Dynamic Languages
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References

- An Efficient Implementation of Self, a dynamically-typed object-oriented language based on prototypes
  Chambers, Unger, Lee, OOPSLA 1989

- Slides by Vijay Menon, CSE 501, Sp09, adapted from slides by Kathleen Fisher
Dynamic Typing

JavaScript:

```javascript
function foo(a, b) {
    t1 = a.x;     // runtime field lookup
    t2 = b.y();   // runtime method lookup
    t3 = t1 + t2; // runtime dispatch on ‘+’
    return t3;
}
```
Overview

- **Self**
  - 20+ year old research language
  - One of earliest JIT compilation systems
  - Pioneered techniques used today

- **JavaScript**
  - Self with a Java syntax
  - Much recent work to optimize
Self

- Prototype-based pure object-oriented language
- Designed by Randall Smith (Xerox PARC) and David Ungar (Stanford University)
  - Successor to Smalltalk-80
  - “Self: The power of simplicity” at OOPSLA ’87
  - Initial implementation done at Stanford; then project shifted to Sun Microsystems Labs
  - Vehicle for implementation research
- Self 4.4 available from selflanguage.org
Design Goals

- Occam’s Razor: Conceptual economy
  - Everything is an object.
  - Everything done using messages.
  - No classes
  - No variables

- Concreteness
  - Objects should seem “real”
  - GUI to manipulate objects directly
How successful?

- Very well-designed language, but...
- Few users: not a popular success
- However, many research innovations
  - Very simple computational model
  - Enormous advances in compilation techniques
  - Influenced the design of Java compilers
Language Overview

- Dynamically typed
- Everything is an object
- All computation via message passing
- Creation and initialization done by copying example object
- Operations on objects:
  - send messages
  - add new slots
  - replace old slots
  - remove slots
Objects and Slots

Object consists of named slots.

- Data
  - Such slots return contents upon evaluation; so act like variables

- Assignment
  - Set the value of associated slot

- Method
  - Slot contains Self code

- Parent
  - References an object to inherit its slots
Messages and Methods

- When a message is sent, search the receiver object for a slot with that name.
- If none found, all parents are searched.
  - Runtime error if more than one parent has a slot with the same name.
- If slot found, its contents are evaluated and returned.
  - Runtime error if no slot found.

```
clone ... 

parent* print ...

parent* 

x 3
x: ←
```
Messages and Methods

obj x  ➔  3

obj print ➔ print point object

obj x: 4 ➔ obj after setting x to 4.

clone

parent*

print

parent*

x ➔ 3

x: ➔ ←
Mixing State and Behavior

<table>
<thead>
<tr>
<th>parent*</th>
<th>+</th>
<th>add points</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>y</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

parent* $\rightarrow$ random number generator

<table>
<thead>
<tr>
<th>parent*</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
<tr>
<td>y</td>
</tr>
<tr>
<td>x:</td>
</tr>
<tr>
<td>y:</td>
</tr>
</tbody>
</table>
Object Creation

- To create an object, we copy an old one.
- We can add new methods, override existing ones, or even remove methods.
  - These operations also apply to parent slots.
Changing Parent Pointers

frog

<table>
<thead>
<tr>
<th>jump</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>eatFly</td>
<td>...</td>
</tr>
</tbody>
</table>

prince

<table>
<thead>
<tr>
<th>dance</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>eatCake</td>
<td>...</td>
</tr>
</tbody>
</table>

```
p jump.
p eatFly.
p parent: prince.
p dance.
```
### Changing Parent Pointers

<table>
<thead>
<tr>
<th>frog</th>
<th>jump</th>
<th>...</th>
<th>prince</th>
<th>dance</th>
<th>...</th>
</tr>
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<td></td>
<td>eatFly</td>
<td></td>
<td></td>
<td>eatCake</td>
<td></td>
</tr>
</tbody>
</table>

```
p jump.
p eatFly.
p parent: prince.
p dance
```
Disadvantages of classes?

- Classes require programmers to understand a more complex model
  - To make a new kind of object, we have to create a new class first
  - To change an object, we have to change the class
  - Infinite meta-class regression
- **But**: Does Self require programmers to reinvent structure?
  - Common to structure Self programs with *traits*: objects that simply collect behavior for sharing
Contrast with C++

- C++
  - Restricts expressiveness to ensure efficient implementation

- Self
  - Provides unbreakable high-level model of underlying machine
  - Compiler does fancy optimizations to obtain acceptable performance
Implementation Challenges I

- Many, many slow function calls:
  - Function calls generally somewhat expensive
  - Dynamic dispatch makes message invocation even slower than typical procedure calls
  - OO programs tend to have lots of small methods
  - Everything is a message: even variable access!

“The resulting call density of pure object-oriented programs is staggering, and brings naïve implementations to their knees” [Chambers & Ungar, PLDI 89]
Implementation Challenges II

- No static type system
  - Each reference could point to any object, making it hard to find methods statically

- No class structure to enforce sharing
  - Copies of methods in every object creates lots of space overhead

Optimized Smalltalk-80 is roughly 10 times slower than optimized C
Optimization Strategies

- Avoid per object space requirements
- Compile, don’t interpret
- Avoid method lookup
- Inline methods wherever possible
  - Saves method call overhead
  - Enables further optimizations
Clone Families
(Objects created from same prototype)

Avoid per object data

Implementation

Model

prototype

Mutable

Fixed

clone family

Mutable

Fixed

Map:

Fixed

Info

Mutable

Map
Dynamic Compilation

- Method is converted to byte codes when entered into the system
- Compiled to machine code when first executed
- Code stored in cache
  - if cache fills, previously compiled method flushed
- Requires entire source (byte) code to be available at runtime

Avoid interpreting
Avoid method lookup

## Lookup Cache

- Cache of recently used methods, indexed by \((\text{receiver type, message name})\) pairs
- When a message is sent, compiler first consults cache
  - if found: invokes associated code
  - if absent: performs general lookup and potentially updates cache
- Berkeley Smalltalk would have been 37\% slower without this optimization
Static Type Prediction

- Compiler predicts types that are unknown but likely:
  - Arithmetic operations (+, -, <, etc.) have small integers as their receivers 95% of time in Smalltalk-80
  - ifTrue had Boolean receiver 100% of the time.
- Compiler inlines code (and test to confirm guess):

```plaintext
if type = smallInt jump to method_smallInt
call general_lookup
```
Inline Caches

- First message send from a call site:
  - general lookup routine invoked
  - call site back-patched
    - is previous method still correct?
      - yes: invoke code directly
      - no: proceed with general lookup & backpatch

- Successful about 95% of the time
- All compiled implementations of Smalltalk and Self use inline caches.
Polymorphic Inline Caches

- Typical call site has <10 distinct receiver types
  - Often can cache all receivers
- At each call site, for each new receiver, extend patch code:
  
  ```
  if type = rectangle jump to method_rect
  if type = circle jump to method_circle
  call general_lookup
  ```

- After some threshold, revert to simple inline cache (megamorphic site)
- Order clauses by frequency
- Inline short methods into PIC code
Customized Compilation

- Compile several copies of each method, one for each receiver type
- Within each copy:
  - Compiler knows the type of self
  - Calls through self can be statically selected and inlined
- Enables downstream optimizations
- Increases code size
Type Analysis

- Constructed by compiler by flow analysis
- Type: set of possible maps for object
  - Singleton: know map statically
  - Union/Merge: know expression has one of a fixed collection of maps
  - Unknown: know nothing about expression
- If singleton, we can inline method
- If type is small, we can insert type test and create branch for each possible receiver (type casing)
Message Splitting

- Type information above a merge point is often better
- Move message send “before” merge point:
  - duplicates code
  - improves type information
  - allows more inlining
PICS as Type Source

- Polymorphic inline caches build a call-site specific type database *as the program runs*
- Compiler can use this runtime information rather than the result of a static flow analysis to build *type cases*
- Must wait until PIC has collected information
  - When to recompile?
  - What should be recompiled?
- Initial fast compile yielding slow code; then dynamically recompile – *hotspots*
Performance Improvements

- Initial version of Self was 4-5 times slower than optimized C
- Adding **type analysis** and **message splitting** got within a factor of 2 of optimized C
- Replacing type analysis with **PICS** improved performance by further 37%

Current Self compiler is within a factor of 2 of optimized C.
Impact on Java

- Sun cancels Self
- Animorphics
  - Smalltalk
  - Java becomes popular
  - Java
    - Animorphics
      - Java
        - Sun buys A.J.
  - Hotspot
    - Sun buys A.J.

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Summary of Self

“Power of simplicity”
- Everything is an object: no classes, no variables
- Provides high-level model that can’t be violated (even during debugging)

- Fancy optimizations recover reasonable performance
- Many techniques now used in Java compilers
- Papers describing various optimization techniques available from Self web site
JavaScript

- Self-like language with Java syntax
  - Dynamic OO language
  - Prototypes instead of classes
  - Nothing to do with Java beyond syntax

- Originated in Netscape

- “Standard” on today’s browsers
High-performance JavaScript

- **Self approach:**
  - V8 (Google Chrome)
  - SquirrelFish Extreme (Safari / WebKit)

- **Trace compilation:**
  - TraceMonkey (Firefox)
  - Tamarin (Adobe Flash/Flex)
V8 (Google Chrome)

- Three primary features
  - Fast property access
    - Hidden classes
  - Dynamic compiler
    - Compile on first invocation
    - Inline caching with back patching
  - Generational garbage collection
    - Segmented by types
- See http://code.google.com/apis/v8/design.html
Trace-Based Compilation

- Interpret initially
- Record trace information
  - Single entry, multiple exit
  - Loop header is typically trace start
- Compile hot trace (hot path through flowgraph)
  - Interpreter jumps to trace code when available
  - Stitch multiple traces together
- Specialize hot path (omit redundant checks)
  - Claim this achieves benefits of inline caching