Working with Bytecodes:

IRBuilder and InstructionStream

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Reasons for working with Bytecode

- Generating Bytecode
  - Implementing compilers for other languages
  - Experimentation with new language features
- Parsing and Interpretation:
  - Analysis (e.g., self and super sends)
  - Decompilation (for systems without source)
  - Printing of bytecode
  - Interpretation: Debugger, Profiler

Overview

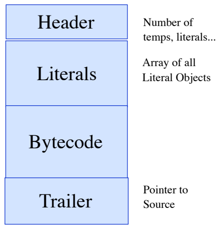
1. Introduction to Squeak Bytecodes
2. Generating Bytecode with IRBuilder
3. Decoding Bytecodes
4. Bytecode Execution

The Squeak Virtual Machine

- Virtual machine provides a virtual processor
- Bytecode: The 'machine-code' of the virtual machine
- Smalltalk (like Java): Stack machine
  - easy to implement interpreters for different processors
  - most hardware processors are register machines
- Squeak VM: Implemented in Slang
  - Slang: Subset of Smalltalk. ("C with Smalltalk Syntax")
  - Translated to C

Bytecode in the CompiledMethod

- CompiledMethods format:



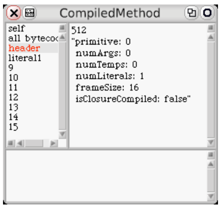
Header — Number of temps, literals...

Literals — Array of all Literal Objects

Bytecode

Trailer — Pointer to Source

`(Number>>#asInteger)inspect`

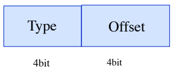


```
self
all bytecod
header
literal1
9
10
11
12
13
14
15
```

```
512
"primitive: 0
 numArgs: 0
 numTemps: 0
 numLiterals: 1
 frameSize: 16
 isClosureCompiled: false"
```

Bytecodes: Single or multibyte

- Different forms of bytecodes:
- Single bytecodes:
  - Example: 120: push self
- Groups of similar bytecodes
  - 16: push temp 1
  - 17: push temp 2
  - up to 31



Type	Offset
4bit	4bit

- Multibyte bytecodes
  - Problem: 4bit offset may be too small
  - Solution: Use the following byte as offset
  - Example: Jumps need to encode large jump offsets

Example: Number>>asInteger

- Smalltalk code:

```
Number>>asInteger
   "Answer an Integer nearest the receiver toward zero."

   ^self truncated
```

- Symbolic Bytecode

```
9 <70> self
10 <D0> send: truncated
11 <7C> returnTop
```

Example: Step by Step

- `9 <70> self`
  - The receiver (self) is pushed on the stack
- `10 <D0> send: truncated`
  - Bytecode 208: send litereral selector 1
  - Get the selector from the first literal
  - start message lookup in the class of the object that is top of the stack
  - result is pushed on the stack
- `11 <7C> returnTop`
  - return the object on top of the stack to the calling method

Squeak Bytecodes

- 256 Bytecodes, four groups:
  - Stack Bytecodes
    - Stack manipulation: push / pop / dup
  - Send Bytecodes
    - Invoke Methods
  - Return Bytecodes
    - Return to caller
  - Jump Bytecodes
    - Control flow inside a method

Stack Bytecodes

- Push values on the stack, e.g., temps, instVars, literals
  - e.g: 16 - 31: push instance variable
- Push Constants (False/True/Nil/1/0/2/-1)
- Push self, thisContext
- Duplicate top of stack
- Pop

Sends and Returns

- Sends: receiver is on top of stack
  - Normal send
  - Super Sends
  - Hard-coded sends for efficiency, e.g. +, -
- Returns
  - Return top of stack to the sender
  - Return from a block
  - Special bytecodes for return self, nil, true, false (for efficiency)

Jump Bytecodes

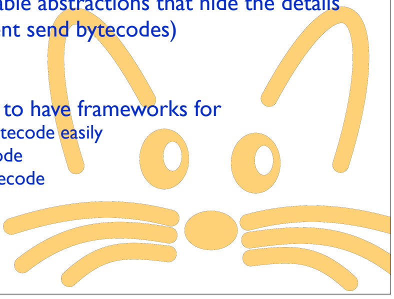
- Control Flow inside one method
- Used to implement control-flow efficiently
- Example:

```
^ 1<2 ifTrue: ['true']
```

```
9 <76> pushConstant: 1
10 <77> pushConstant: 2
11 <B2> send: <
12 <99> jumpFalse: 15
13 <20> pushConstant: 'true'
14 <90> jumpTo: 16
15 <73> pushConstant: nil
16 <7C> returnTop
```

What you should have learned...

- ... dealing with bytecodes directly is possible, but very boring.
- We want reusable abstractions that hide the details (e.g. the different send bytecodes)
- We would like to have frameworks for
  - Generating bytecode easily
  - Parsing bytecode
  - Evaluating bytecode



Generating Bytecodes

- IRBuilder: A tool for generating bytecode
- Squeak 3.7: IRBuilder has no support for blocks
- New version: Part of the new compiler (on SqueakMap)
- Following slides will use 3.7 IRBuilder
- Like an Assembler for Squeak

IRBuilder: Simple Example

- Number>>asInteger

```
iRMethod := IRBuilder new
   rargs: #(self); "receiver and args"
   pushTemp: #self;
   send: #truncated;
   returnTop;
   ir.

aCompiledMethod := iRMethod compiledMethod.

aCompiledMethod valueWithReceiver:3.5
                   arguments: #()
```

IRBuilder: Stack Manipulation

- popTop - remove the top of stack
- pushDup - push top of stack on the stack
- pushLiteral:
- pushReceiver - push self
- pushThisContext

IRBuilder: Symbolic Jumps

- Jump targets are resolved:
- Example: false ifTrue: ['true'] ifFalse: ['false']

```
iRMethod := IRBuilder new
   rargs: #(self);              "receiver and args"
   pushLiteral: false;
   jumpAheadTo: #false if: false;
   pushLiteral: 'true';         "ifTrue: ['true']"
   jumpAheadTo: #end;
   jumpAheadTarget: #false;
   pushLiteral: 'false';        "ifFalse: ['false']"
   jumpAheadTarget: #end;
   returnTop;
   ir.
```

IRBuiler: Instance Variables

- Access by offset
- Read: getField:
  - receiver on top of stack
- Write: setField:
  - receiver and value on stack
- Example: set the first instance variable to 2

```
iRMethod := IRBuilder new
        rargs: #(self);     "receiver and args declarations"
        pushLiteral: 2;
        pushTemp: #self;
        setField: 1;
        pushTemp: #self;
        returnTop;
        ir.

    aCompiledMethod := iRMethod compiledMethod.
    aCompiledMethod valueWithReceiver: 1@2 arguments: #()
```

IRBuilder: Temporary Variables

- Accessed by name
- Define with addTemp: / addTemps:
- Read with pushTemp:
- Write with storeTemp:
- Examle: set variables a and b, return value of a

```
iRMethod := IRBuilder new
      rargs: #(self); "receiver and args"
      addTemps: #(a b);
      pushLiteral: 1;
      storeTemp: #a;
      pushLiteral: 2;
      storeTemp: #b;
      pushTemp: #a;
      returnTop;
      ir.
```

IRBuilder: Sends

- normal send

```
builder pushLiteral: ‘hello’
builder send: #size;
```

- super send

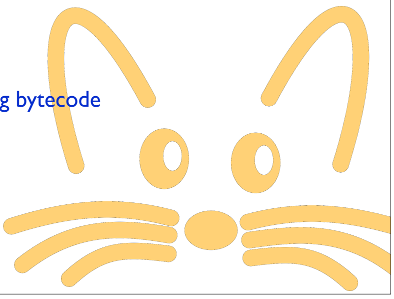
```
....
builder send: #selector toSuperOf: aClass;
```

  - The second parameter specifies the class were the lookup starts.

IRBuilder: Lessons learned

- IRBuilder: Easy bytecode generation

- Next: Decoding bytecode



Parsing and Interpretation

- First step: Parse bytecode
  - enough for easy analysis, pretty printing, decompilation
- Second step: Interpretation
  - needed for simulation, complex analyis (e.g., profiling)
- Squeak provides frameworks for both:
  - InstructionStream/InstructionClient (parsing)
  - ContextPart (Interpretation)

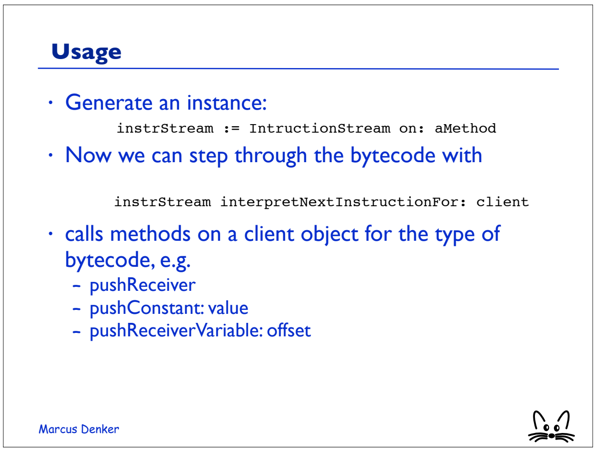
The InstructionStream Hierarchy

```
InstructionStream
  ContextPart
    BlockContext
    MethodContext
  Decompiler
  InstructionPrinter
  InstVarRefLocator
  BytecodeDecompiler
```

InstructionStream

- Parses the byte-encoded instructions
- State:
  - pc: programm counter
  - sender: the method (bad name!)

```
Object subclass: #InstructionStream
    instanceVariableNames: 'sender pc'
    classVariableNames: 'SpecialConstants'
    poolDictionaries: ''
    category: 'Kernel-Methods'
```



Usage

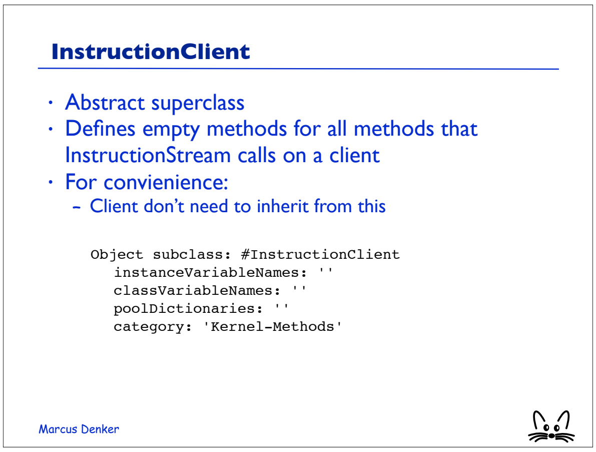
- Generate an instance:

```
instrStream := IntructionStream on: aMethod
```

- Now we can step through the bytecode with

```
instrStream interpretNextInstructionFor: client
```

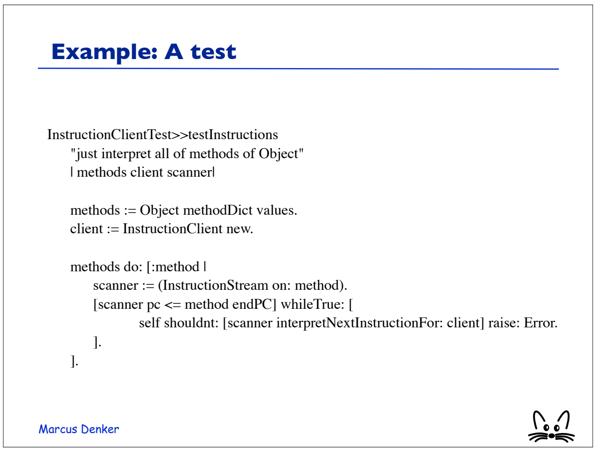
- calls methods on a client object for the type of bytecode, e.g.
  - pushReceiver
  - pushConstant: value
  - pushReceiverVariable: offset



InstructionClient

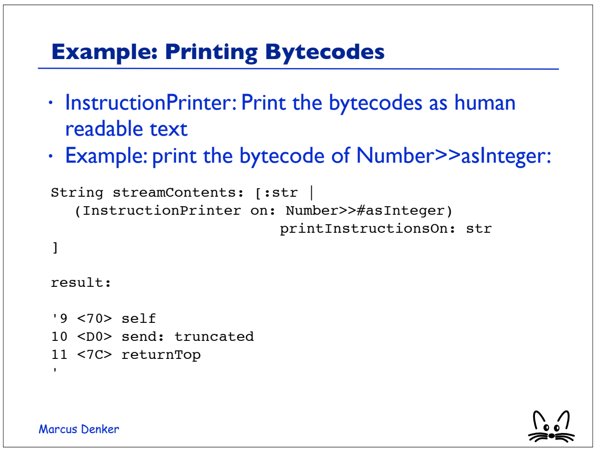
- Abstract superclass
- Defines empty methods for all methods that InstructionStream calls on a client
- For convienience:
  - Client don't need to inherit from this

```
Object subclass: #InstructionClient
   instanceVariableNames: ''
   classVariableNames: ''
   poolDictionaries: ''
   category: 'Kernel-Methods'
```



Example: A test

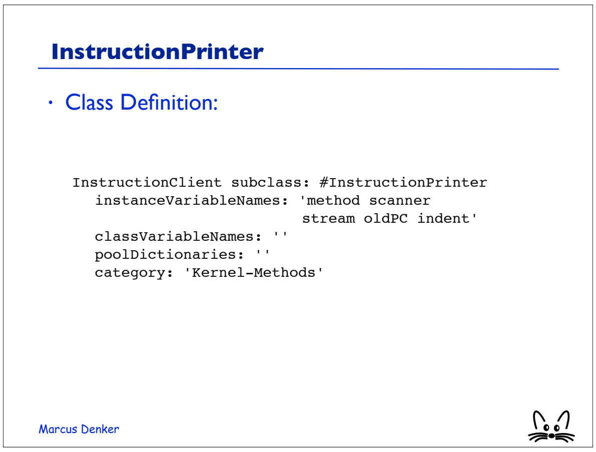
```
InstructionClientTest>>testInstructions
    "just interpret all of methods of Object"
    | methods client scanner|

    methods := Object methodDict values.
    client := InstructionClient new.

    methods do: [:method |
        scanner := (InstructionStream on: method).
        [scanner pc <= method endPC] whileTrue: [
                self shouldnt: [scanner interpretNextInstructionFor: client] raise: Error.
        ].
    ].
```



Example: Printing Bytecodes

- InstructionPrinter: Print the bytecodes as human readable text
- Example: print the bytecode of Number>>asInteger:

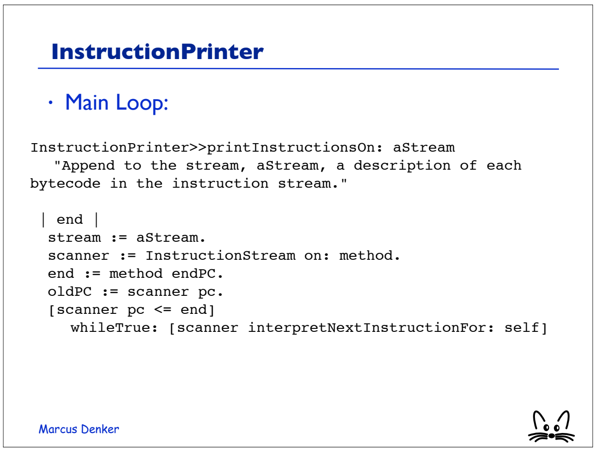
```
String streamContents: [:str |
   (InstructionPrinter on: Number>>#asInteger)
                           printInstructionsOn: str
]

result:

'9 <70> self
10 <D0> send: truncated
11 <7C> returnTop
'
```



InstructionPrinter

- Class Definition:

```
InstructionClient subclass: #InstructionPrinter
   instanceVariableNames: 'method scanner
                           stream oldPC indent'
   classVariableNames: ''
   poolDictionaries: ''
   category: 'Kernel-Methods'
```



InstructionPrinter

- Main Loop:

```
InstructionPrinter>>printInstructionsOn: aStream
   "Append to the stream, aStream, a description of each
bytecode in the instruction stream."

 | end |
  stream := aStream.
  scanner := InstructionStream on: method.
  end := method endPC.
  oldPC := scanner pc.
  [scanner pc <= end]
     whileTrue: [scanner interpretNextInstructionFor: self]
```

InstructionPrinter

- Overwrites methods form InstructionClient to print the bytecodes as text
- e.g. the method for pushReceiver:

```
InstructionPrinter>>pushReceiver
   "Print the Push Active Context's Receiver
    on Top Of Stack bytecode."

   self print: 'self'
```

Example: InstVarRefLocator

```
InstructionClient subclass: #InstVarRefLocator
   instanceVariableNames: 'bingo'
   ....

interpretNextInstructionUsing: aScanner
   bingo := false.
   aScanner interpretNextInstructionFor: self.
   ^bingo

popIntoReceiverVariable: offset
   bingo := true

pushReceiverVariable: offset
   bingo := true

storeIntoReceiverVariable: offset
   bingo := true
```

InstVarRefLocator

- Analyse a method, answer true if it references an instance variable
- We implement CompiledMethod>>#hasInstVarRef

```
hasInstVarRef
   | scanner end printer |

   scanner := InstructionStream on: self.
   printer := InstVarRefLocator new.
   end := self endPC.

   [scanner pc <= end] whileTrue: [
      (printer interpretNextInstructionUsing: scanner) ifTrue: [^true].
   ].
   ^false
```

InstVarRefLocator

- Example for a simple bytecode analyzer
- Usage: `aMethod hasInstVarRef`

```
(TestCase>>#debug) hasInstVarRef   --> true
```

- (has reference to variable testSelector)

```
(Integer>>#+) hasInstVarRef   --> false
```

- (has no reference to a variable)

Example: Decompiling Bytecode

- BytecodeDecompiler

```
InstructionStream subclass: #BytecodeDecompiler
   instanceVariableNames: 'irBuilder blockFlag'
   classVariableNames: ''
   poolDictionaries: ''
   category: 'Compiler-Bytecodes'
```

- Usage:

```
BytecodeDecompiler new decompile: (Number>>#asInteger)
```

Decompiling

- uses IRBuilder for building IR (Intermediate Representation)
- Code for the bytecode pushReceiver:

```
BytecodeDecompiler>>pushReceiver

   irBuilder pushReceiver
```

ContextPart: Semantics for Execution

- Sometimes we need more than parsing
  - “stepping” in the debugger
  - system simulation for profiling

```
InstructionStream subclass: #ContextPart
   instanceVariableNames: 'stackp'
   classVariableNames: 'PrimitiveFailToken QuickStep'
   poolDictionaries: ''
   category: 'Kernel-Methods'
```

Simulation

- Provides a complete Bytecode interpreter
- Run a block with the simulator:

```
(ContextPart runSimulated: [3 factorial])
```

Profiling: MesageTally

- Usage:

```
MessageTally tallySends: [3 factorial]

This simulation took 0.0 seconds.
**Tree**
1 SmallInteger(Integer)>>factorial
  1 SmallInteger(Integer)>>factorial
    1 SmallInteger(Integer)>>factorial
      1 SmallInteger(Integer)>>factorial
```

- Other example:

```
MessageTally tallySends: [’3’ + 1]
```

End

- Short overview of Squeak bytecode
- Introduction to bytecode generation with IRBuilder
- Parsing bytecode with InstructionStream
- Example for interpretation

- Questions?