...
- Smalltalk offers some interesting reflective capabilities :
  - `Object`, classes and metaclasses

Reflection in Smalltalk : classes

! Classes in Smalltalk are **first-class values**

- **Point of reflection** to reason about objects
- **Group objects** with identical behaviour
  - Method `#allInstances` returns all instances of a given class
    - `Transcript class allInstances`
- "**Factory**" for creating instances
  - Contain the instance creation methods (constructors)
- Describes the implementation of a set of objects
  - Contain methods for reasoning about that implementation
    - `#compiledMethodAt:`
    - `#instVarNames`
    - `#compile:classified:notifying:`

Reflection in Smalltalk : classes

Introspection

- Retrieve all instances of a class

```
Transcript class
    ➡ ThreadSafeTranscript

(ThreadSafeTranscript allInstances at: 1) == Transcript
    ➡ true
```

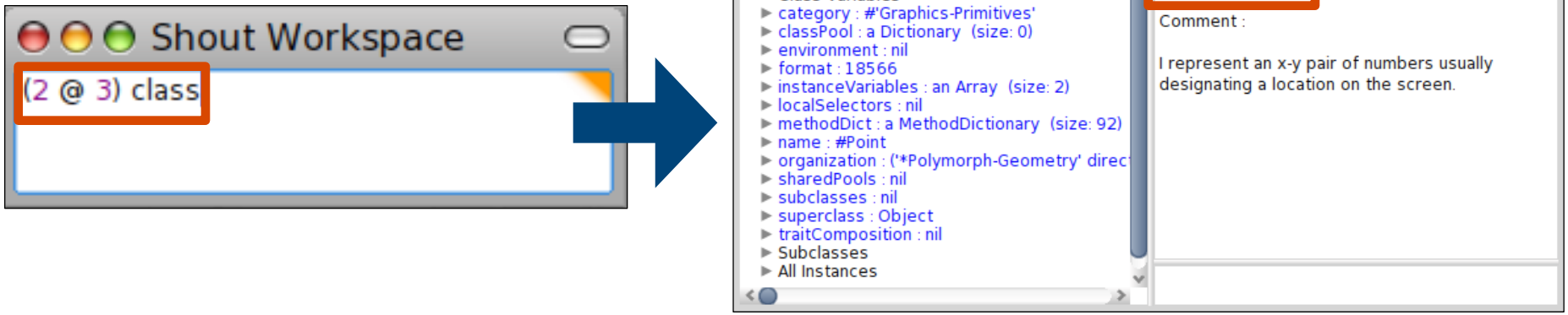
- In the above case:
  - **`Transcript`** is one of the instances of class **`ThreadSafeTranscript`**

Reflection in Smalltalk : classes

Introspection

- Asking an instance to what class it belongs

```
(2@3) class
    ➡ Point
```



Reflection in Smalltalk : classes

Introspection

- Inspecting the implementation details of a class:
  - names of instance variables defined by class

```
OrderedCollection instVarNames
    ➡ #('array' 'firstIndex' 'lastIndex')
```

  - names of methods implemented by class

```
OrderedCollection selectors
    ➡ #(#copyFrom:to: #with:collect: #grow #addAll: ...)
```

  - method with a given selector

```
OrderedCollection compiledMethodAt: #size
  ➡ answers the compiled method associated with the message
    selector #size in the method dictionary of the class
    OrderedCollection
```

  - source code of method with a given selector

```
(OrderedCollection compiledMethodAt: #size) getSource
    ➡ gets the source code of the method named #size on class
      OrderedCollection
```

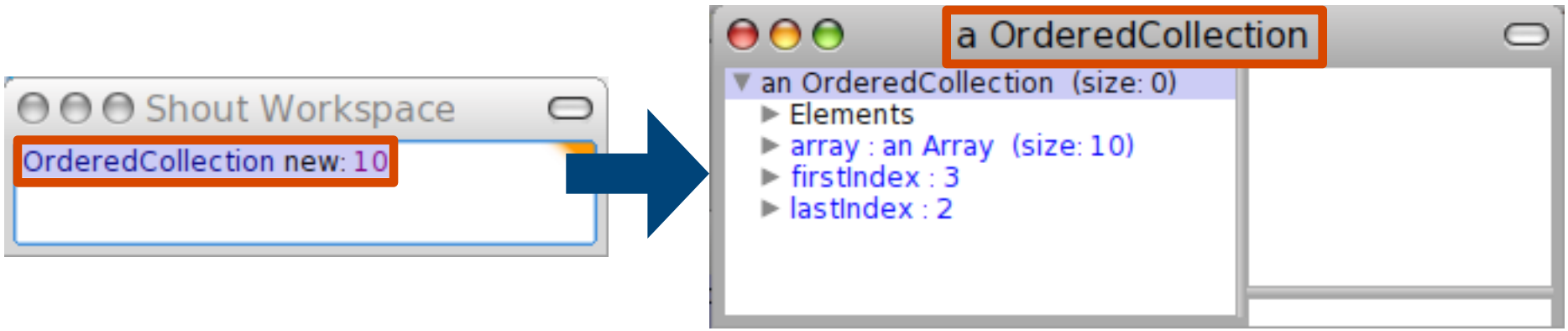
Reflection in Smalltalk : classes

Intercession

- Creating a new instance of a class

```
OrderedCollection new: 10
```

- Creates a new instance of OrderedCollection, with size 10



Reflection in Smalltalk : classes

Intercession

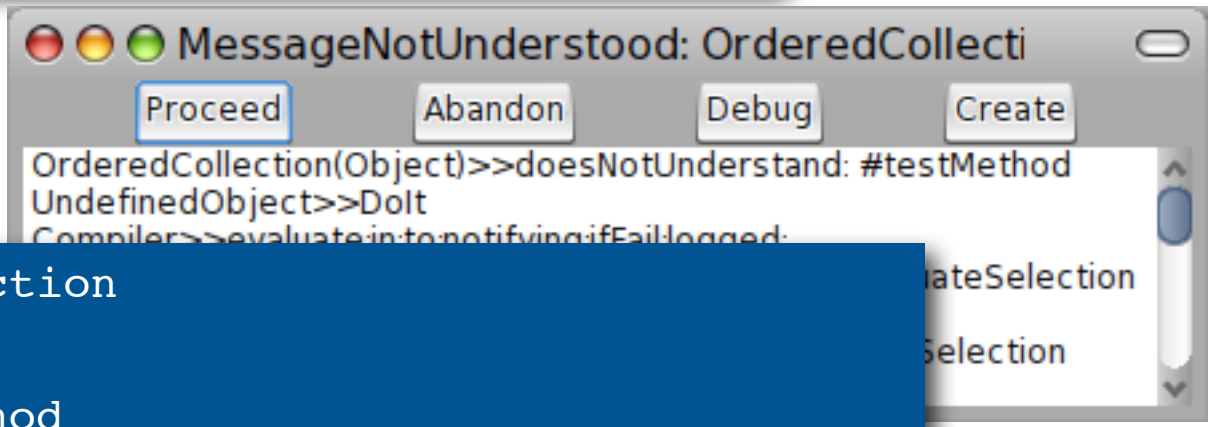
- Dynamically adding a new method to some class:

```
<class> compile: <text> classified: <category>
```

- Try this first:

```
#(1 2) asOrderedCollection testMethod
```

➡results in "method not understood" error



- Example:

```
OrderedCollection
 compile:
    'testMethod
        Transcript show: ''it worked...'' '
 classified: 'testing'
```

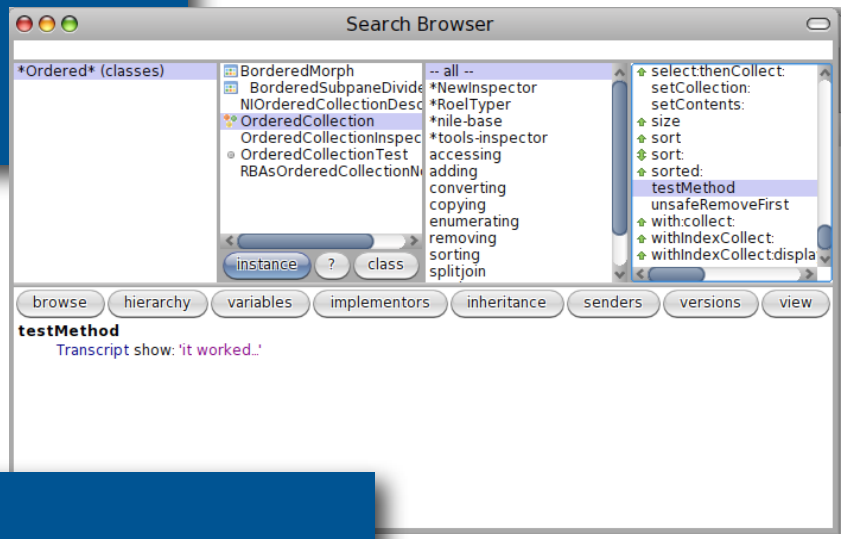
Reflection in Smalltalk : classes

Intercession

- Try it:

```
#(1 2) asOrderedCollection
    testMethod
```

➡ prints "it worked..." on the transcript



- To remove the method again:

```
OrderedCollection
    removeSelector: #testMethod
```

Reflection (revisited)

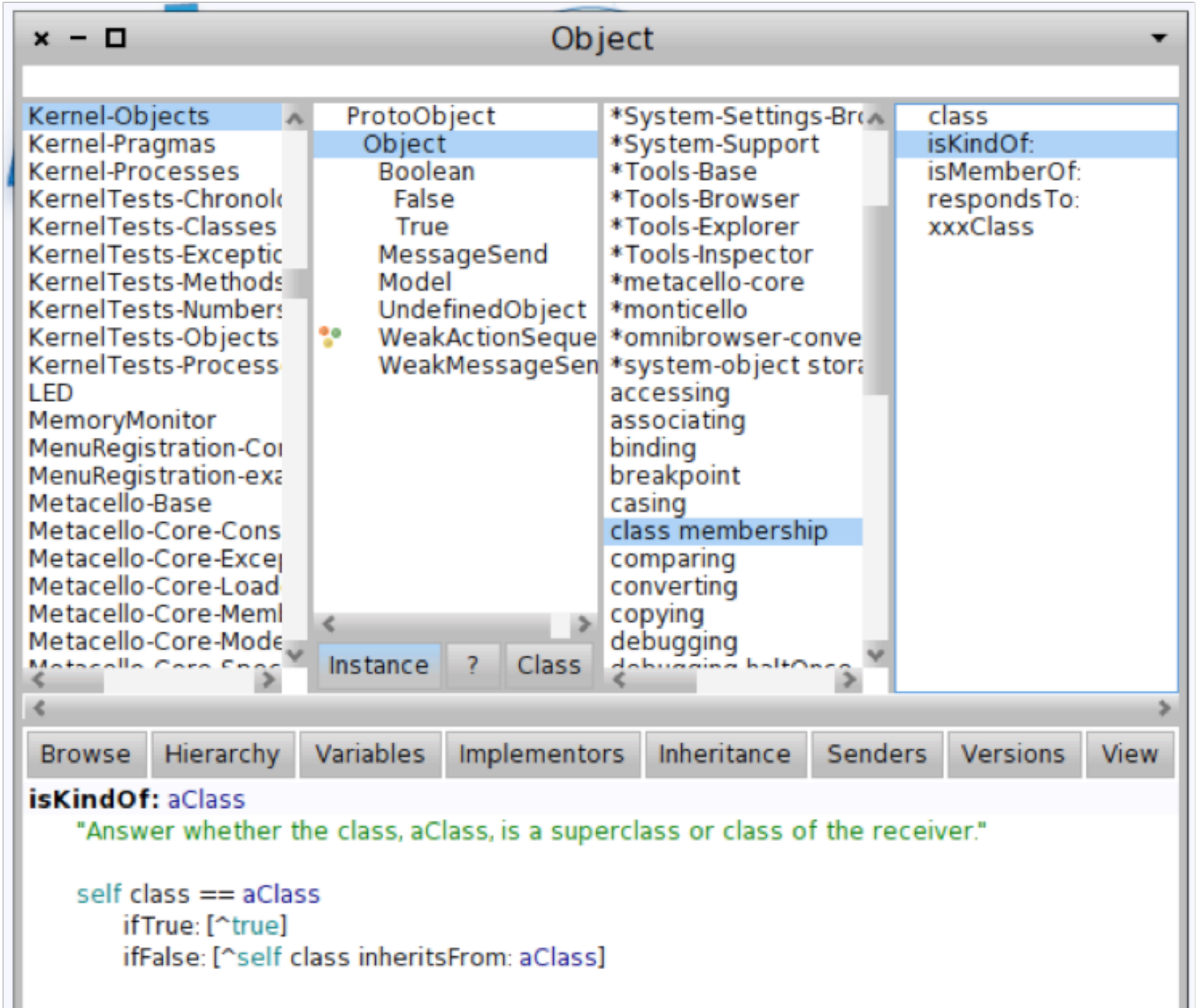
- Reflection is the ability of a program to examine and control its own implementation
- Computational reflection is good for
  - extending a language
  - building programming environments
  - advanced software development tools
  - ...
- Smalltalk offers some interesting reflective capabilities :
  - `Object`, classes and metaclasses

Reflection in Smalltalk
A particular class : `Object`

- is a class that models all instances
  - Every object is (indirectly) an instance of class `Object`
  - as in Java
- provides some methods to reason about instances
  - Understood by all instances (regardless their class)
    - `#basicSize` gives number of instance variables of any object
    - `#instVarAt:` and `#instVarAt:put:` access any instance variable

```
2@3 instVarAt: 1 put: 42 ; yourself
➡ 42@3
```

    - e.g., used by inspector
- all classes subclass from `Object`
  - and thus inherit these introspective methods

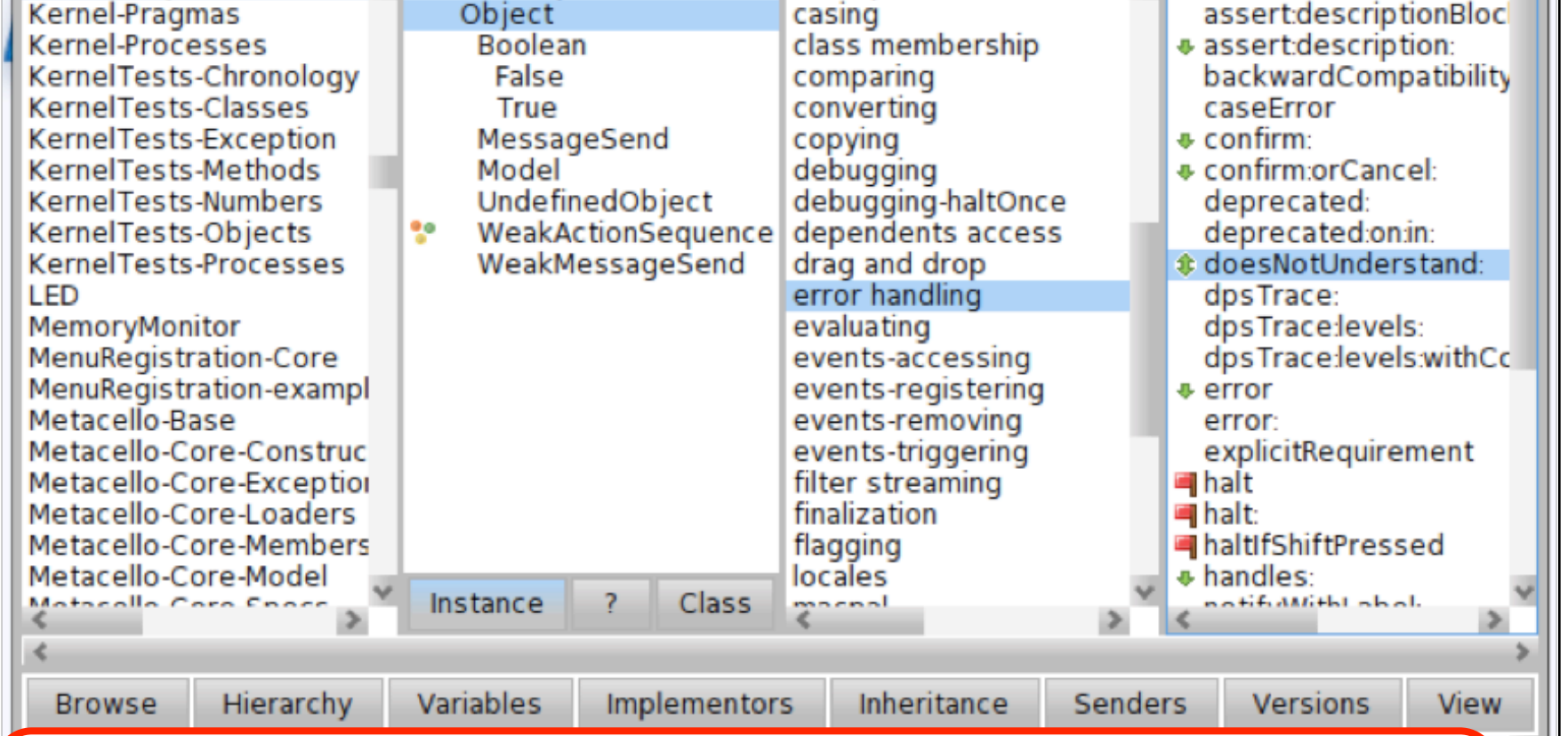

Object
Kernel-Objects
Kernel-Pragmas
Kernel-Processes
KernelTests-Chronol
KernelTests-Classes
KernelTests-Exceptic
KernelTests-Methods
KernelTests-Numbers
KernelTests-Objects
KernelTests-Process
LED
MemoryMonitor
MenuRegistration-Co
MenuRegistration-exa
Metacello-Base
Metacello-Core-Cons
Metacello-Core-Excep
Metacello-Core-Load
Metacello-Core-Meml
Metacello-Core-Mode
ProtoObject
Object
Boolean
False
True
MessageSend
Model
UndefinedObject
WeakActionSeque
WeakMessageSen
Instance
?
Class
*System-Settings-Br
*System-Support
*Tools-Base
*Tools-Browser
*Tools-Explorer
*Tools-Inspector
*metacello-core
*monticello
*omnibrowser-conve
*system-object stora
accessing
associating
binding
breakpoint
casing
class membership
comparing
converting
copying
debugging
class
isKindOf:
isMemberOf:
respondsTo:
xxxClass
Browse
Hierarchy
Variables
Implementors
Inheritance
Senders
Versions
View
isKindOf: aClass
"Answer whether the class, aClass, is a superclass or class of the receiver."
self class == aClass
ifTrue: [^true]
ifFalse: [^self class inheritsFrom: aClass]

#doesNotUnderstand:

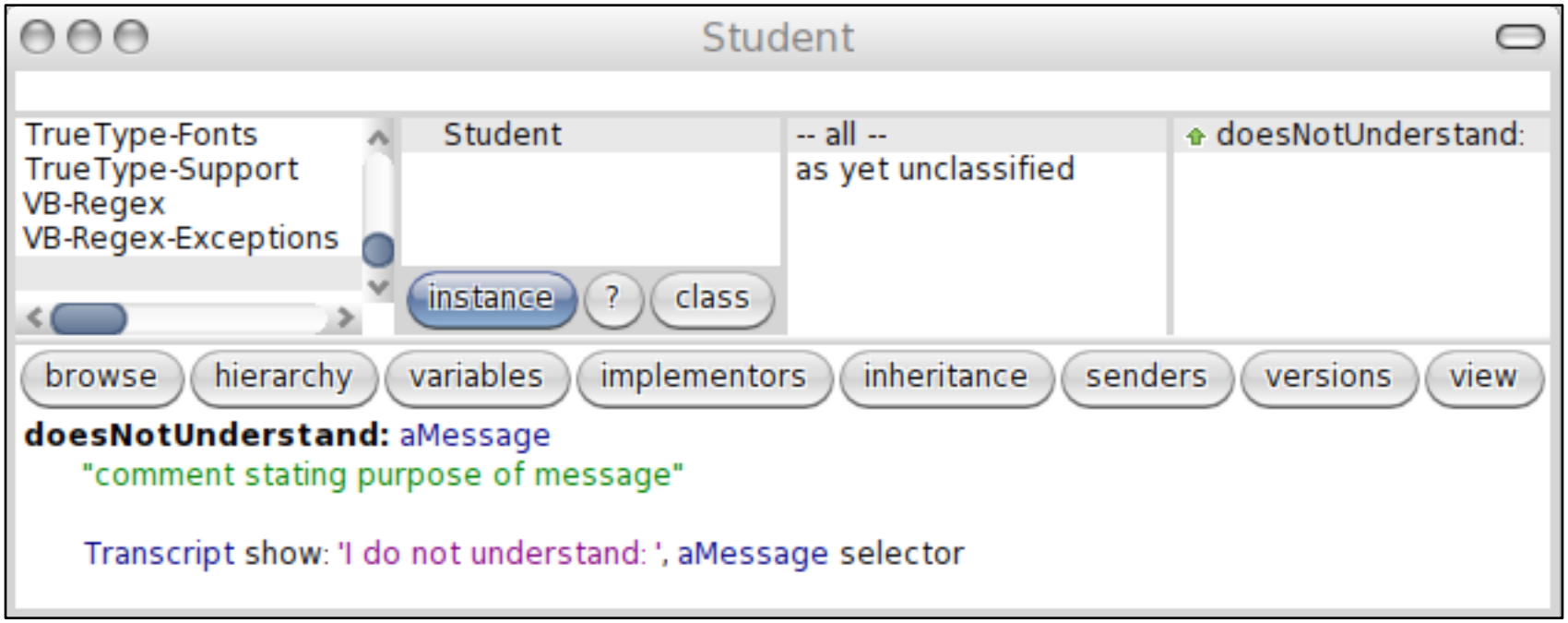
Intercession

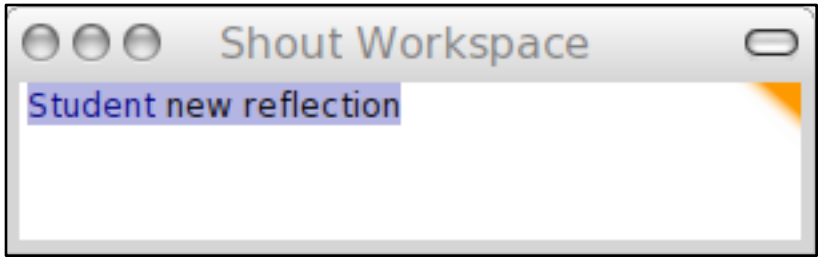
- Ability to intervene in method lookup mechanism
- Hook implemented by Smalltalk VM
  - Message `#doesNotUnderstand:` sent by VM to an object when a message is not understood by that object
  - Standard behaviour (defined on `Object`): error message!

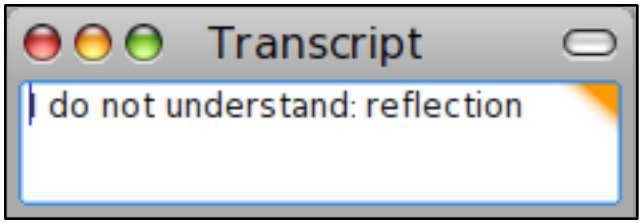
- Mechanism to report type errors in dynamically typed Smalltalk language
  - Powerful: you can customize it!


Kernel-Pragmas
Kernel-Processes
KernelTests-Chronology
KernelTests-Classes
KernelTests-Exception
KernelTests-Methods
KernelTests-Numbers
KernelTests-Objects
KernelTests-Processes
LED
MemoryMonitor
MenuRegistration-Core
MenuRegistration-exampl
Metacello-Base
Metacello-Core-Construc
Metacello-Core-Exceptio
Metacello-Core-Loaders
Metacello-Core-Members
Metacello-Core-Model
Object
Boolean
False
True
MessageSend
Model
UndefinedObject
WeakActionSequence
WeakMessageSend
Instance
?
Class
casing
class membership
comparing
converting
copying
debugging
debugging-haltOnce
dependents access
drag and drop
error handling
evaluating
events-accessing
events-registering
events-removing
events-triggering
filter streaming
finalization
flagging
locales
assert:descriptionBloc
assert:description:
backwardCompatibility
caseError
confirm:
confirm:orCancel:
deprecated:
deprecated:on:in:
doesNotUnderstand:
dpsTrace:
dpsTrace:levels:
dpsTrace:levels:withCc
error
error:
explicitRequirement
halt
halt:
haltIfShiftPressed
handles:
Browse
Hierarchy
Variables
Implementors
Inheritance
Senders
Versions
View
doesNotUnderstand: aMessage
"Handle the fact that there was an attempt to send the given message to the receiver but the receiver does not understand this message (typically sent from the machine when a message is sent to the receiver and no method is defined for that selector)."
"Testing: (3 activeProcess)"
"fixed suggested by Eliot miranda to make sure
[Object new blah + 1]
on: MessageNotUnderstood
do: [:e | e resume: 1] does not loop indefinitively"
| exception resumeValue |
(exception := MessageNotUnderstood new)
message: aMessage;
receiver: self.

Example


Student
TrueType-Fonts
TrueType-Support
VB-Regex
VB-Regex-Exceptions
Student
instance
?
class
-- all --
as yet unclassified
doesNotUnderstand:
browse
hierarchy
variables
implementors
inheritance
senders
versions
view
doesNotUnderstand: aMessage
"comment stating purpose of message"
Transcript show: 'I do not understand: ', aMessage selector


Shout Workspace
Student new reflection


Transcript
I do not understand: reflection

Reflection (revisited)

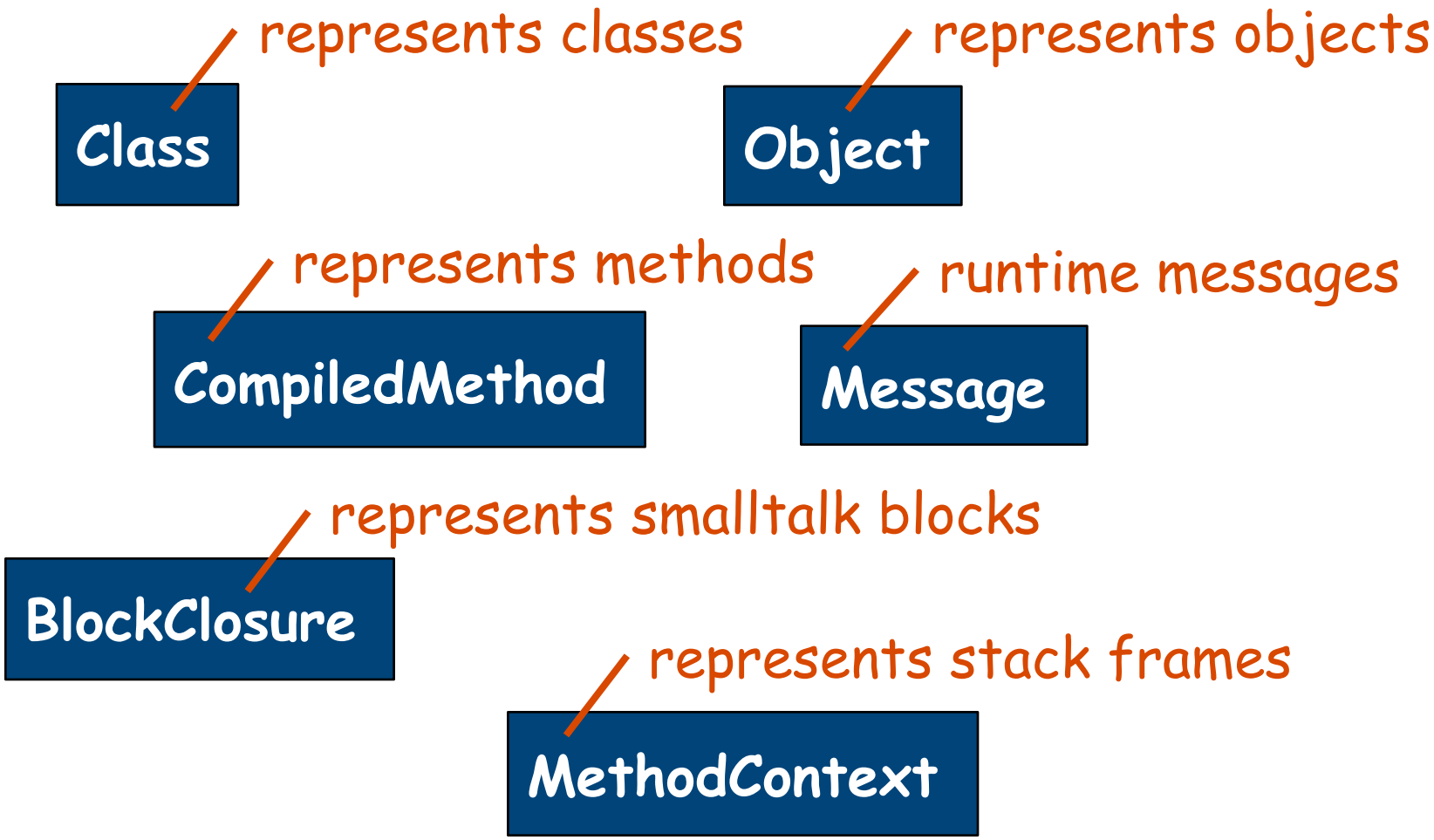
- Reflection is the ability of a program to examine and control its own implementation
- Computational reflection is good for
  - extending a language
  - building programming environments
  - advanced software development tools
  - ...
- Smalltalk offers some interesting reflective capabilities :
  - `Object`, classes and metaclasses

MOP: Reflection in Smalltalk

- **M**eta **O**bject **P**rotocol
  - In Smalltalk, everything is an **object** and objects communicate using **messages.**
  - The meta/reflective protocol also uses objects

- We have already seen some part of the MOP
  - Examples on the previous slides
  - More to come...

Some example meta-objects



Metaclass Mystery

- Assumption
  - Everything is an object
  - Every object has a class
- Conclusion
  - A class is an object
  - A class has a class
- Mystery
  - But what is the class of a class?

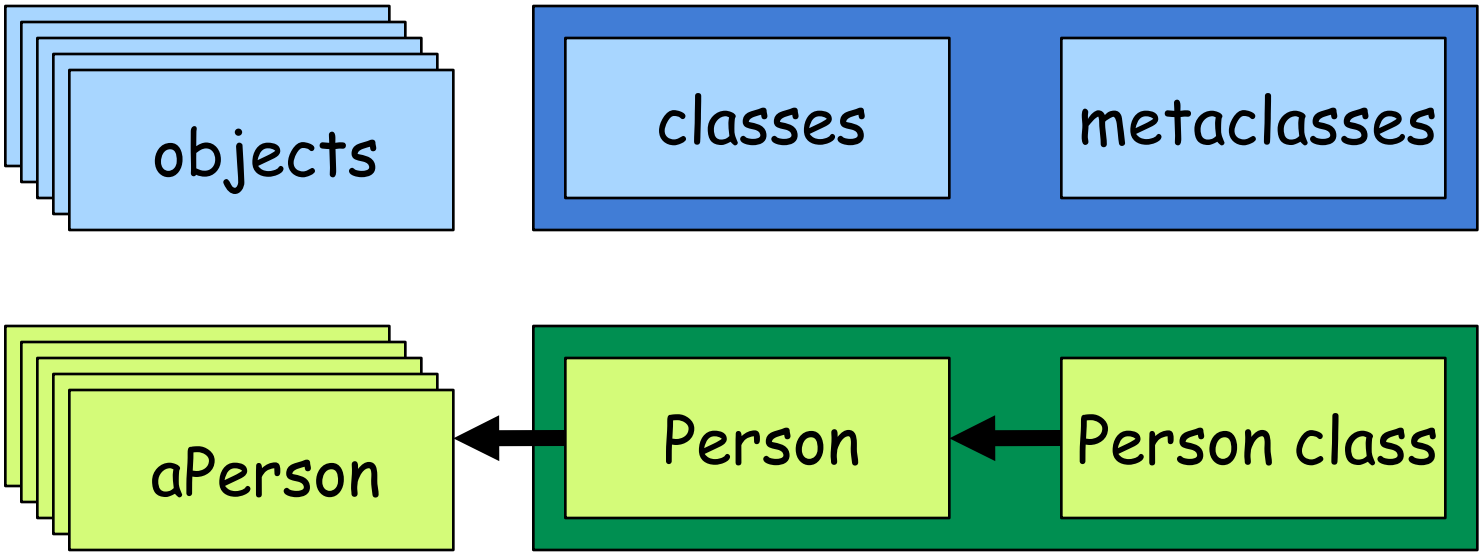
```
2@3
```
➡ an instance (a point)

```
(2@3) class
```
➡ a class `(Point)`

```
(2@3) class class
```
➡ a metaclass

Classes and meta classes

- Objects are instances of a class
- Classes are instances of meta classes
- Each class is the **sole** instance of a meta class
  (is a convention - Singleton design pattern)
- Meta classes describe class behaviour and state (subclasses, method dictionary, etc.)

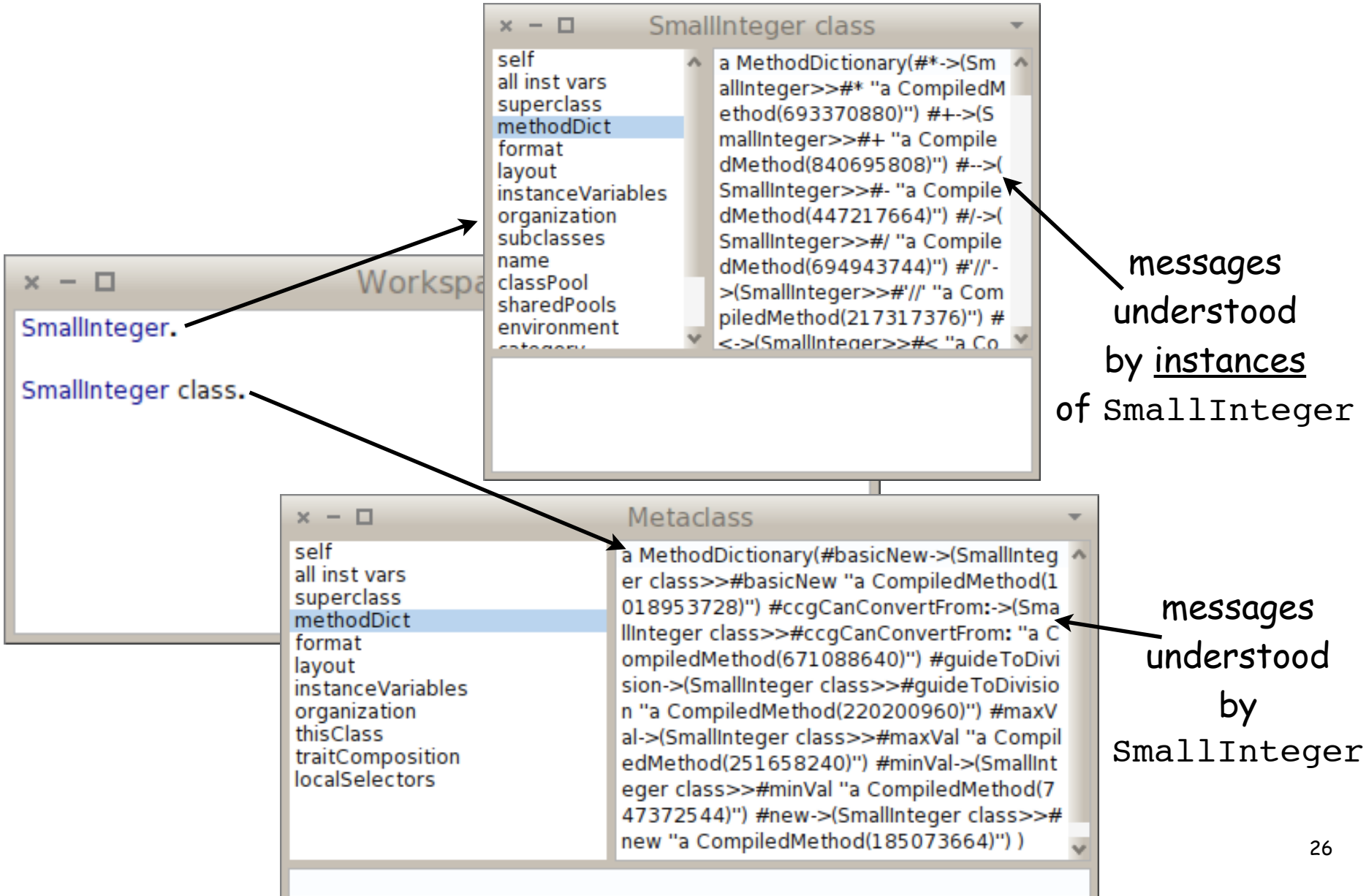


Reflection in Smalltalk : metaclasses

- The class of a class is a metaclass.
- The metaclass of `SmallInteger` is `SmallInteger class`
- The name of `SmallInteger class` is `'SmallInteger class'`

```
1 class
   ➡ SmallInteger
1 class class
   ➡SmallInteger class
SmallInteger class name = 'SmallInteger class'
   ➡ true
```

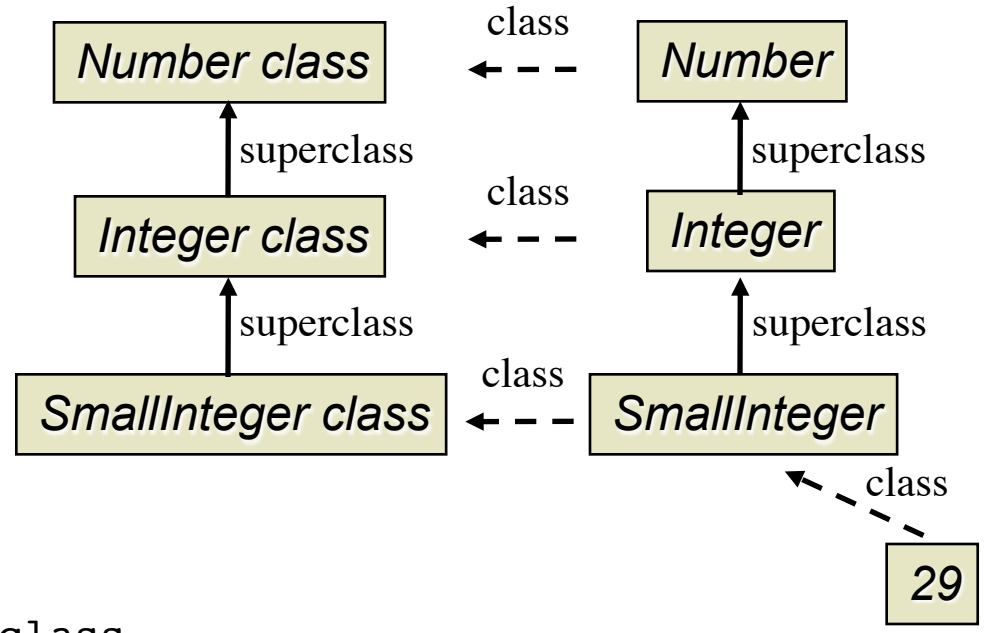
Reflection in Smalltalk : metaclasses



messages understood by instances of `SmallInteger`

messages understood by `SmallInteger`

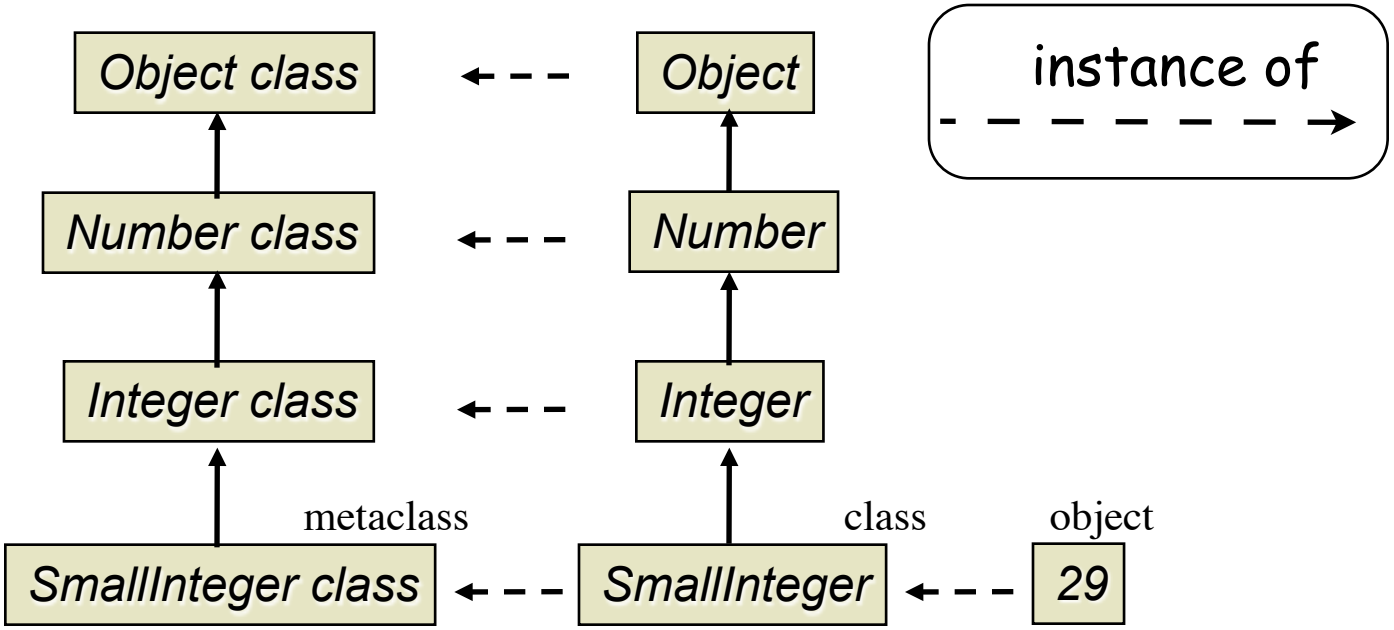
Reflection in Smalltalk : metaclass hierarchy




```
29 class
➡ SmallInteger
SmallInteger superclass
➡ Integer
SmallInteger class superclass
➡ Integer class
SmallInteger superclass superclass
➡ Number
SmallInteger class superclass superclass
➡ Number class
SmallInteger class superclass superclass
   == SmallInteger superclass superclass class
➡ true
```

Reflection in Smalltalk : metaclass hierarchy

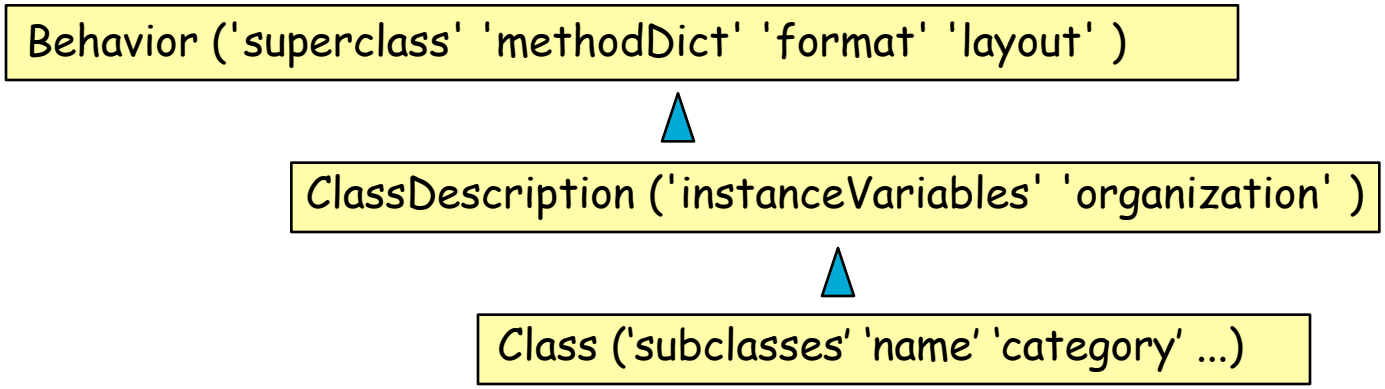
- Metaclasses form a hierarchy that mirrors the regular class hierarchy.
  - This allows subclasses to inherit class methods from superclasses (e.g., instance creation methods)

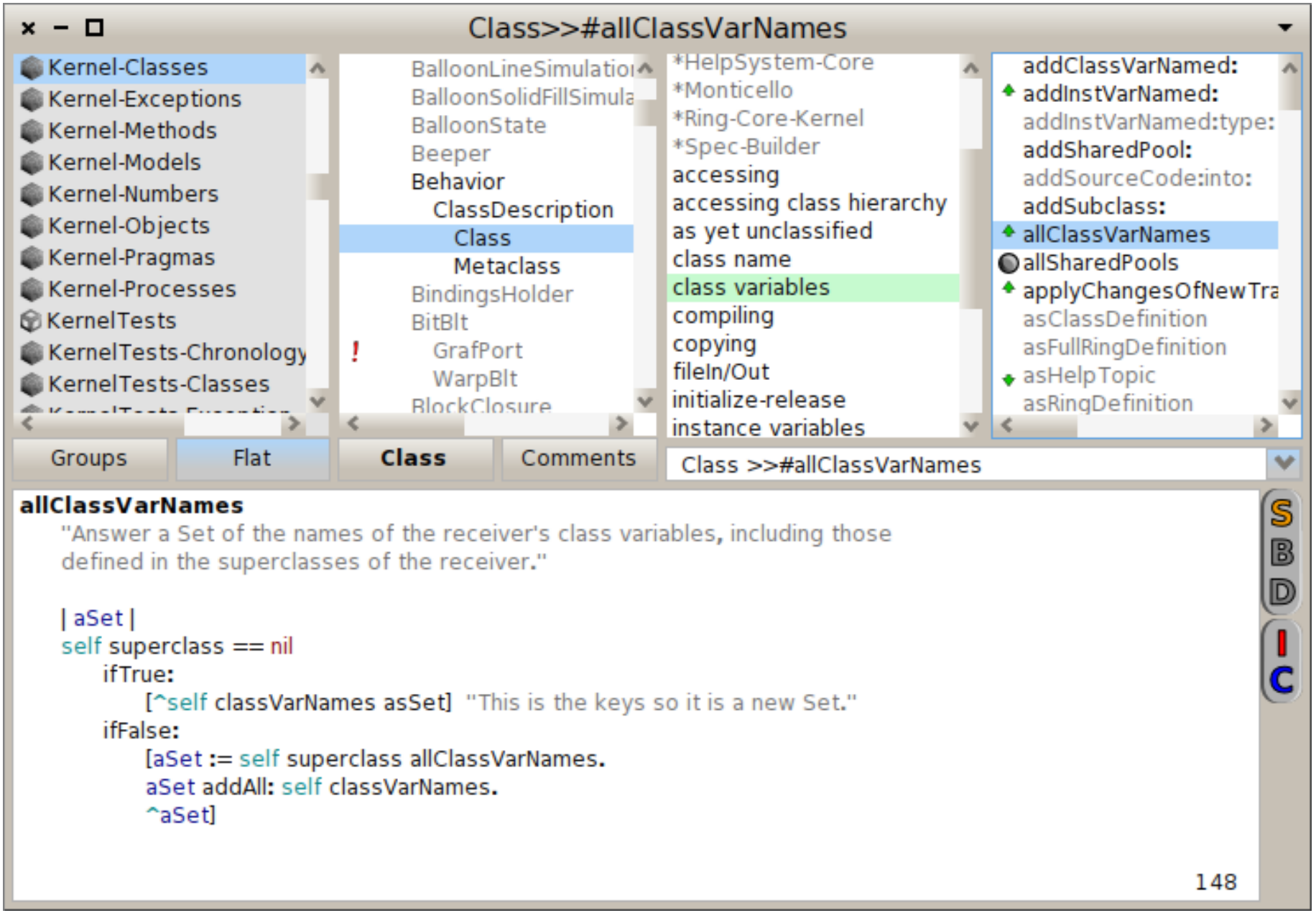


Reflection in Smalltalk
a particular metaclass : `Class`

- Just like `Object` is a class that models all instances,

  `Class` is a class that models all classes
- Provides some methods to reason about classes
  - Understood by all classes
    - **`addSubclass:`** create a subclass of receiver class
    - **`classVarNames:`** answers collection of names of class variables
    - subclasses: answer a set containing the receiver's subclasses
- Class hierarchy:




Class>>#allClassVarNames
Kernel-Classes
Kernel-Exceptions
Kernel-Methods
Kernel-Models
Kernel-Numbers
Kernel-Objects
Kernel-Pragmas
Kernel-Processes
KernelTests
KernelTests-Chronology
KernelTests-Classes
BalloonLineSimulatio
BalloonSolidFillSimula
BalloonState
Beeper
Behavior
ClassDescription
Class
Metaclass
BindingsHolder
BitBlt
GrafPort
WarpBlt
BlockClosure
*HelpSystem-Core
*Monticello
*Ring-Core-Kernel
*Spec-Builder
accessing
accessing class hierarchy
as yet unclassified
class name
class variables
compiling
copying
fileIn/Out
initialize-release
instance variables
addClassVarNamed:
addInstVarNamed:
addInstVarNamed:type:
addSharedPool:
addSourceCode:into:
addSubclass:
allClassVarNames
allSharedPools
applyChangesOfNewTra
asClassDefinition
asFullRingDefinition
asHelpTopic
asRingDefinition
Groups
Flat
Class
Comments
Class >>#allClassVarNames
allClassVarNames
"Answer a Set of the names of the receiver's class variables, including those
defined in the superclasses of the receiver."
| aSet |
self superclass == nil
ifTrue:
[^self classVarNames asSet] "This is the keys so it is a new Set."
ifFalse:
[aSet := self superclass allClassVarNames.
aSet addAll: self classVarNames.
^aSet]
148
S
B
D
I
C

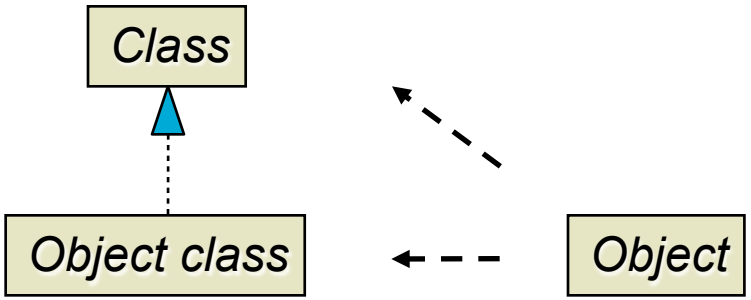
Warning !

From this point on some slides are
(still) based on VisualWorks Smalltalk

More Metaclass Mystery

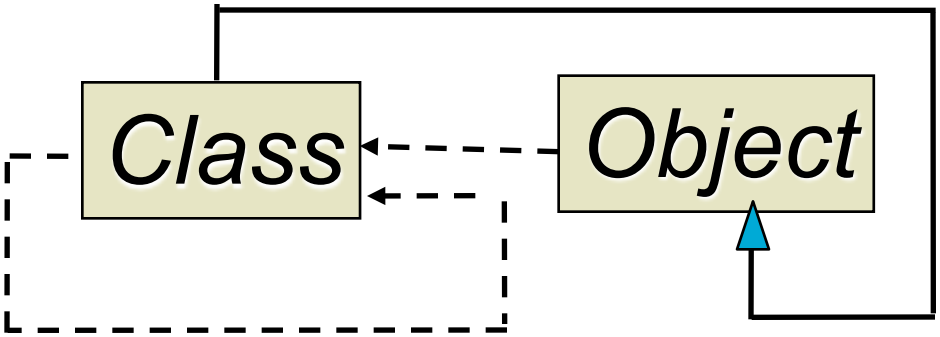
- Just like `Object` is the root of all classes,

  `Object class` is the root of all metaclasses
- But:
  - `Object class superclass` => `Class`
  - Indeed, since `Object` is a class, `Object` is an instance of `Class` or of a (direct or indirect) subclass of `Class`.
- Therefore: `Object class` is a (direct or indirect) subclass of `Class`.

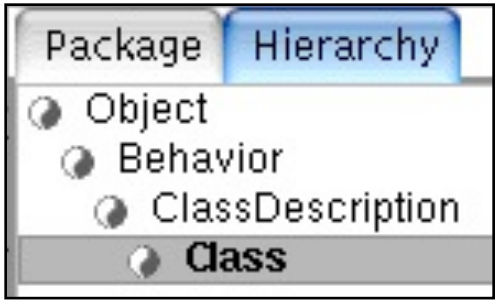


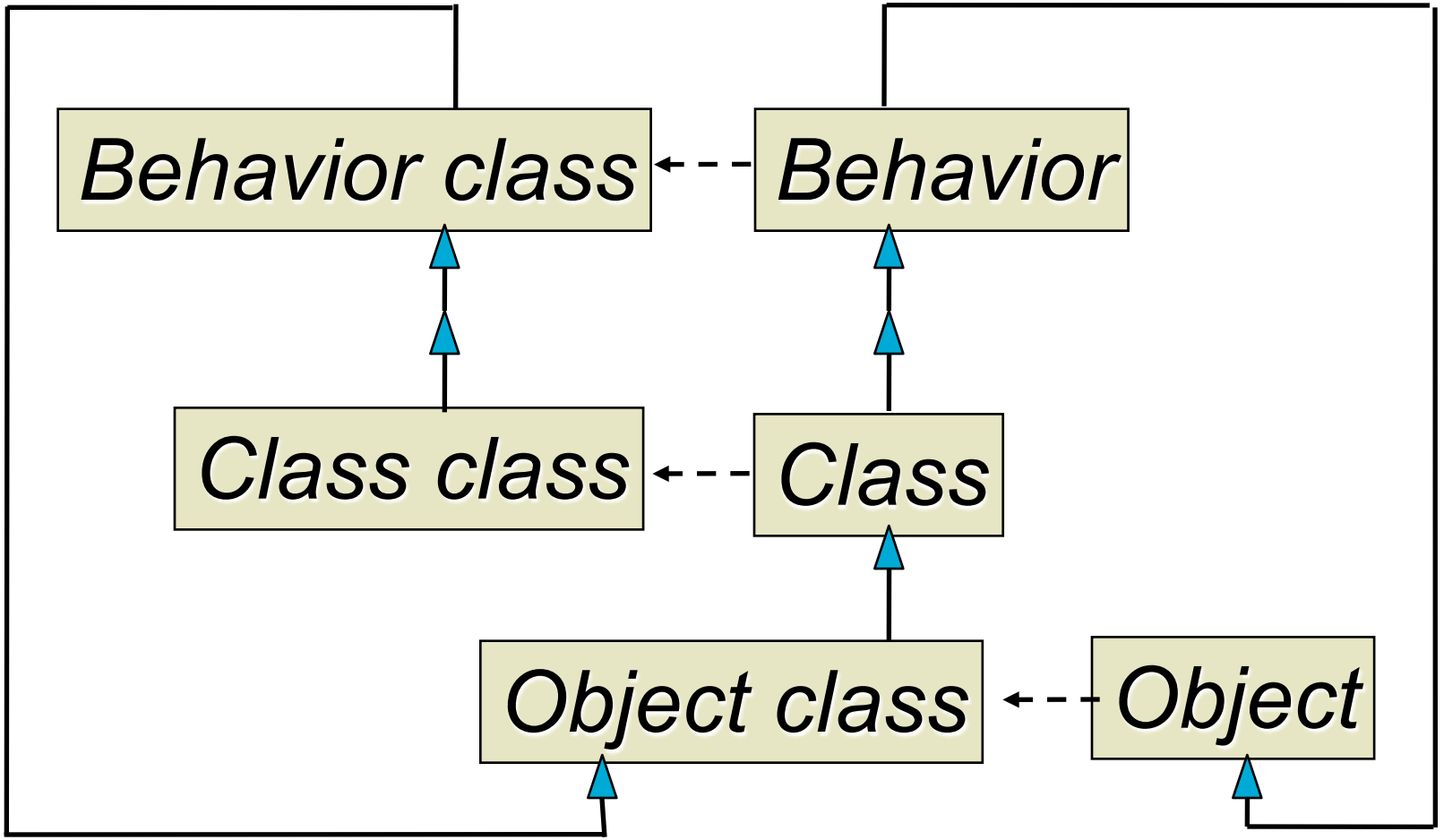
Do we need metaclasses?

- Metaclasses are not strictly necessary.
  - but we have to bootstrap somewhere...
- Every class could be an instance of `Class`.
  - Each class would then have exactly the same behaviour
  - So no special instance creation methods



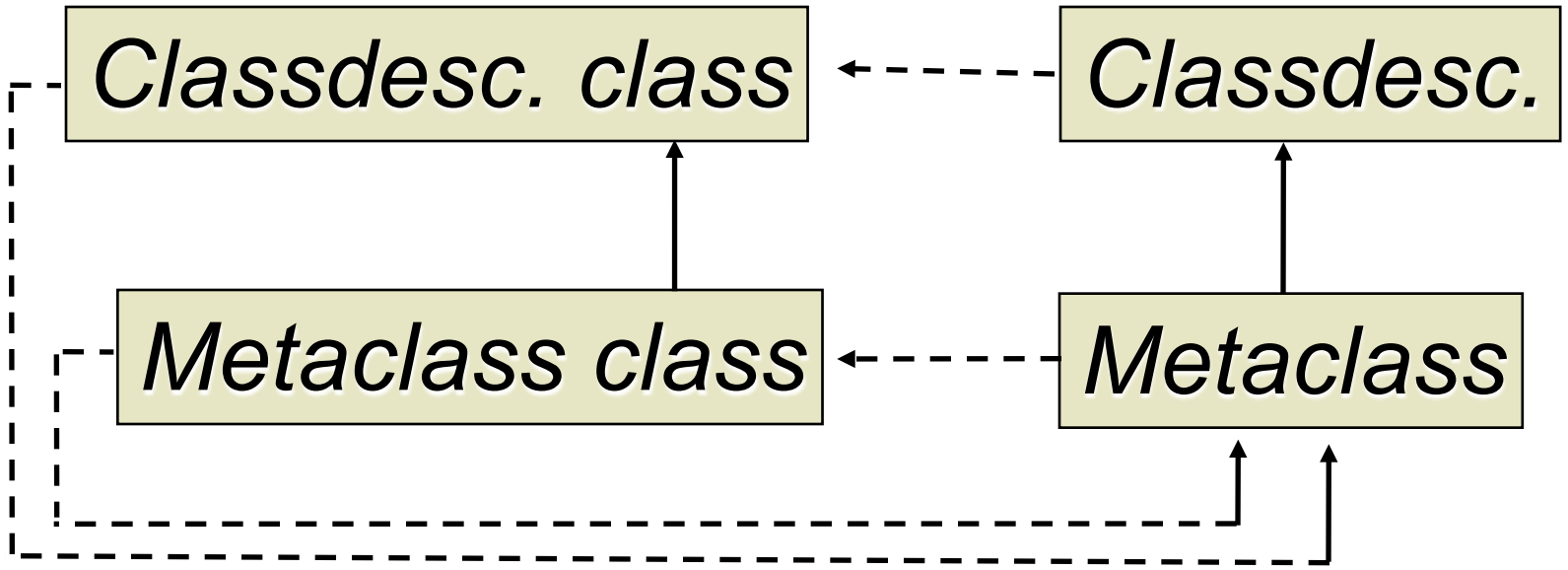
Metaclass Madness





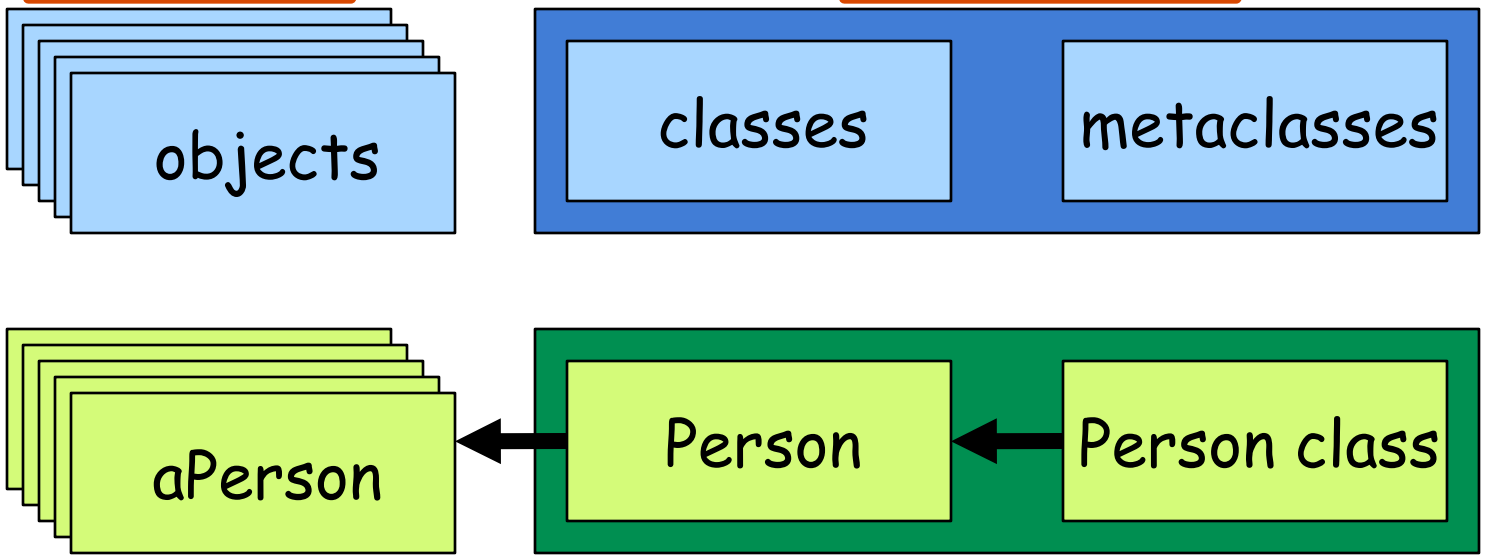
More Metaclass Madness

- Every metaclass is an instance of Metaclass.



The metaclass loop

- Objects are instances of a class
- Classes are instances of meta classes
- Each class is the **sole** instance of a meta class
  (is a convention - Singleton design pattern)
- Meta classes describe class behaviour and state (subclasses, method dictionary, etc.)
- Meta classes are instances of the class Metaclass

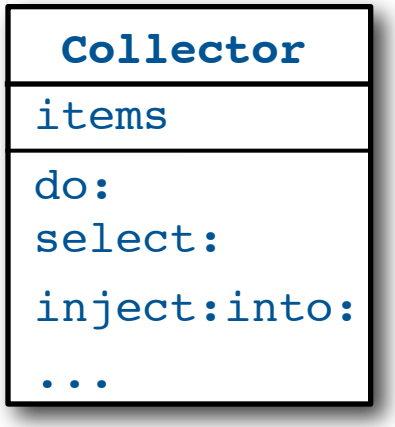


Examples of reflection in Smalltalk

- Let us get back to the essence and look at an interesting use of reflection in Smalltalk:
  - Scaffolding patterns
    - are programming idioms that support the rapid development of prototypes using Smalltalk

Example: scaffolding pattern

- We want to have a class that keeps some items in a collection
- and that allows to enumerate over those elements
- by using enumerators similar to those defined on the collection classes
  - basically by delegating to the appropriate enumeration method defined on the collection




```
do: aBlock
    ^items do: aBlock
select: aBlock
    ^items select: aBlock
inject: aValue into: aBlock
    ^items inject: aValue into: aBlock
...
```

Example: scaffolding pattern

- Solution 1: manual implementation

  - manually implement all the item enumeration methods
  - very repetitive: always the same pattern

```
<selector>
    ^items <selector>
```

where **<selector>** is an enumerator message like

```
do: aBlock
select: aBlock
inject: aValue into: aBlock
```

Example: scaffolding pattern

- Solution 2: static generation of methods
  - all methods exhibit exactly the same pattern
  - straightforward to statically generate the code for all the enumeration methods from a generic code template
  - using string replacement or macro expansion

Sidetrack: macro expansion

- ‘**<1s>**
  ^items **<1s>**’
  expandMacrosWith: ‘**do: aBlock**’
  ➡ ‘**do: aBlock**
  ^items **do: aBlock**’
- ‘**<1s>**<n><t>”This is generated code”<n><t>^items **<1s>**’
  expandMacrosWith: ‘**do: aBlock**’
  ➡ ‘**do: aBlock**
  “This is generated code”
  ^items **do: aBlock**’
- <1s>, <2s>, ... = arguments to be replaced
- <n> = newline
- <t> = tab

Example: scaffolding pattern

- Solution 2: static generation of methods

Method template with hole <1s> representing method signature and message to be sent.

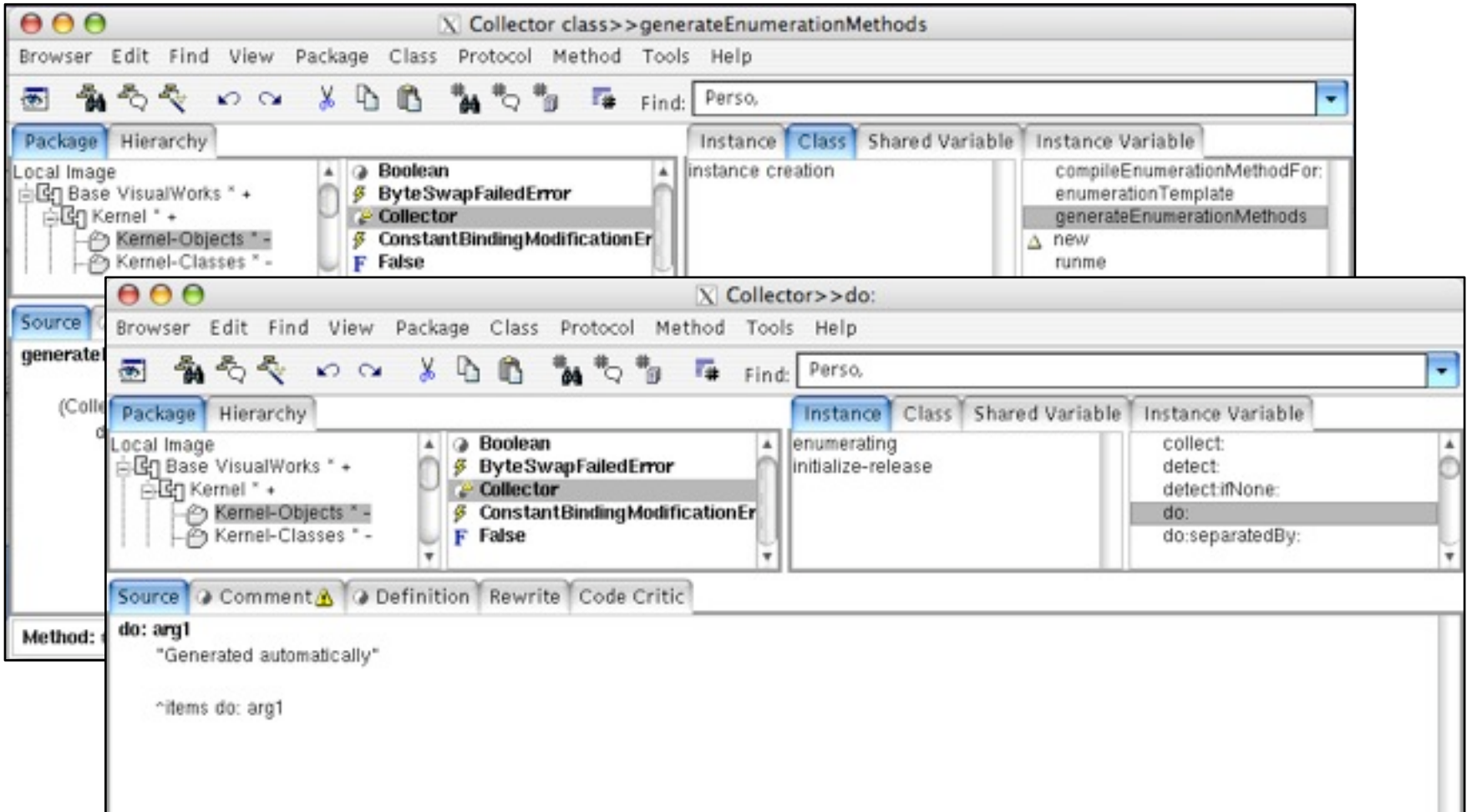
```
enumerationTemplate
    ^'<1s><n><t>"Generated automatically"<n><n><t>^items <1s>'.

compileEnumerationMethodFor: selector
    | codeTemplate code |
    codeTemplate := self enumerationTemplate.
    code := WriteStream on: String new.
        selector keywords with: (1 to: selector numArgs)
          do: [:keyword :nr | code nextPutAll: keyword;
                              space; nextPutAll: 'arg';
                              print: nr; space].
    self
        compile: (codeTemplate expandMacrosWith: code contents)
        classified: #enumerating

generateEnumerationMethods
    (Collection organization listAtCategoryNamed: #enumerating)
        do: [:selector | self compileEnumerationMethodFor: selector]
```

Note that selectors can contain multiple keywords and arguments too.

Selectors are just copied from Collection hierarchy: all enumerating methods on Collection.

Example: scaffolding pattern

- Solution 2 at work: static generation of methods



Example: scaffolding pattern

- Solution 3: Dynamic forwarding

```
isEnumerationSelector: selector
  | enumerationSelectors |

  enumerationSelectors := Collection organization
                      listAtCategoryNamed: #enumerating.
  ^enumerationSelectors includes: selector


doesNotUnderstand: aMessage

  ^(self isEnumerationSelec     aMessage selector)
     ifTrue: [items
               perform: aMessage     ector
               withArguments: aMes     arguments
     ifFalse: [super doesNotUndersta     Message]
```

inherently not possible
in statically typed languages

Example: scaffolding pattern

- Solution 4: On the fly code generation (by need)

Mixture of solution 2 and 3

```
doesNotUnderstand: aMessage
  | selector |
  selector := aMessage selector.
  (self isEnumerationSelector: selector)
        ifFalse: [^super doesNotUnderstand: aMessage].
  self compileEnumerationMethodFor: selector.
  ^self perform: selector withArguments: aMessage arguments
```