Abstract Interpretation for Dummies

Program Analysis without Tears

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What *is* Abstract Interpretation?

- An interpretation:
  - a way of understanding something
- Abstract:
  - omitting some of the details

An Example: Portland

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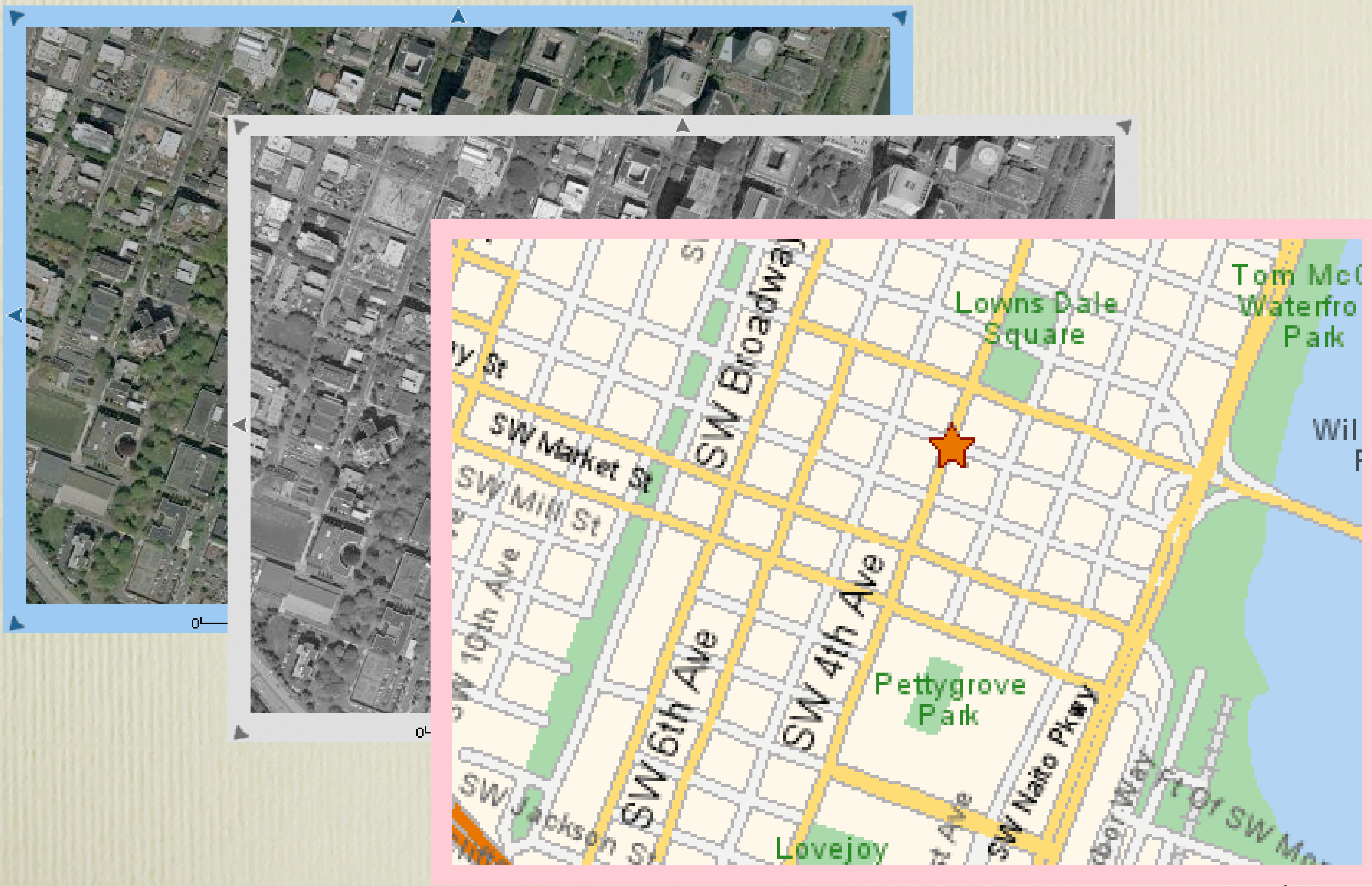
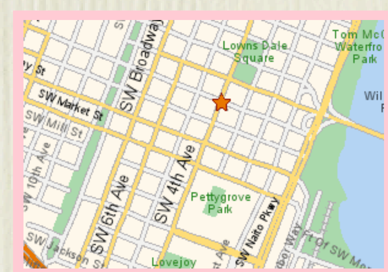


An Example: Portland

- Each interpretations makes available different information
  - all have less information than the real city!
  - in general, information content is disjoint
  - some interpretations dominate others, but
- Different interpretations have different uses
  - the map is more useful for driving than the photograph
  - it would be more useful still if it showed one-way streets!



Examples from Computing

- "Concrete" artifact is a program with the "standard" semantics
  - *e.g.*, + is an operation that performs arithmetic
- "Abstract" artifact is a program with a non-standard semantics
  - *e.g.*, + is an operation that builds an expression tree, or computes the type of the answer

Fraction >> **reduced**

```
reduced
    | gcd numer denom |
    numerator = 0 ifTrue: [↑0].
    gcd ← numerator gcd: denominator.
    numer ← numerator // gcd.
    denom ← denominator // gcd.
    denom = 1 ifTrue: [↑numer].
    ↑Fraction numerator: numer    denominator: denom
```

Fraction >> **reduced**

1. Interpret inst vars as their types

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    numer ← <integer> // gcd.
    denom ← <integer> // gcd.
    denom = 1 ifTrue: [↑numer].
    ↑Fraction numerator: numer denominator: denom
```

Fraction >> **reduced**

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Fraction >> **reduced**

2. Interpret constants as their types

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    denom ←   <integer>  // gcd.
    denom = 1 ifTrue: [↑numer].
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Fraction >> **reduced**

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Fraction >> **reduced**

3. Interpret operations ...

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  <integer>←    <integer>  // <integer>
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    ↑<fraction>
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Fraction >> **reduced**

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reduced
    | gcd numer denom |
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  <integer> ←  <integer> // <integer>
  <integer> ←    <integer>  // <integer>
  <integer> =    <integer> ifTrue: [↑<integer>]
    ↑<fraction>
```

Fraction >> **reduced**

4. Collect answers

```
reduced
    | gcd numer denom |
    <integer>  = <integer> ifTrue: [↑<integer>]
<integer>← <integer>  gcd:  <integer>   .
  <integer>←  <integer> // <integer>
  <integer>←    <integer>  // <integer>
  <integer>=    <integer> ifTrue: [↑<integer>]
    ↑<fraction>
```

Fraction >> **reduced**

4. Collect answers

```
reduced
    | gcd numer denom |
```

↑<integer>

↑<integer>

↑<fraction>

My application: Inferring method requirements

- When a method sends a message `m` to `self`, infer that its class should have a method on `m`
- When a method sends a message `n` to `super`, infer that its superclass should have a method on `n`
- When a method sends a message `c` to `self class`, infer that its metaclass should have a method on `c`

Back to ESUG 2003 ...

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- Virtual Categories

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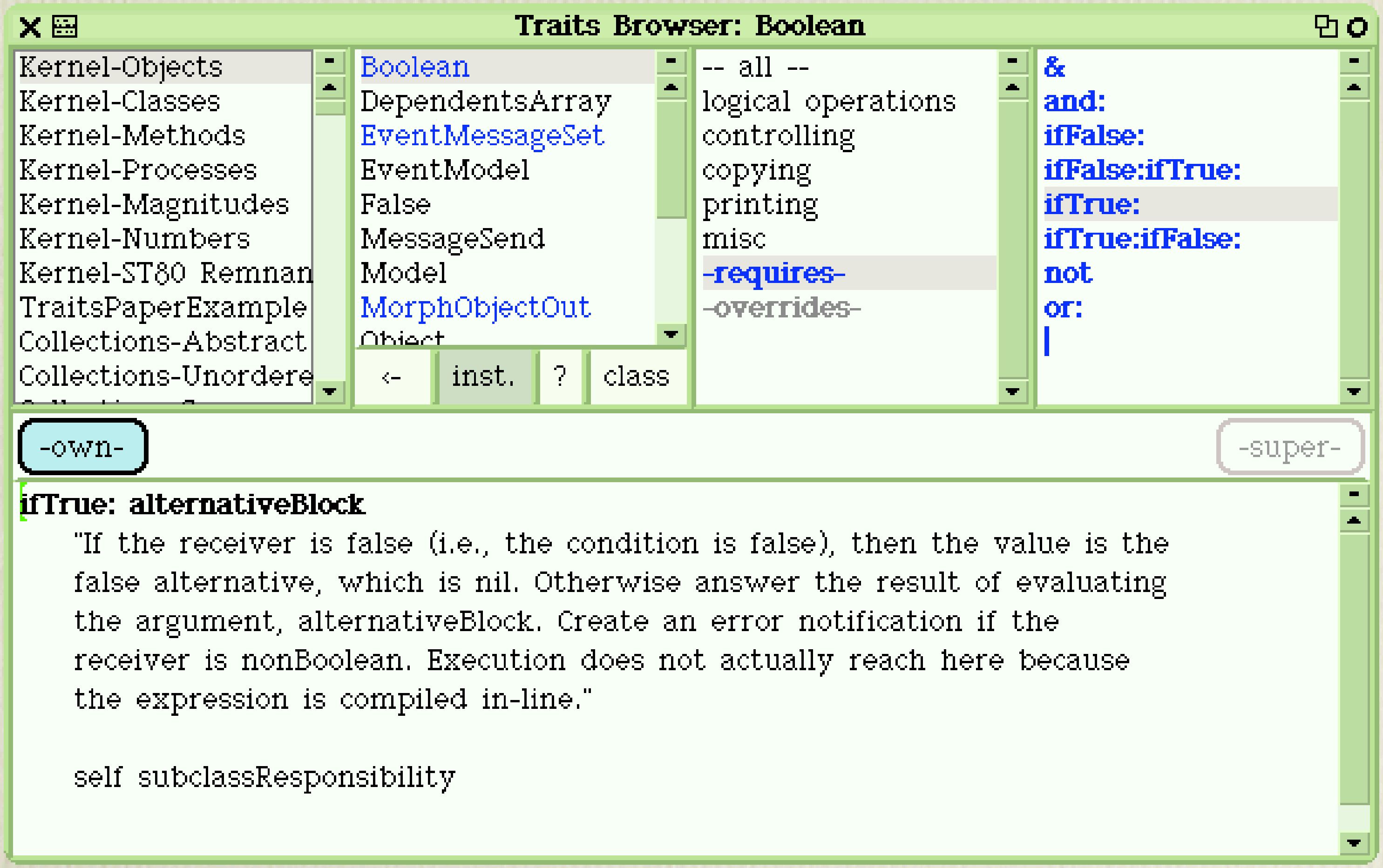
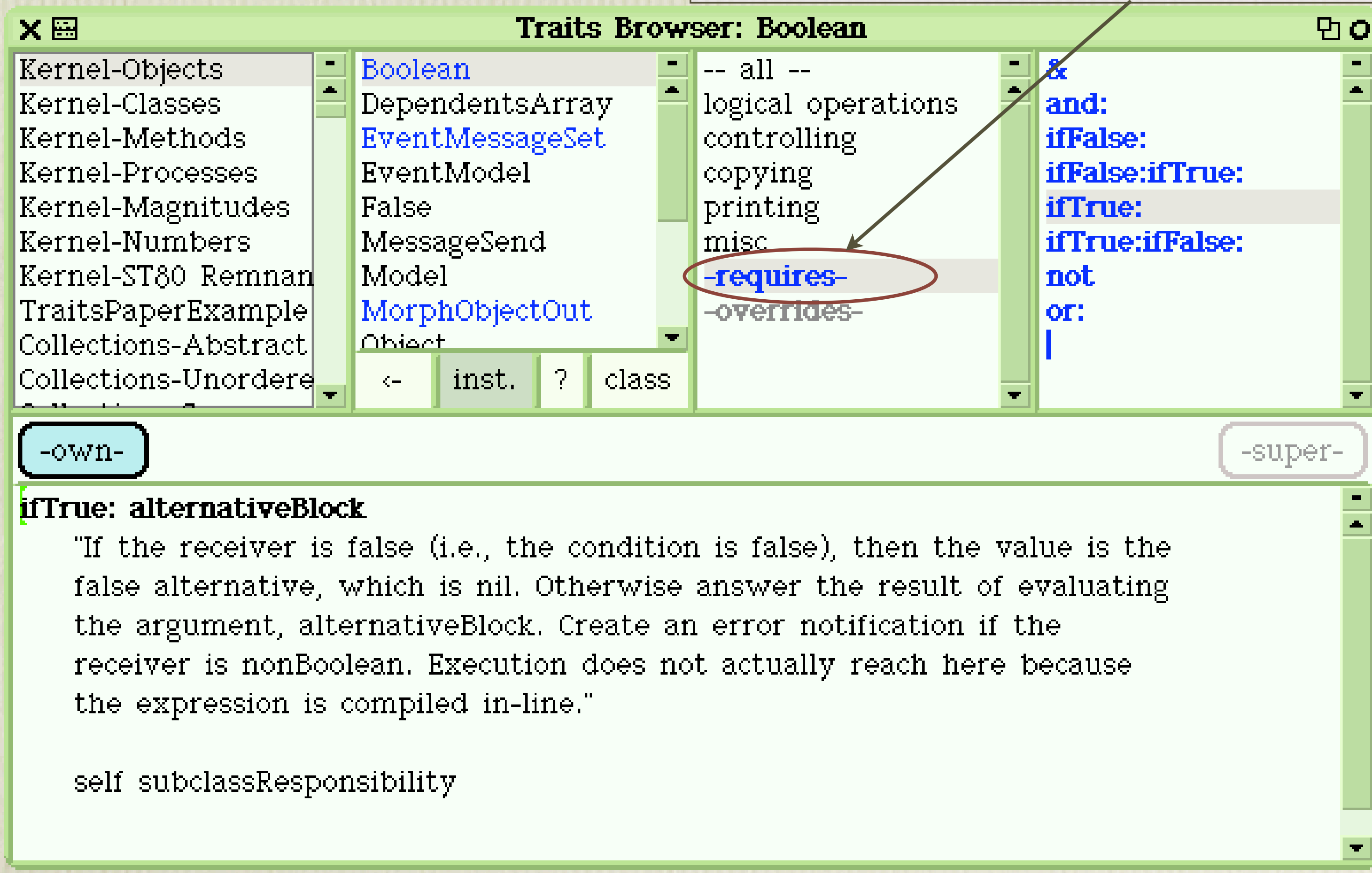


Back to ESUG 2003 ...

- Virtual Categories

categorization of methods by the browser, based on their characteristics; always up-to-date



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Collecting information about self-sends requires that we parse the source code of all of the methods ...

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~~Collecting information about self-sends requires that we parse the source code of all of the methods ...~~

John Brant

- I think you can do this by looking at the byte code
- We did something similar once in the refactoring browser

Squeak Byte Code

- instructions for a simple stack-based VM

```
17 <00> pushRcvr: 0
18 <75> pushConstant: 0
19 <B6> send: =
20 <99> jumpFalse: 23
21 <75> pushConstant: 0
22 <7C> returnTop
23 <00> pushRcvr: 0
24 <01> pushRcvr: 1
25 <E0> send: gcd:
26 <68> popIntoTemp: 0
…
```

```
reduced
    | gcd numer denom |
    numerator = 0 ifTrue: [↑0].
    gcd ← numerator gcd:
                        denominator.
    …
```

CompiledMethod

- In Squeak, the class CompiledMethod is a subclass of ByteArray.
  - It contains both the instructions (bytes) and the literal table (objects)
  - While the on-disk format is standardized, the in-memory format of the literals depends on the byte order of the processor
- Use CompiledMethod >> literalAt: and InstructionStream to look at CompiledMethods

InstructionStream Hierarchy

InstructionStream
- ContextPart
  - BlockContext
  - MethodContext
- Decompiler
- InstructionPrinter
- <Your intepreter>

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  - InstructionPrinter
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interpret the byte-encoded Smalltalk instruction set. maintain a program counter (pc) for streaming through CompiledMethods.

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adds the semantics for execution, and keeps track of sending context

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decompile a method into Smalltalk text by a three-phase process: postfix byte code → prefix symbolic code → node tree → text

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Print-out a symbolic representation of the byte-codes

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        - BlockContext
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My concrete subclass of InstructionStream which collects information about self-, super- and class-sends

InstructionStream **subclass:** #**SendsInfo**

- The core class of my abstract interpreter
  - or for any similar *single method* interpreter
- Example usage:

```
si ← SendsInfo on: ArrayedCollection>>#writeOn: .
si collectSends
```

InstructionStream **subclass:** #**SendsInfo**

- The core class of my abstract interpreter
  - or for any similar *single method* interpreter
- Example usage:

```
si ← SendsInfo on: ArrayedCollection>>#writeOn: .
si collectSends
    answers a SendsInfo that prints as
 [#(#basicSize)
  #(#writeOn:)
  #(#isWords #isPointers)]
```

SendsInfo >> #**collectSends**

- “main loop” of the interpreter

```
collectSends
    | end |
    end ← self method endPC.
    [pc <= end]
        whileTrue:
            [self interpretNextInstructionFor: self]
```

SendsInfo >> #**collectSends**

- "main loop"

instruction interpreter inherited from InstructionStream

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    | end |
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    | end |
    end ← self method endPC.
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```

this SendsInfo is the argument
as well as the target

SendsInfo >> #**collectSends**

- "main loop" of the interpreter

```
collectSends
    | end |
    end ← self method endPC.
    [pc <= end]
        whileTrue:
            [self interpretNextInstructionFor: self]
```

InstructionStream >>**interpretNextInstructionFor:**

```
interpretNextInstructionFor: client
    "Send to client, a message that specifies the type of the next instruction."

    | byte type offset method |
    method ← self method.
    byte ← method at: pc.
    type ← byte // 16.
    offset ← byte \\ 16.
    pc ← pc + 1.
    type=0 ifTrue: [↑client pushReceiverVariable: offset].
    type=1 ifTrue: [↑client pushTemporaryVariable: offset].
    type=2  ifTrue: [↑client pushConstant: (method literalAt: offset+1)].
    type=3 ifTrue: [↑client pushConstant: (method literalAt: offset+17)].
    type=4 ifTrue: [↑client pushLiteralVariable: (method literalAt: offset+1)].
    type=5 ifTrue: [↑client pushLiteralVariable: (method literalAt: offset+17)].
    ...
```

Instruction set Methods

- To detect self- and class-sends, we have to simulate the stack
  - But we can *abstract* over the set of values pushed on stack
  - We need distinguish only between **self**, **self class**, and other **stuff**
    - actually, there are also **blocks** and **small integers** representing the number of arguments to the block

Sample Instruction Set Methods

```
pushTemporaryVariable: offset
    self push: #stuff

pushConstant: value
    self push: value

pushReceiver
    self push: #self
```

The critical instruction set method

```
send: selector super: superFlag numArgs: numArgs
    "Simulate the action of bytecodes that send a message with selector…
     The arguments of the message are found in the top numArgs
      locations on the stack and the receiver just below them."
    | stackTop |
    …
    self pop: numArgs.
    stackTop ← self pop.
    superFlag
        ifTrue: [superSentSelectors add: selector]
        ifFalse: [stackTop == #self
                ifTrue: [self tallySelfSendsFor: selector].
            stackTop == #class
               ifTrue: [classSentSelectors add: selector]].
```

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What about loops?

- Simplifying assumption:
  - any send in a loop does not change from a self-send to a object-send
    - this is true because we consider `temp message` to always be an object-send, even if `temp == self`.
  - so we never need to go around a loop more than once
    - we can just ignore backward jumps

SendsInfo >>jump:

```
jump: distance
   "Simulate the action of a 'unconditional jump' bytecode
    whose  offset is distance."
   distance < 0
      ifTrue: [↑ self].
   distance = 0
      ifTrue: [self error: 'bad compiler!'].
   ...
```

What about forward jumps?

```
classPool
    "Answer the dictionary of class variables."
    classPool == nil
        ifTrue: [↑Dictionary new]
        ifFalse: [↑classPool]
```

- instructions like 16 are "merge points" in the instruction sequence:
  - execution can reach a merge point in two ways.
  - which stack should we use?

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```
 9 <0D> pushRcvr: 13
10 <73> pushConstant: nil
11 <C6> send: ==
12 <9A> jumpFalse: 16
13 <40> pushLit: Dictionary
14 <CC> send: new
15 <7C> returnTop
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Merging stacks

- Every conditional forward jump marks its destination address as a merge point
    - we save the state of the stack at the jump point in a dictionary keyed by the merge point

```
jump: distance if: aBooleanConstant
    "Simulate the action of a 'conditional jump' bytecode ..."
    | destination |
    distance < 0 ifTrue:[↑ self].
    distance = 0 ifTrue:[self error: 'bad compiler!'].
    destination ← self pc + distance.
    self pop.           "remove the condition from the stack."
    savedStacks at: destination put: stack copy.
```

Merging stack (2)

- We have to check for the possibility of a merge point at every instruction!
  - We do this by overriding `InstructionStream >>` **`interpretNextInstructionFor:`**

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```
SendsInfo>>interpretNextInstructionFor: client
    self atMergePoint
        ifTrue: [self mergeStacks].
    super interpretNextInstructionFor: client
```

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- We have to check for the possibility of a merge point at every instruction!
  - We do this by overriding `InstructionStream >>` **`interpretNextInstructionFor:`**
- Merging stacks is conservative:
  - If element *i* in either stack is `#self`, then element *i* in the merged stack is also `#self`.

Dealing with Blocks

- The code for blocks is compiled in-line, and copied onto the stack at execution time

```
9 <10> pushTemp: 0
10 <89> pushThisContext:
11 <76> pushConstant: 1
12 <C8> send: blockCopy:
13 <A4 05> jumpTo: 20
15 <69> popIntoTemp: 1
16 <70> self
17 <11> pushTemp: 1
18 <E0> send: remove:
19 <7D> blockReturn
20 <CB> send: do:
21 <87> pop
22 <10> pushTemp: 0
23 <7C> returnTop
```

```
removeAll: aCollection

    aCollection do: [:each | self remove: each].
    ↑ aCollection
```

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removeAll: aCollection

  aCollection **do:** [:each | self **remove:** each].

Number of arguments of the block

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```

1. Sending a block copy remembers the number of arguments
2. When we drop into the block, empty stack and push some dummy arguments
3. No merge of stacks is needed at 20 (or after any unconditional jump

Performance

- Initially: 27 seconds to analyze every method (~45 000) in the image (600 μs per method).
- Where did the time go?
  - Dictionaries: `SendsInfo >> #atMergePoint` is usually false
  - `OrderedCollection`: stack manipulations are slow
  - `InstructionStream>>interpretNextInstructionFor:` uses linear dispatch
- Fix these things ... 260 μs per method

Conclusions

- AI was easy to implement
  - spare time at last two days of ESUG 2003 and flight home
  - Thanks to John Brant and Vassili Bykov
- AI implementation was more accurate than implementation based on parsing source
  - `Morph>>layoutInBounds:` contains the statement:

    ```
    (owner ifNil:[self]) cellPositioning
    ```

    which AI detects as self-send
- AI is fast
  - Bytescodes are designed for fast interpretation