CSE 413
Programming Languages & Implementation

Hal Perkins

Spring 2023

Dynamic Languages

References

- *An Efficient Implementation of Self, a dynamically-typed object-oriented language based on prototypes,* Chambers, Unger, Lee, OOPSLA 1989
- Earlier versions of this lecture by Vijay Menon, CSE 501, adapted from slides by Kathleen Fisher

Dynamic Typing (reminder)

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
  - 30+(!) year old research language
  - One of earliest JIT compilation systems
  - Pioneered techniques used today

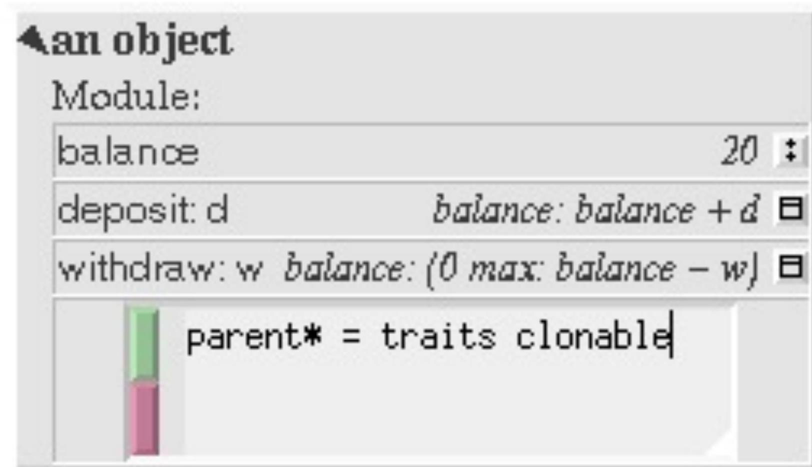
- JavaScript
  - Self with a Java syntax (plus other things…)
  - Lots of interest in making it fast in recent years since it is the available execution engine in all web browsers

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
- Current version 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
  - JavaScript object model based on Self

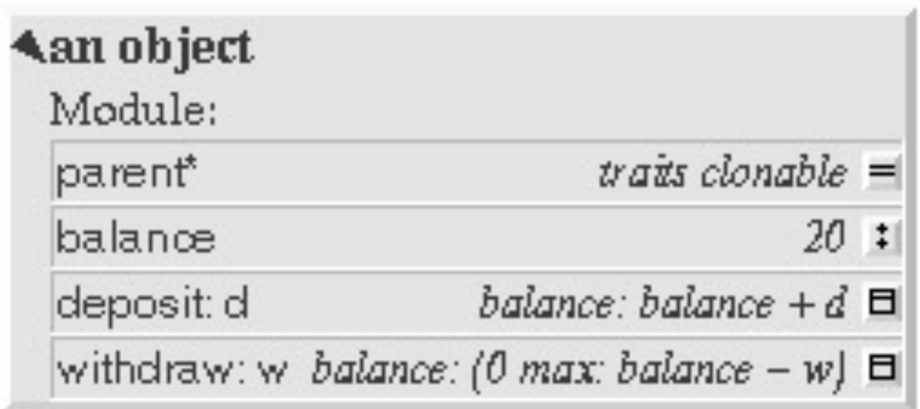
Language Overview

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

Objects and Slots

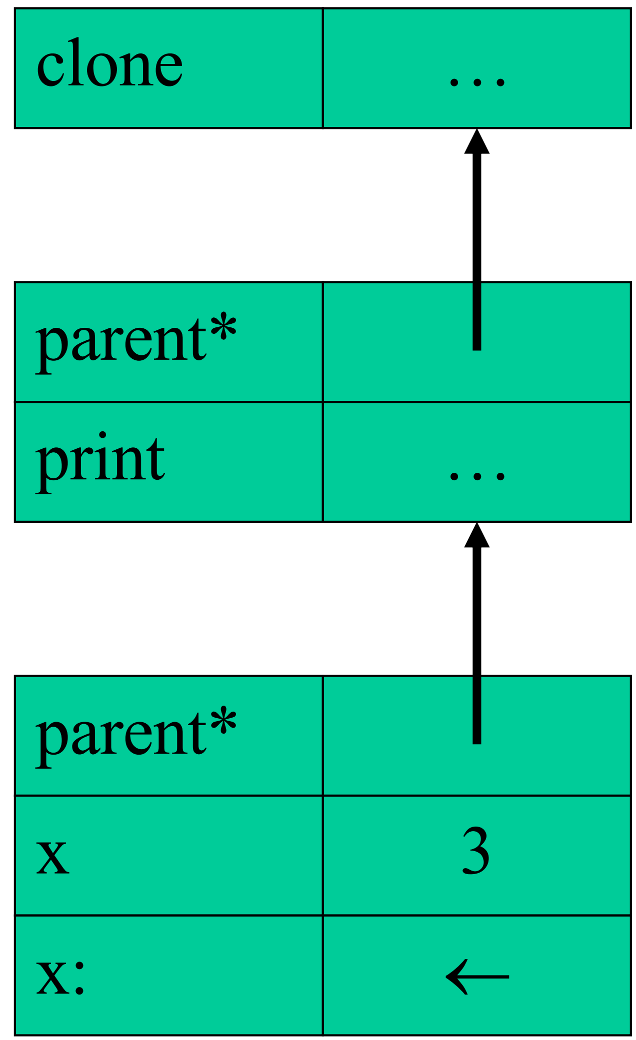
Object consists of named slots.

- 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

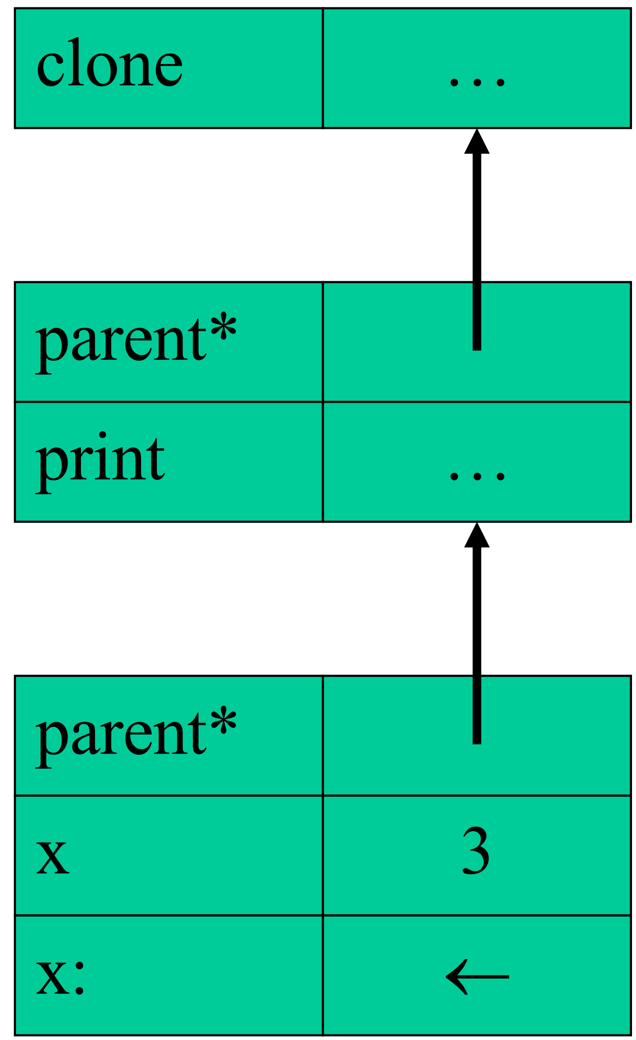


Messages and Methods

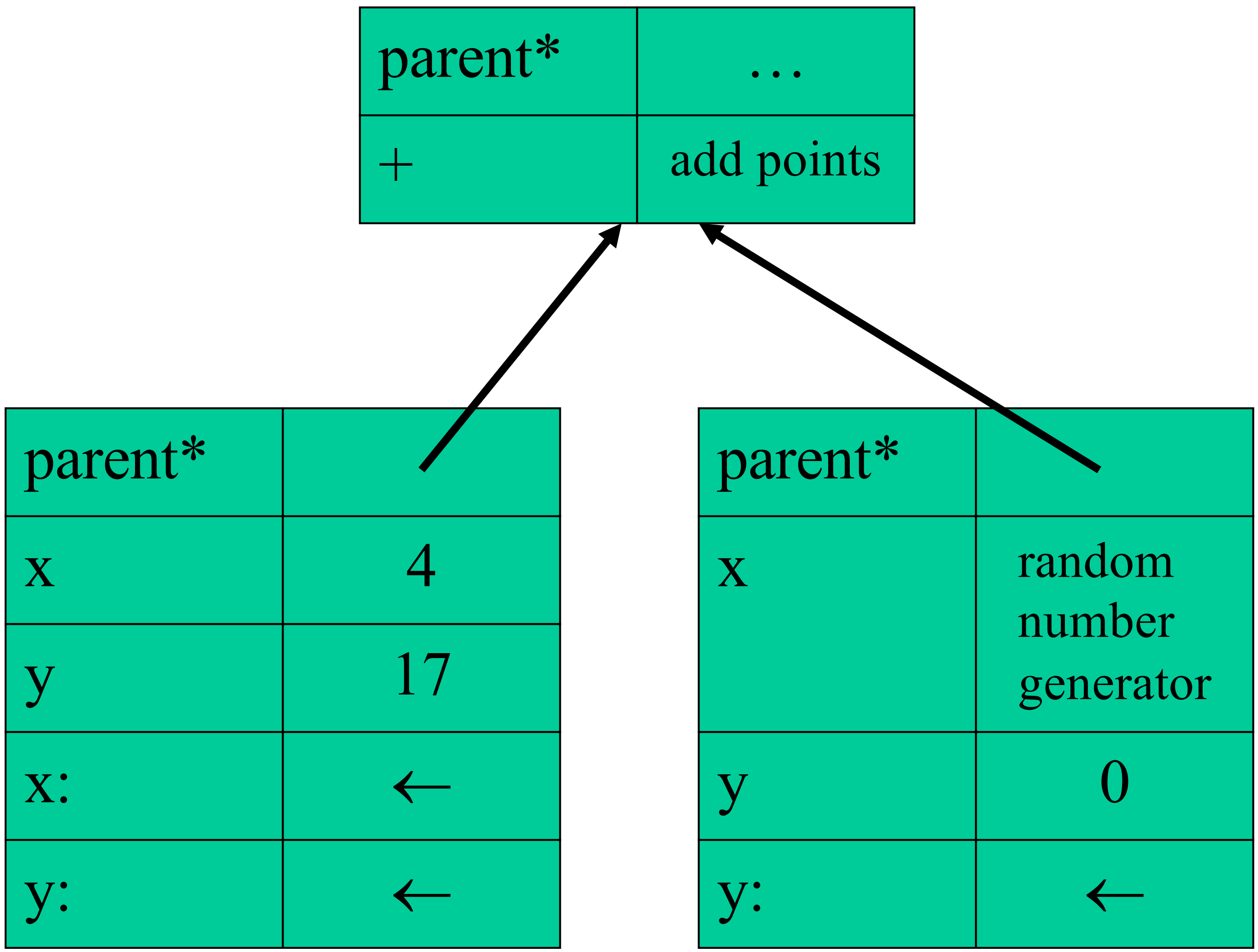
obj x → 3

obj print → *print point object*

obj x: 4 → obj *after setting x slot to 4.*

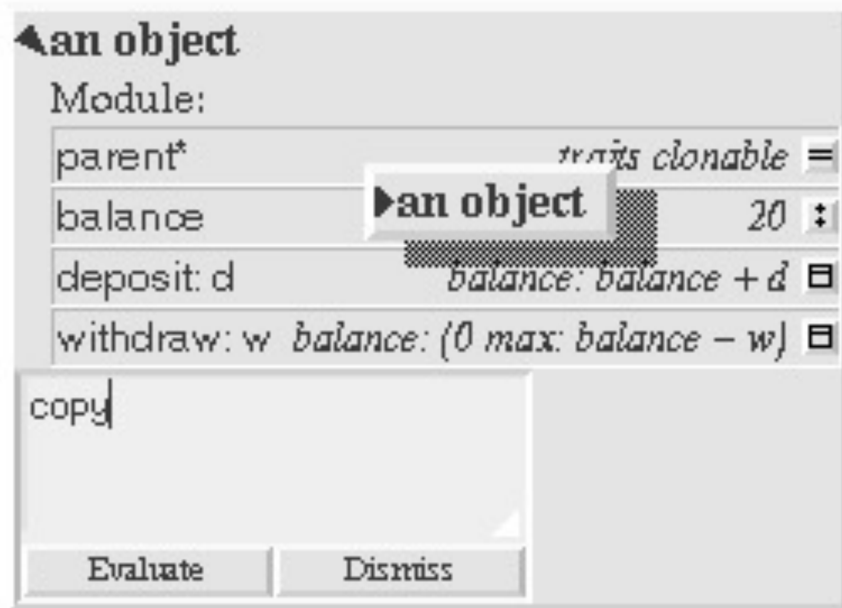


Mixing State and Behavior



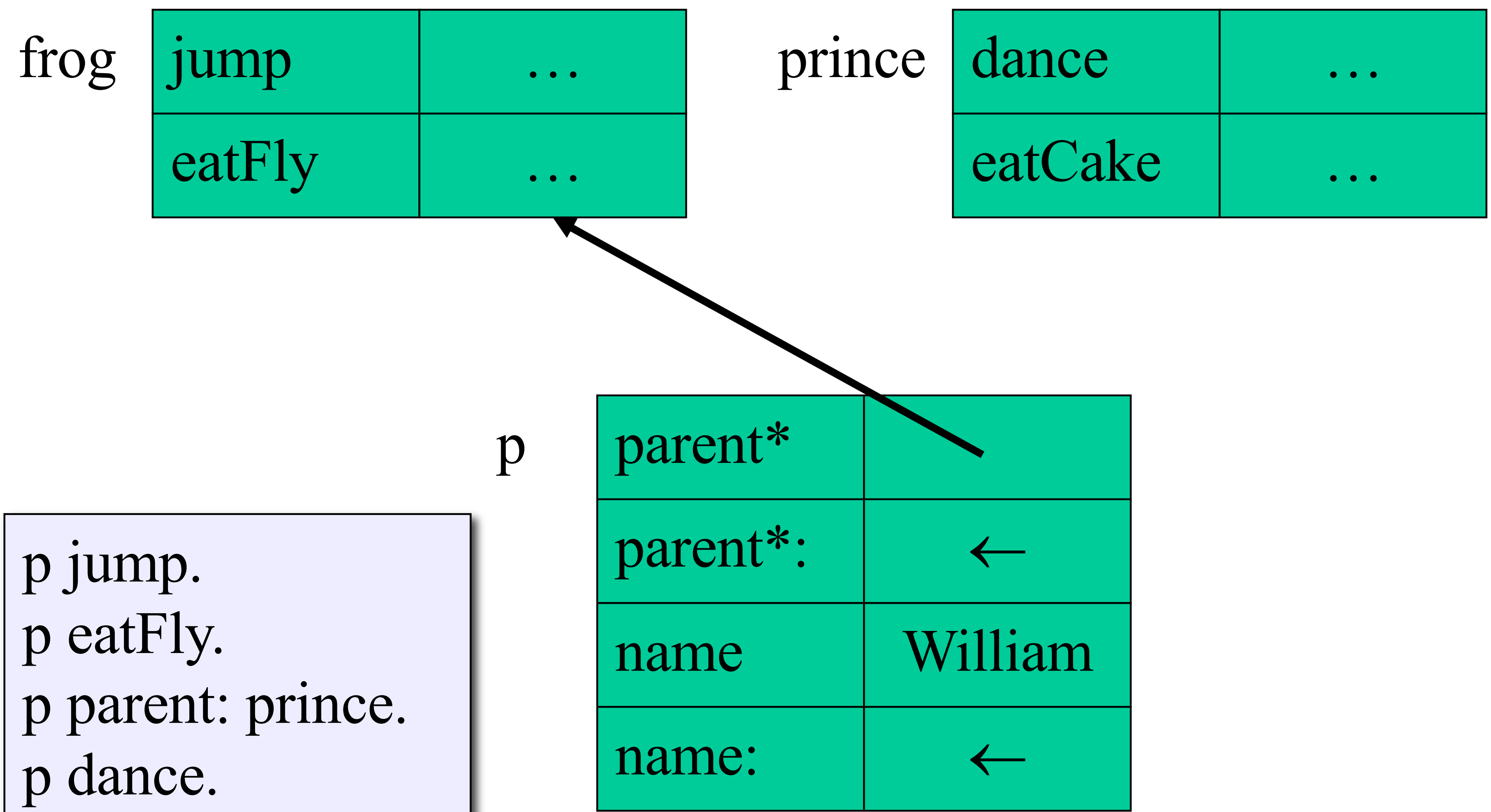
Object Creation

- To create an object, we copy an old one
- We can add new methods, override existing ones, or even remove methods



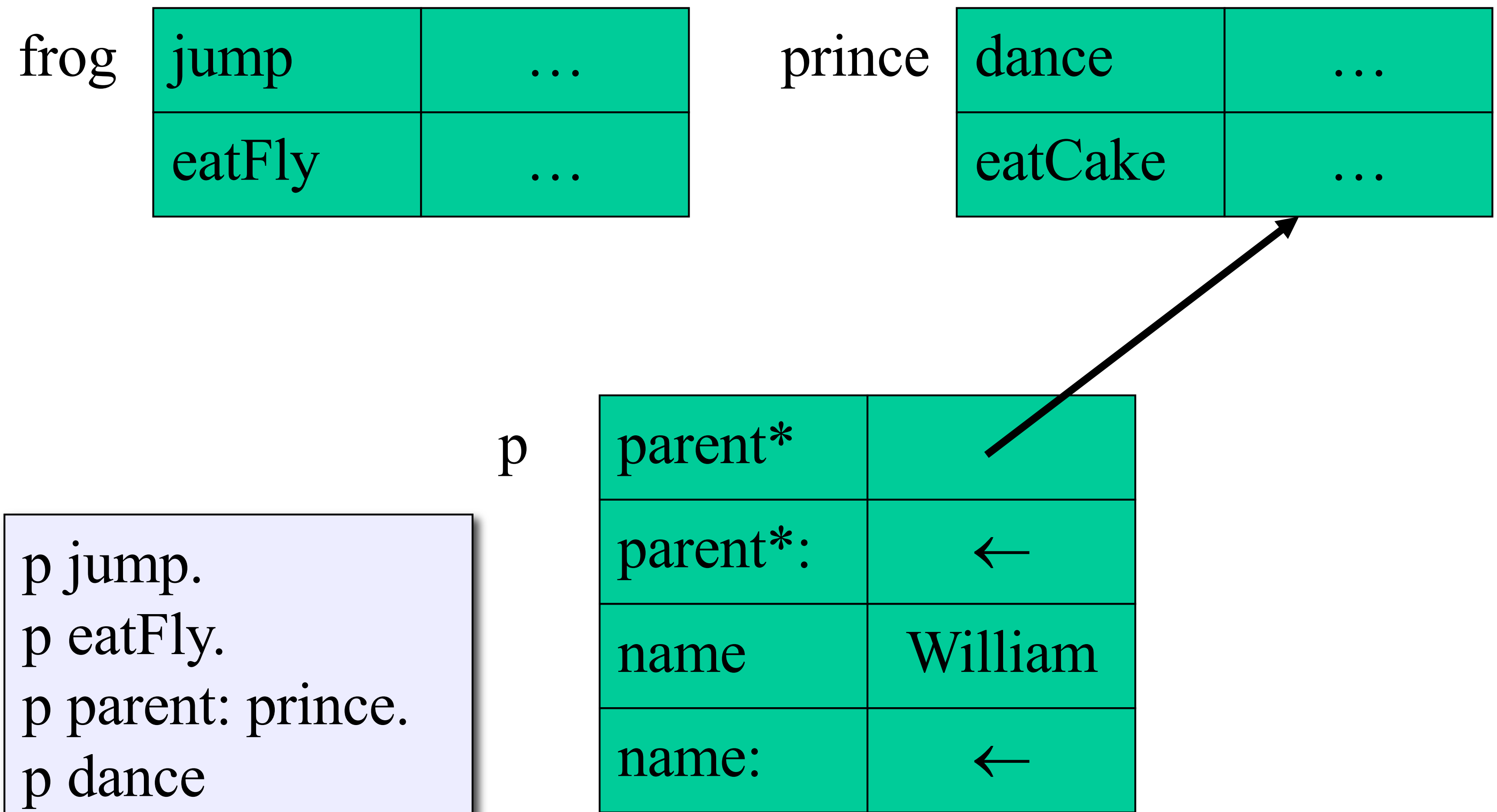
- These operations also apply to parent slots

Changing Parent Pointers




```
p jump.
p eatFly.
p parent: prince.
p dance.
```

Changing Parent Pointers



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 (What is the class of a class? Or: Is a class an object, and if not, what is it?)
- 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++ / Java

- C++ / Java
  - Restricts expressiveness to ensure efficient implementation and type safety
    - “message not understood” is not possible
- 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

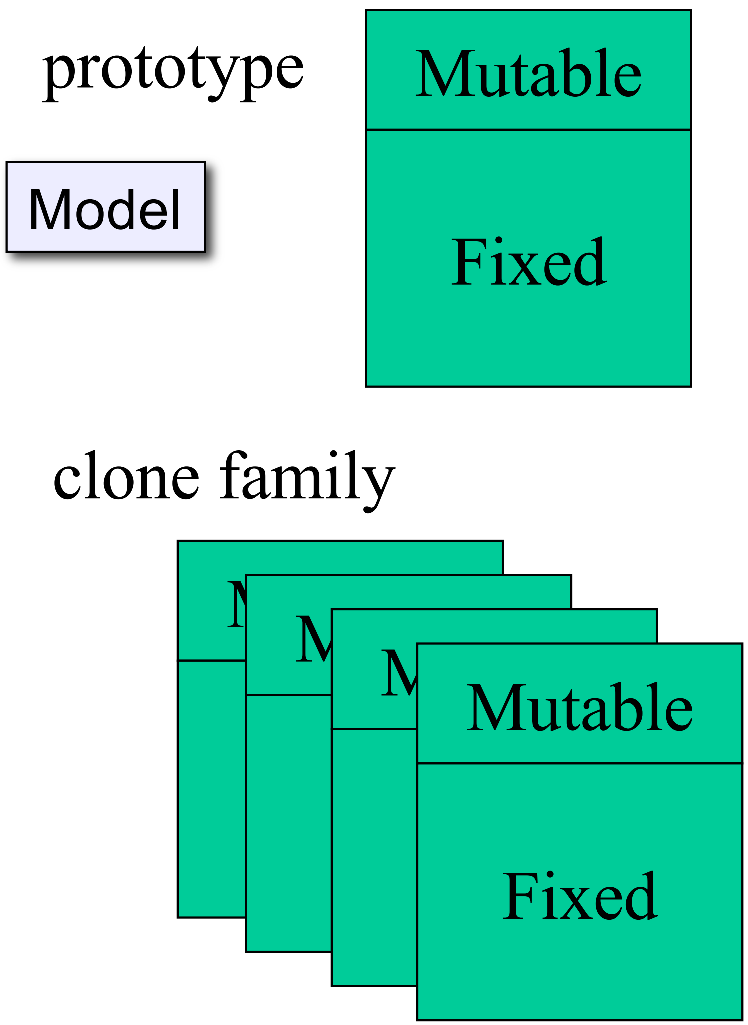
> Optimized Smalltalk-80 is roughly 10 times slower than optimized C

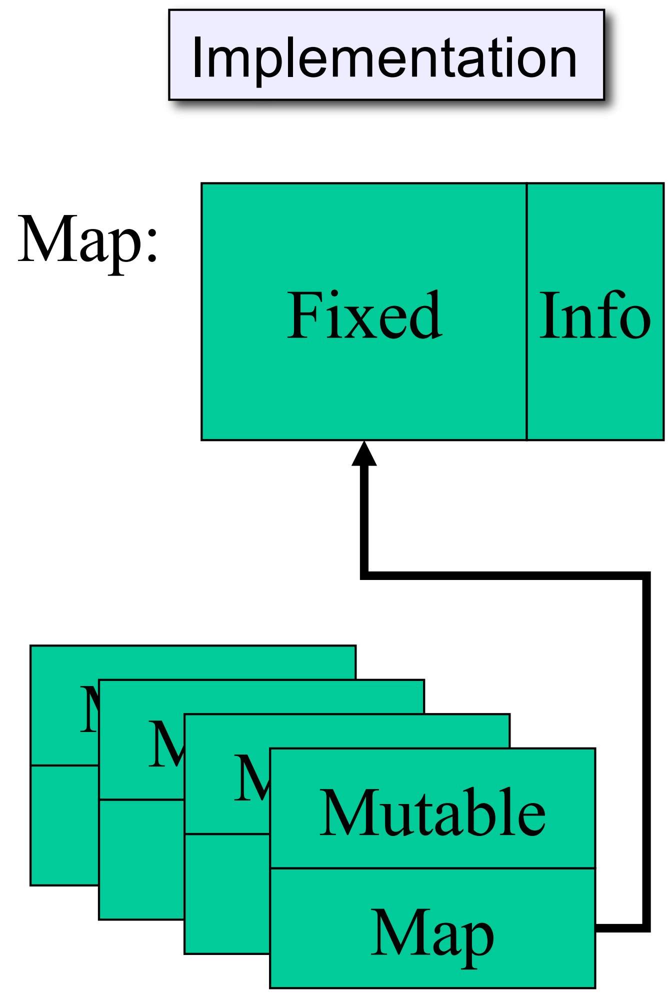
Optimization Strategies

- 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)

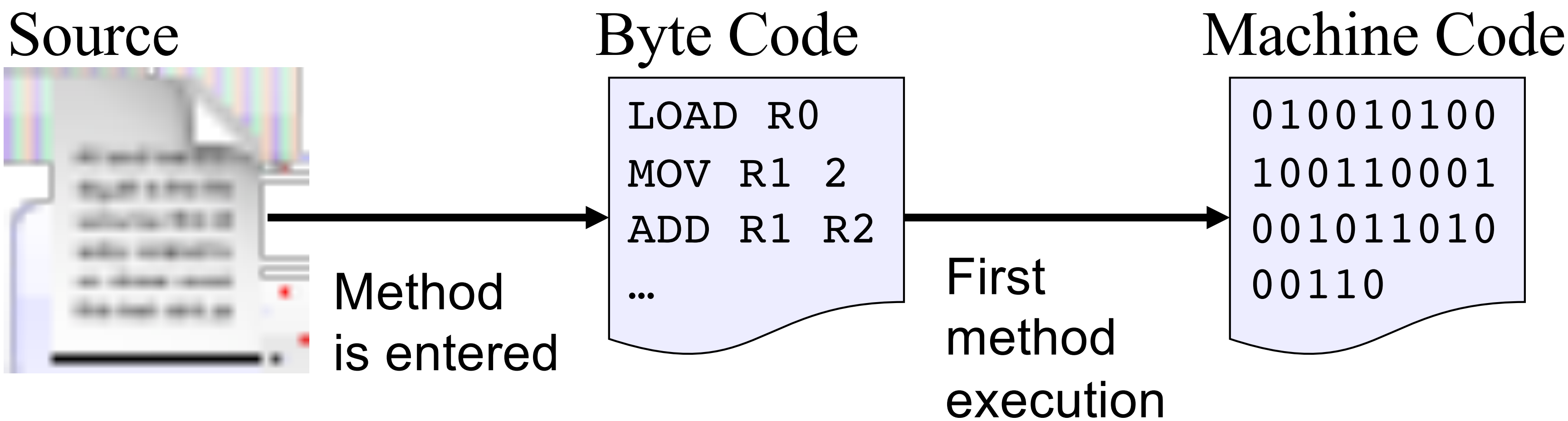
Avoid per object data





Dynamic Compilation

Avoid interpreting



- 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 method lookup

Lookup Cache

- Cache of recently used methods, indexed by (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

Avoid method lookup

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):

```
if type = smallInt jump to method_smallInt
call general_lookup
```

Avoid method lookup

Inline Caches

- First message send from a *call site*:
  - general lookup routine invoked & backpatch
- Call site back-patched previously
  - 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.

Avoid method lookup

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

Inline methods

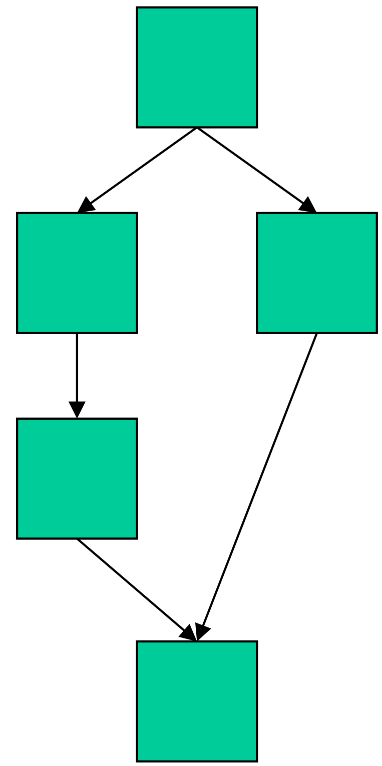
Customized Compilation

- 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

Inline methods

Type Analysis

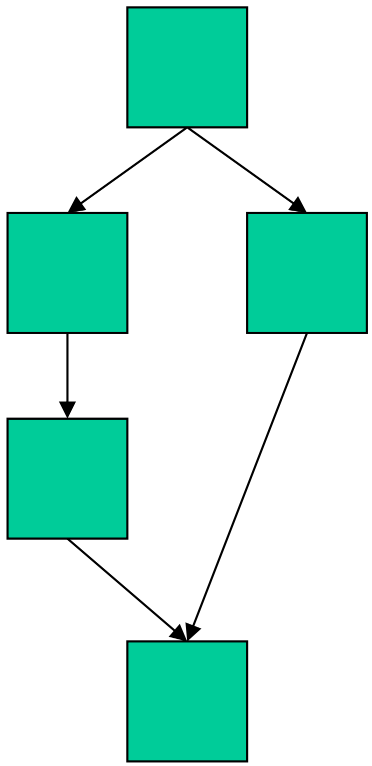
- Constructed by compiler using flow analysis
- Type: set of possible maps for object
  - Singleton: know map statically
  - Union/Merge: know expression has one of a fixed collection of maps
  - Unknown: know nothing about expression
- If singleton, we can inline method
- If type is small, we can insert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



Inline methods

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

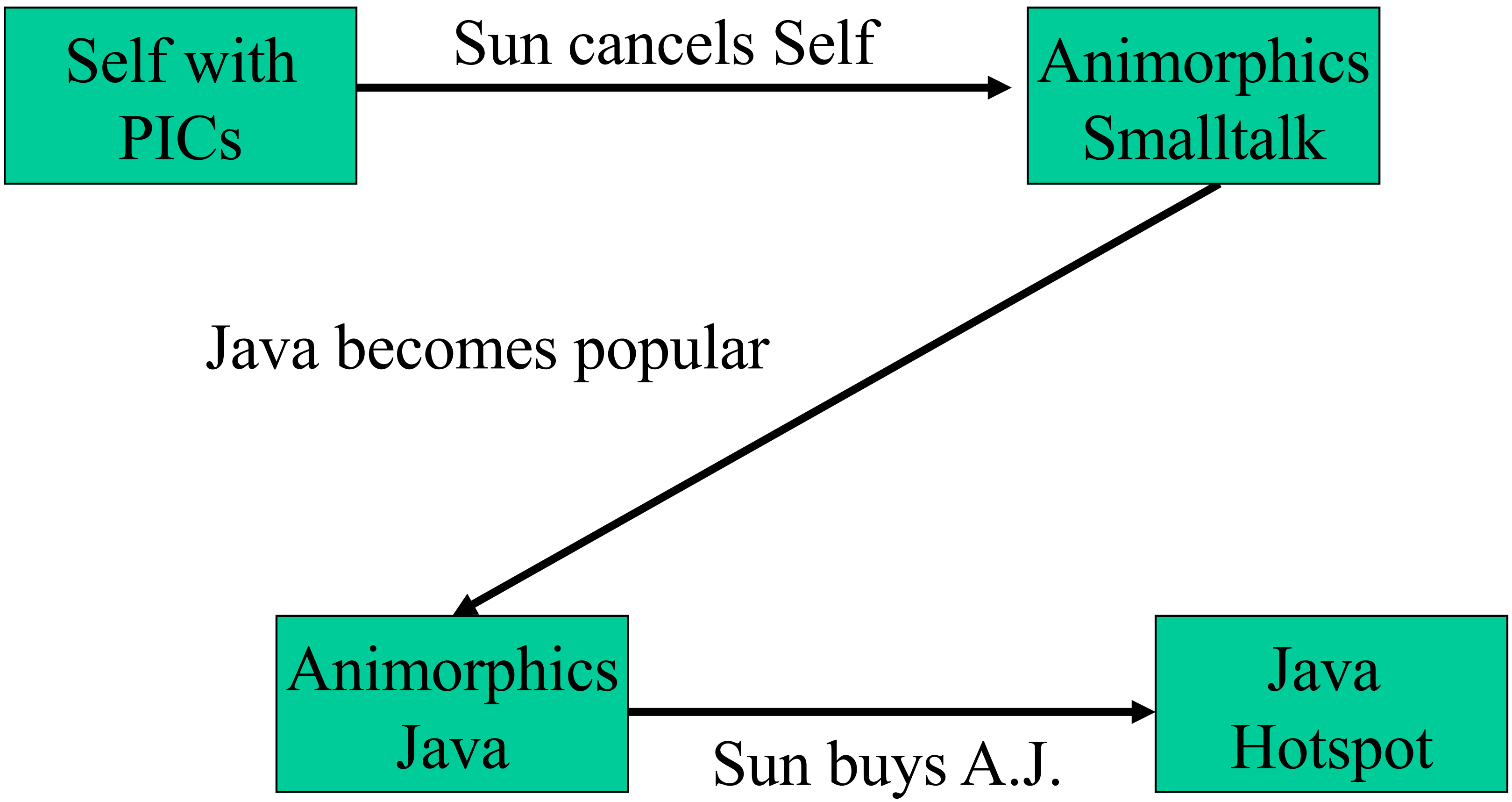
- Polymorphic inline caches build a call-site specific type database *as the program runs*
- Compiler can use this runtime information rather than the result of a static flow analysis to build *type cases*
- Must wait until PIC has collected information
  - When to recompile?
  - What should be recompiled?
- 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%

Fairly recent Self compiler is within a factor of 2 of optimized C.

Impact on Java



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
  - First-class closures as values
  - 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

Conclusions?

- For you to decide…