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Open, extensible dynamic programming systems

or *just how deep is the 'dynamic' rabbit hole?*

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dynamic

dynamic?

- data?
  - extending objects and definitions
  - modifying the type system
    - modifying the *dynamic* type system
- behaviour?
  - extending the program during execution
    - modifying the *dynamic* effects of execution
- something that subsumes/unifies both, obviates one?

‘dynamic languages’ provide *direct tools* to do this

language

language?

- syntax
  - valid sentences of the language
- semantics
  - finding a meaning for those sentences
- implementation
  - translation of semantics into ‘more primitive’ equivalents
- runtime
  - the machine and its intrinsic mechanisms
- pragmatics
  - interaction with libraries, users, and everything

when?

- compile time? run time?
- staged? continuous?

dynamic languages

dynamic language?

- syntax
  - redefining ‘valid sentence’
- semantics
  - redefining or extending the range of meaning
- implementation
  - creating meaning from ‘primitive’ execution mechanisms
  - ability to directly modify machine code, *including ...*
- runtime
  - creating new ‘primitive’ execution mechanisms
- pragmatics
  - discovering, attaching to, using external resources

at any time during development, compilation, deployment, execution

> The assertion that ‘a language is dynamic’ is more an assertion about the *ease of use* of dynamic features than it is a clear statement of the capabilities of the language. [WP]

techniques and tools

introspection

- from determining the type of a polymorphic value
- to full analysis of the system's code as data

1st-class dynamic functions

- construction of new behaviour at any time
- immediate or delayed execution

active introspection (intercession)

- full access to the compiler
  - compiler implementation is 1st-class dynamic functions
- full access to the runtime
  - runtime mechanisms are 1st-class dynamic functions
- (re)define language elements
  - new syntax, grammar, semantics, optimisations

questions for this talk

how much of the language/system can we make dynamic?

how dynamic can we make it?

how general can we make it?

how simple can we make it?

less is more

> It seems that perfection might be attained not when there is nothing left to add but rather when there is nothing left to take away.
>
> Antoine de Saint-Exupéry, *Terre des Hommes, III :L'Avion*, 1939

extreme late binding

- less mechanism $\Rightarrow$ fewer assumptions to early bind
- fewer assumptions $\Rightarrow$ easier to late-bind everything
- eliminate early-bound assumptions $\Rightarrow$ generality

self-hosting system

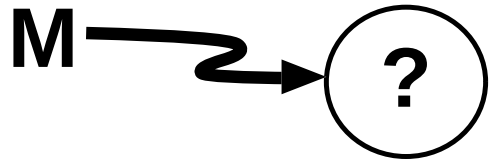
self-hosting system

- completeness
- understandability
- independence
- portability

objects

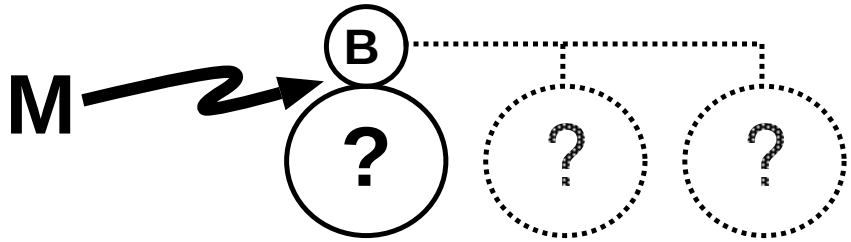
minimal object:

- encapsulates behaviour
- (subsumes state)

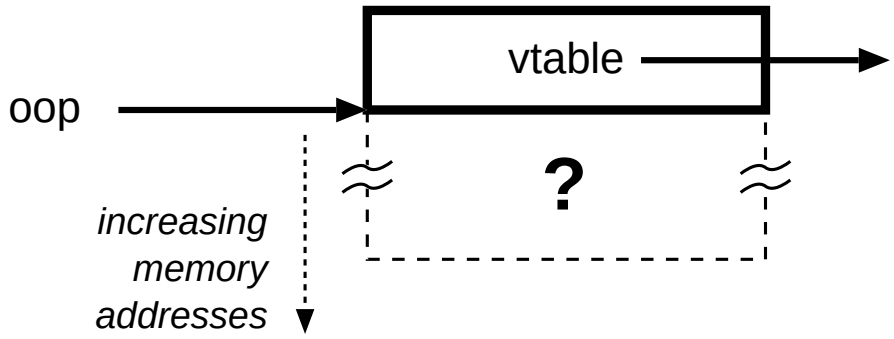


no assumptions about object contents

- decouple implementation from representation
- representation arbitrary
- behaviour replaceable (and shareable)
- implementation of behaviour replaceable (and shareable)



the minimal object

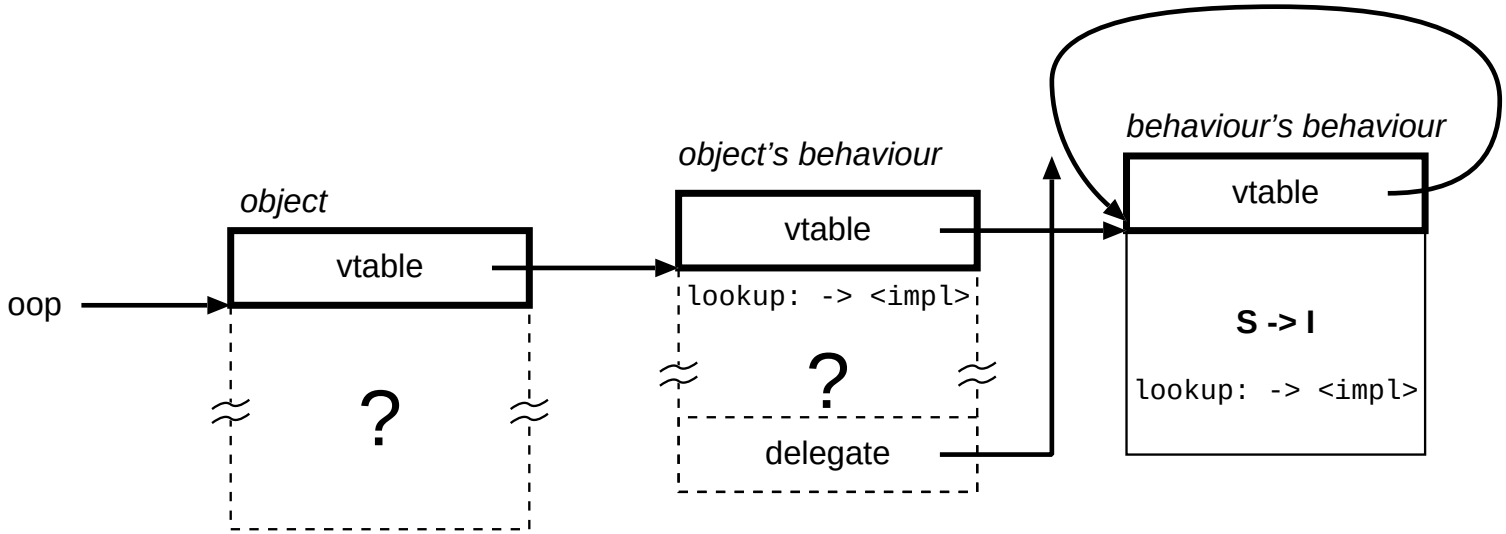



```
send(message, object, ...) :=
  method := object[-1].lookup(message)
  method(object, ...)
```

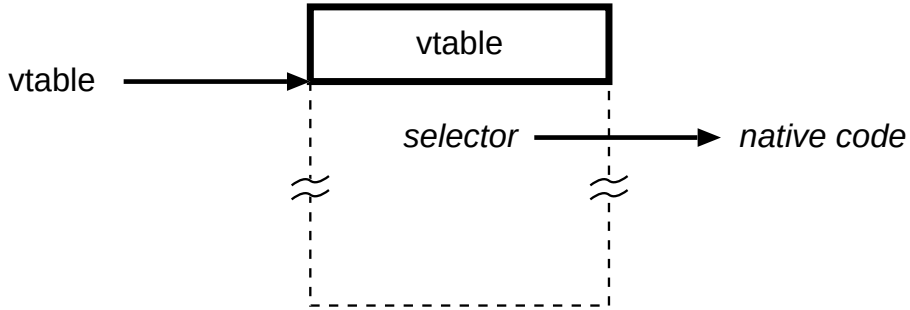
vtable protocol

```
  vtable.lookup(aSelector)
  vtable.methodAtPut(aSelector, aMethodImplementation)
  vtable.intern(aString)
  vtable.allocate(objectSize)
```

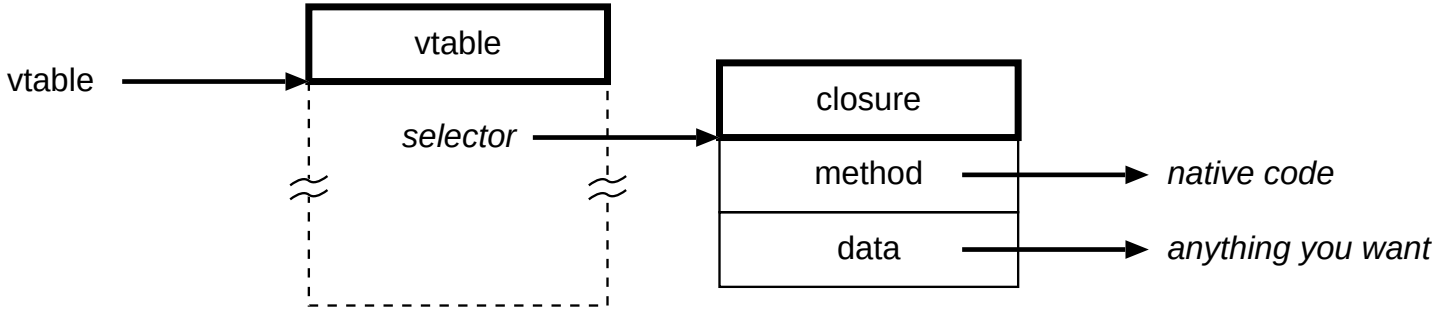
everything is an object



methods as closures



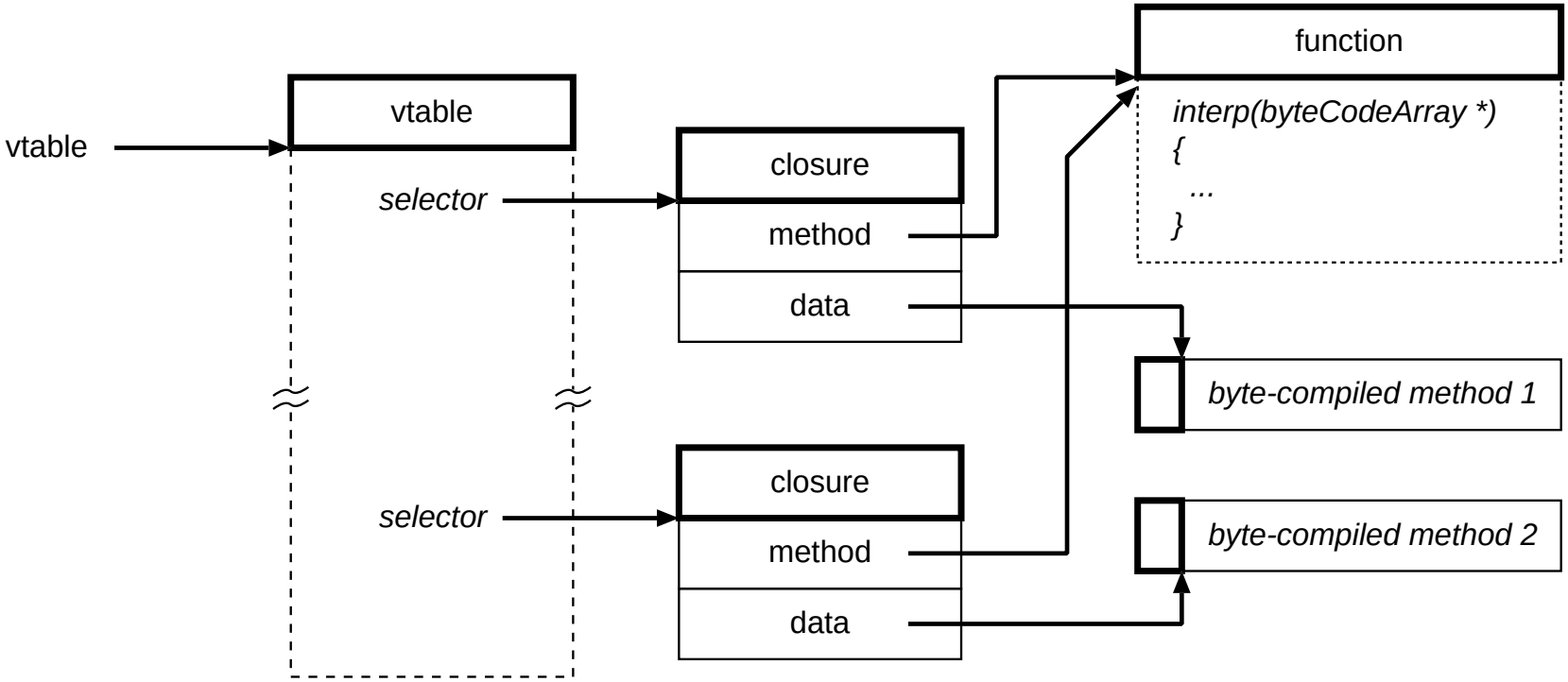
generalise relationship between message send and implementation of response:



- closure implementation can be shared
- closure data can be shared
- closure can reimplement ‘apply’

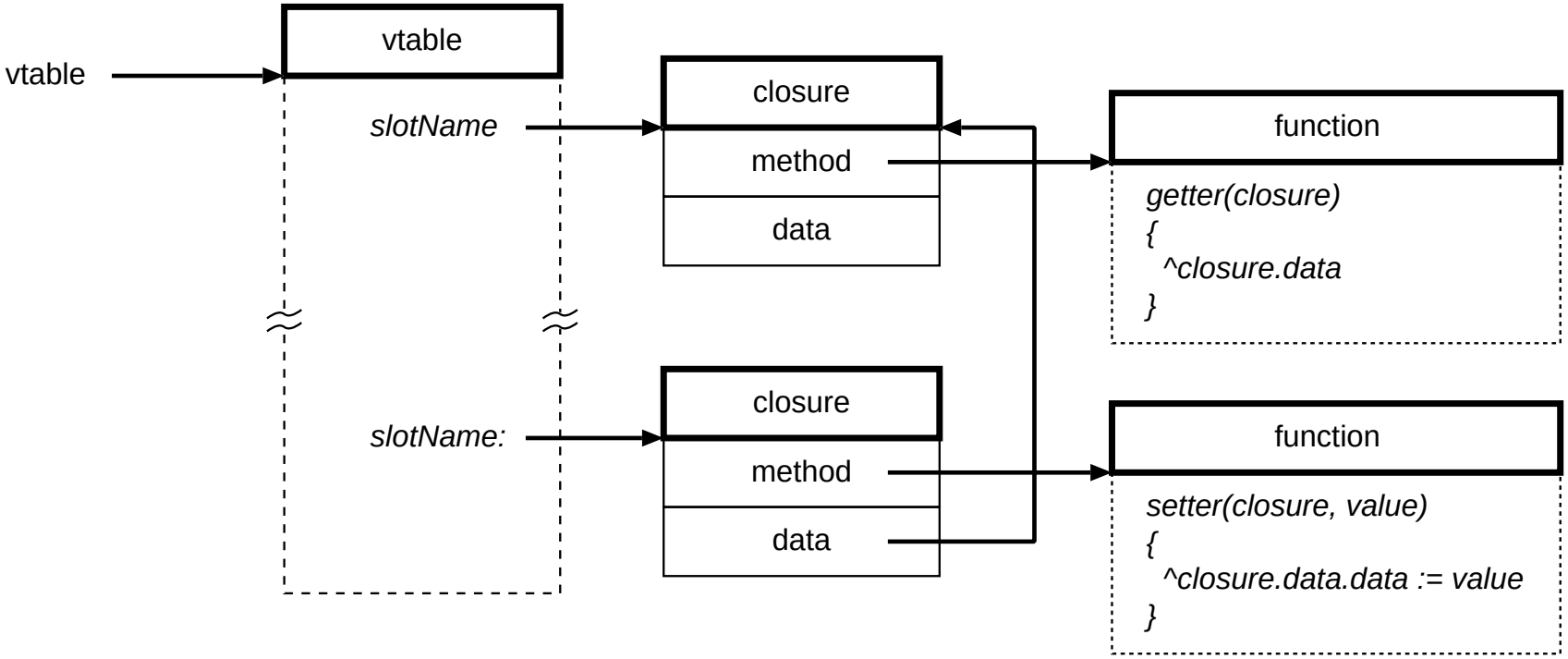
mixed-mode execution

- one ABI, multiple execution mechanisms
- transparent to sender
- profile-based optimisations (JIT), cross-paradigm calls, etc...



methods as value holders

- one getter one setter method, shared by all
- getter closure holds value
- setter closure assigns value of getter closure
- slot lookup as fast as method cache



revised vtable methods

after exposing the entire implementation:

```
selector  intern: nameString
closure   withMethod: aMethod data: anything
vtable    methodAt: aSelector put: aClosure
vtable    lookup: aSelector
vtable    allocate: objectSize
```

with intrinsic delegation mechanism (unnecessary but simplifies bootstrapping):

`object` **`vtable`** → `self[-1]`

`vtable` **`delegate`** → new `vtable` delegating to `self`

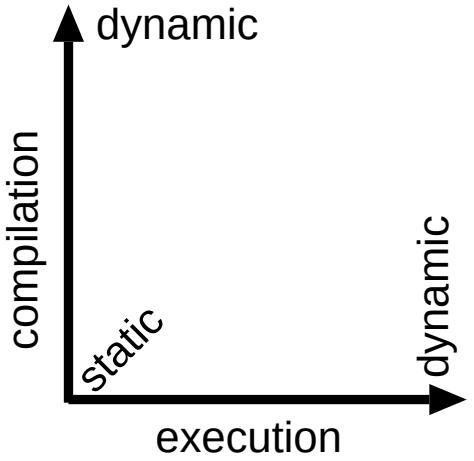
thus:

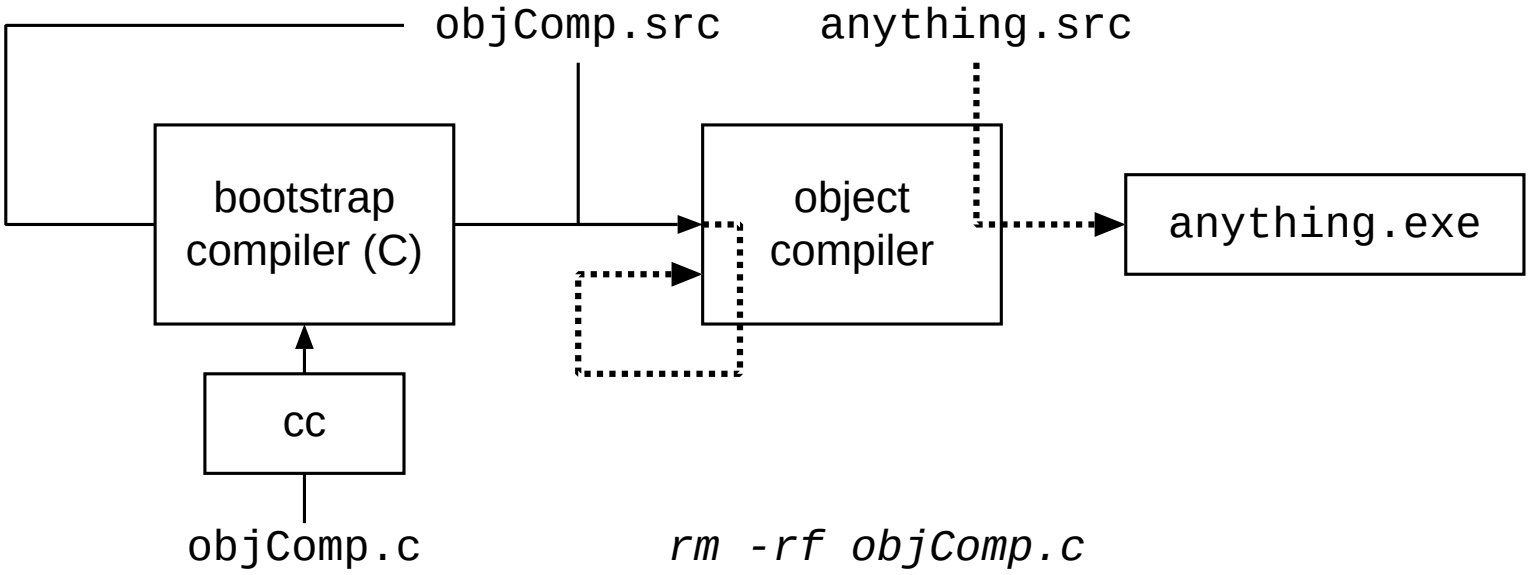
```
myPrototype := object vtable delegate allocate: 0

myPrototype new := [
  ↑self vtable allocate: self objectSize
]
```

static implementation of a dynamic universe

independent axes

- compilation (static/offline vs.dynamic/incremental)
- execution (static/early-bound vs.dynamic/late-bound)





⇒ hello world

the object compiler

demo

- self-hosting static compiler for an extreme late-bound execution model
- dynamic environment creation

```
vtable methodAt:aSelector put:aClosure
```

- dynamic execution mechanism

```
vtable lookup:aSelector
```

⇒ reflect

object compiler (in itself):2200 LOC

does it scale? ⇒ sqvm

objects *are*; methods *do*

consider Smalltalk

- represent ‘does’ with some ‘is’ (CompiledMethod)
- wave magic wand (apply VM to image)
- *representation* of ‘does’ *indirectly* moves messages around between the ‘is’

- methods have no dynamic effect without a VM
- the VM is not an object
- the actions of methods cannot be described purely in object terms
  - bind, apply, sequence

method objects imply how objects might be animated; the animation itself comes from ‘outside’

we need to bring it ‘inside’

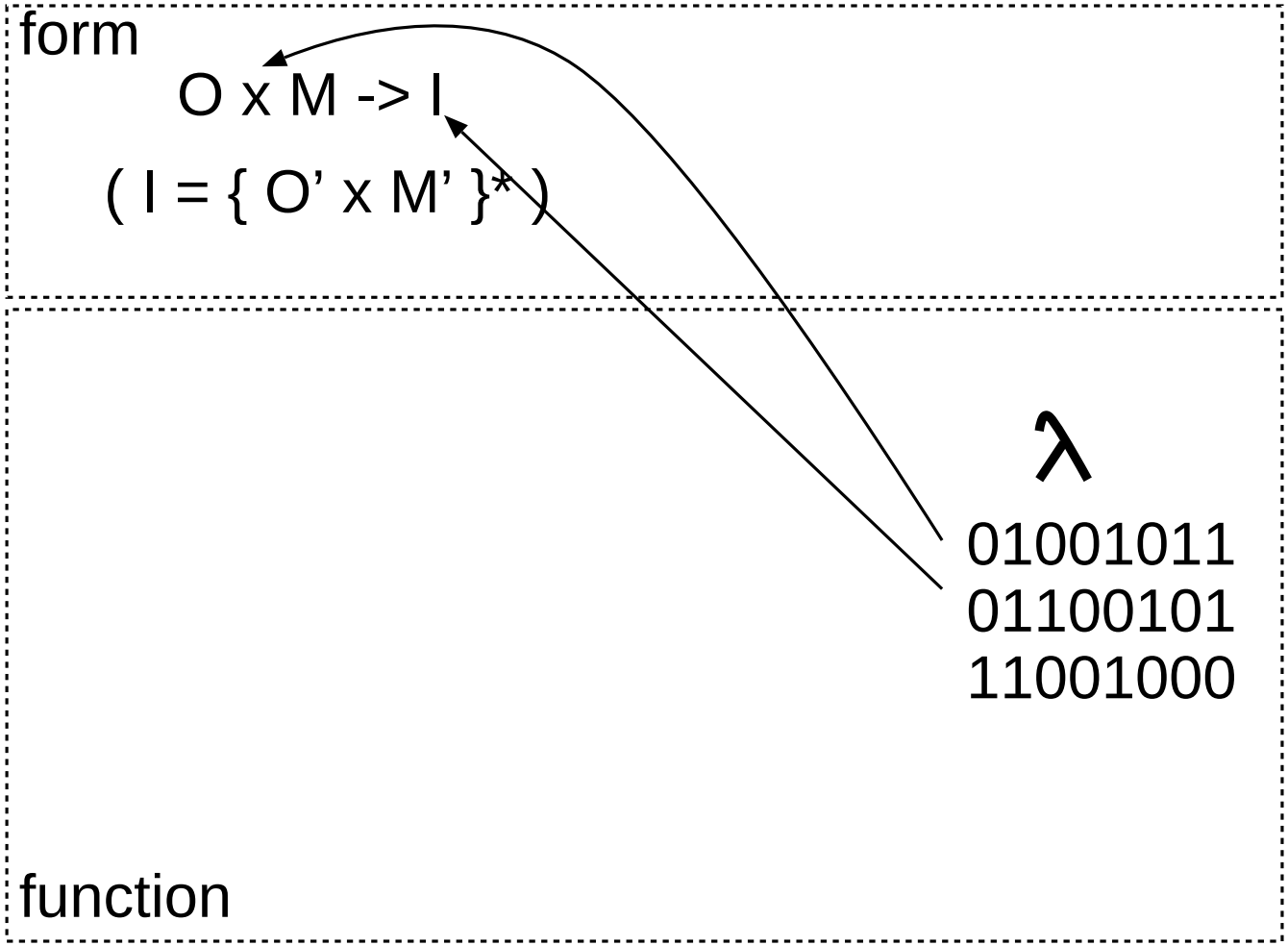
objects are form

form

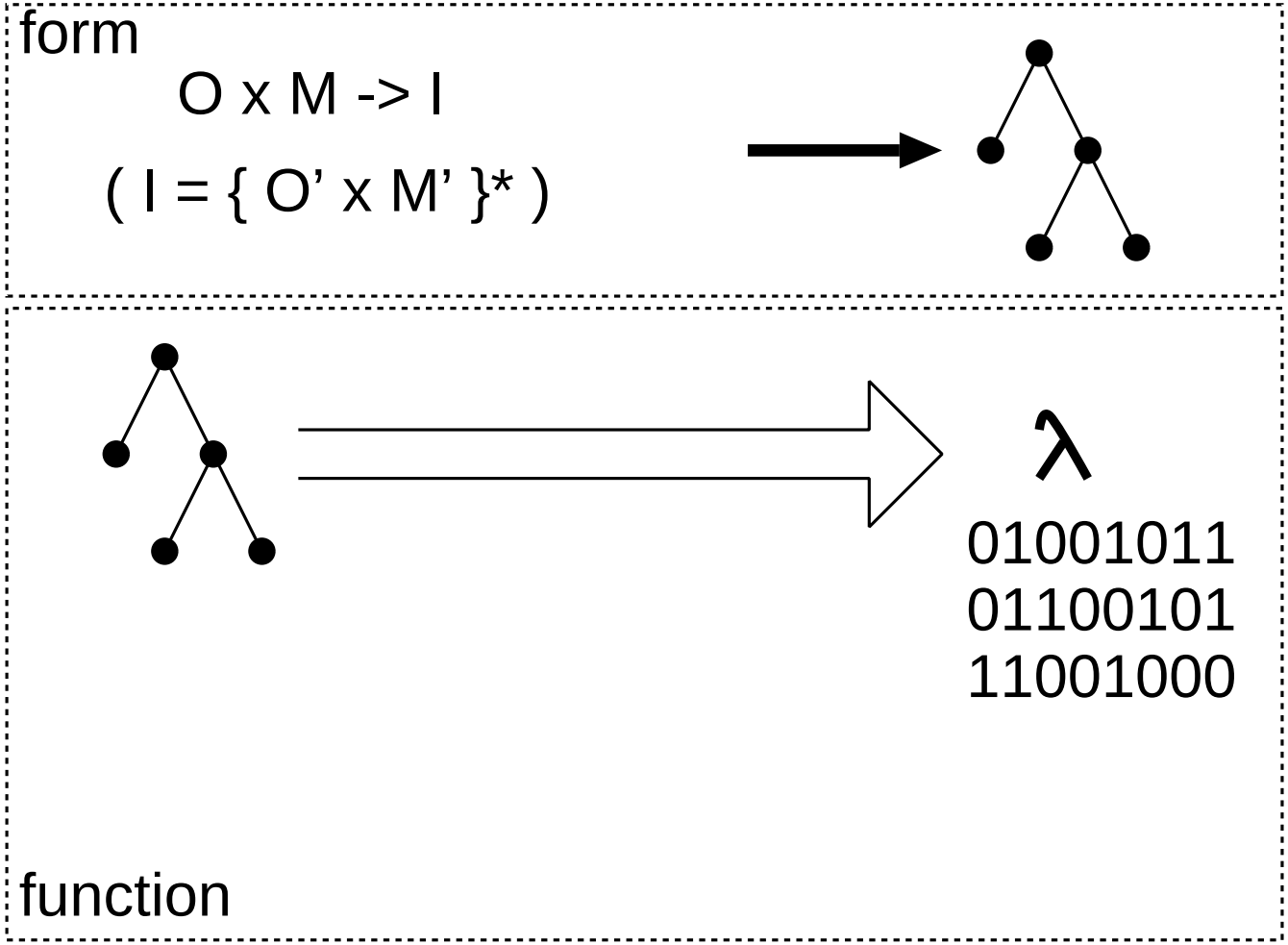
$$O \times M \rightarrow I$$

$$(I = \{ O' \times M' \}^*)$$

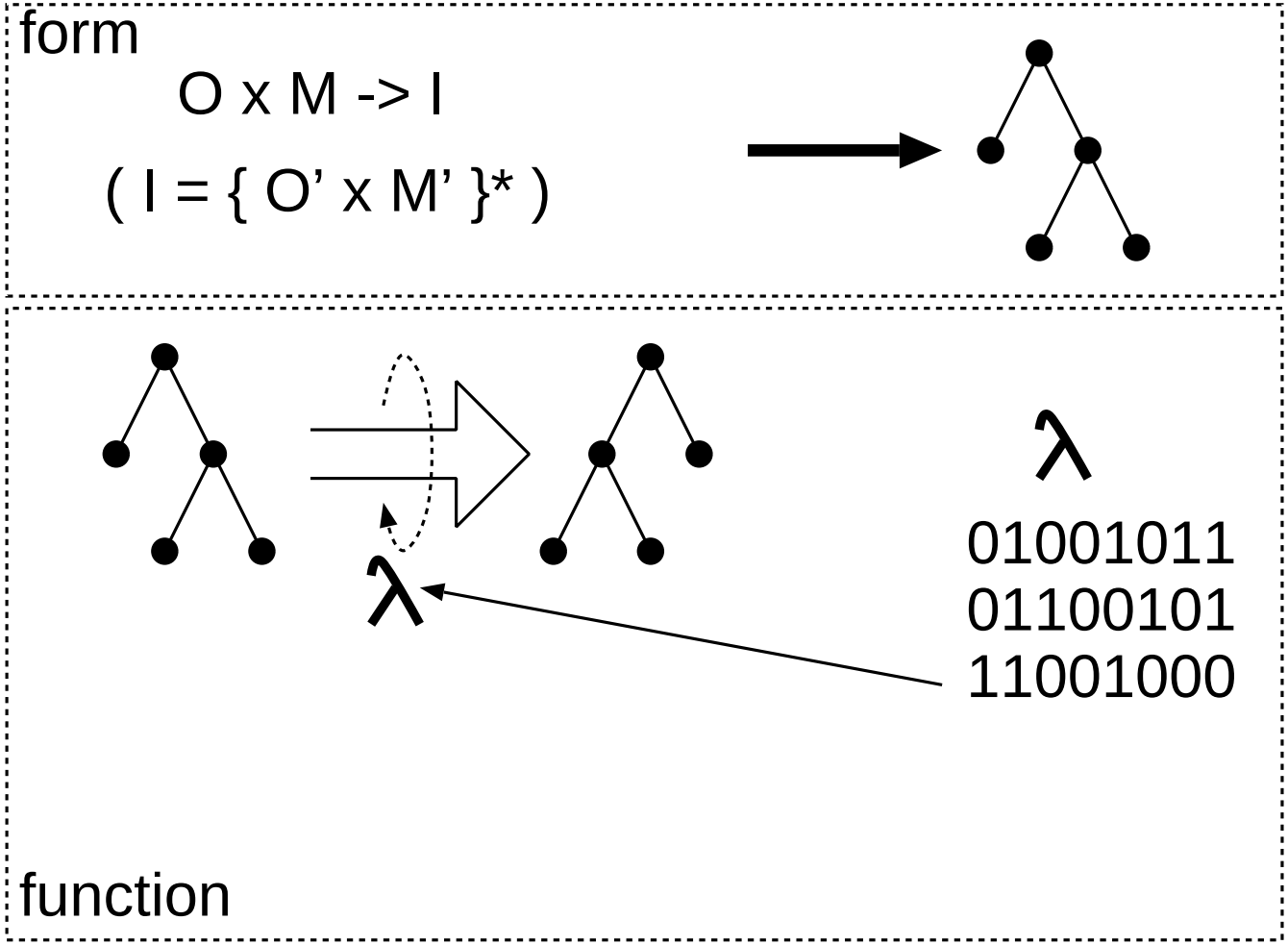
form needs function



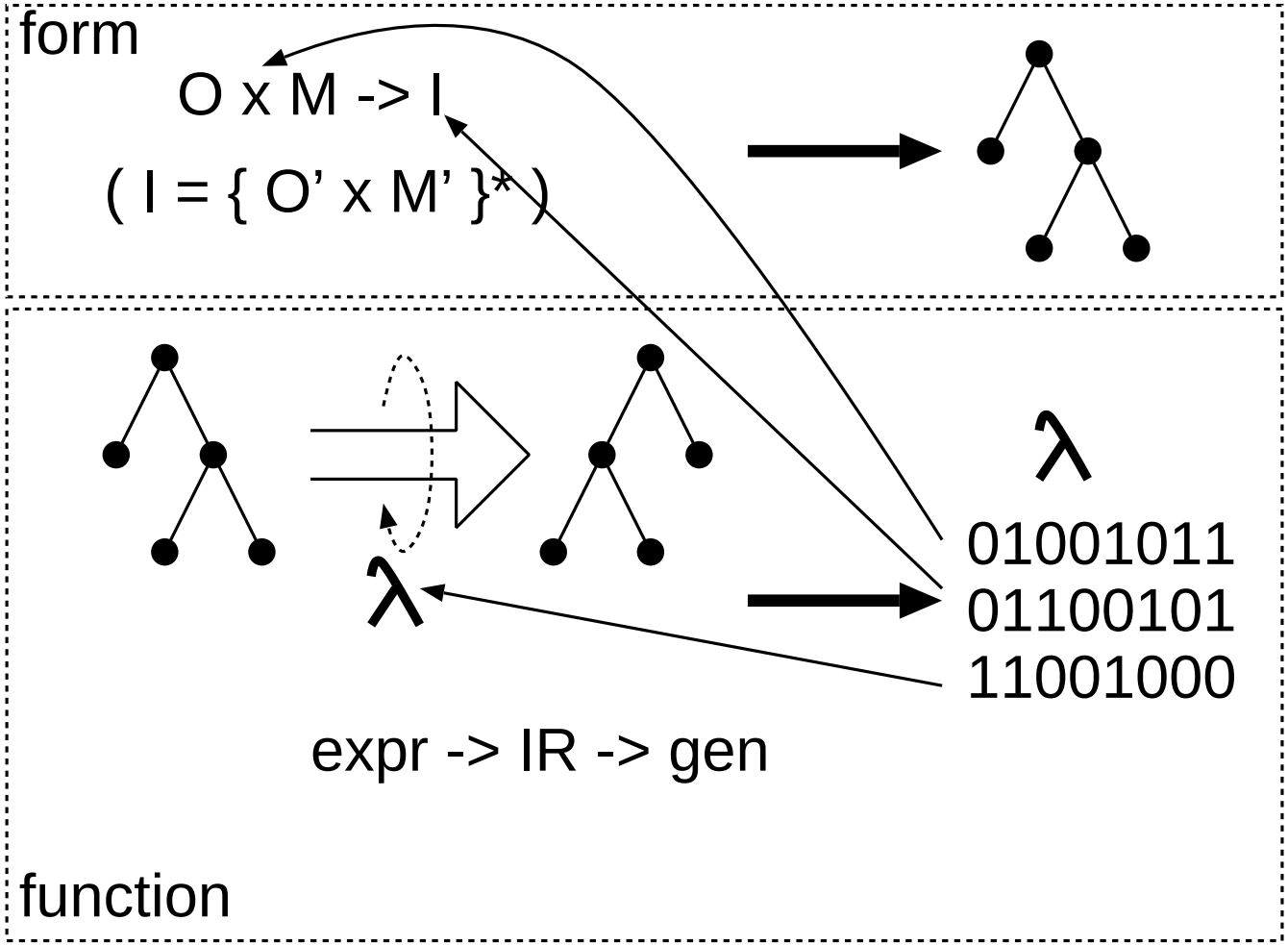
form describes function



functions transform form into function



form describes function implements form



functions

representation:s-expressions

- simple
- structured (eqv.AST)
- reasoning

domain:primitive operations and values

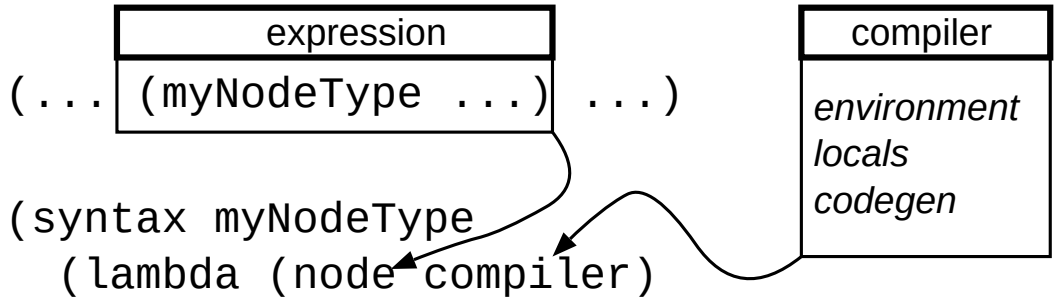
- closest to metal
- ‘animation’ of system (bind, apply, sequence) occurs at machine instruction level
- impedance with OS, libraries:C ABI

cf., Pre-Scheme (Richard Kelsey, 1997)
LISP-70 (Larry Tesler et al., 1973)

semantics

evaluation

- atoms (42, "hello world") compile to primitive literal
- sequences evaluate elements and apply first to rest; unless ...
- sequence head defined as syntax ⇒ delegate compilation




```
(syntax myNodeType
  (lambda (node compiler)
    ;; rewrite and/or codegen and/or side-effect
    ...))
```

- single mechanism for ‘intrinsic’ and ‘extended’ syntax
- intrinsic:quote syntax define set and or if while let lambda return send

⇒ operator ++

- syntactic sugar for `send` ⇒ seamless connection to representation

⇒ message send, definition

implementation

```
(printf "%d\n" (+ 3 4))

| vpu entry |
entry := Label new.
(vpu := VPU new)
   define: entry;
   enter;
   ldInt: 3;
   ldInt: 4;
   add;
   ldPtr: '%d\n';
   call: 2 target: (Label dlsym: 'printf');
   ret;
   compile.
↑ entry address
```

implementing semantics

```
(syntax while
  (lambda (node compiler)
    (let ((vpu [compiler vpu]))
      (or [[node size] == '3] (syntax-error node))
      [vpu begin:  '2]
      [vpu br:     '1]
      [vpu define: '0]
      [[node third] compile: compiler]  ; body
      [vpu drop]
      [vpu define: '1]
      [[node second] compile: compiler] ; condition
      [vpu bt:     '0]
      [vpu end:    '2]
      [vpu ldInt:  '0])
    0))
```

complexity of implementation

transform s-expressions to VPU instructions

`compile.src`: 620 LOC (including intrinsics)

VPU implementation

`VPU.src`:	420 LOC
+	176 LOC (ppc)
+	118 LOC (i386)
	714

syntax and grammar

advanced recursive-descent parsing techniques (Birman, 1970)

- easy to write, read, understand
- more general and powerful than ‘traditional’ table-driver parsers
- just as amenable to analytic techniques

need to go back even earlier:Meta-II (Val Schorre, 1962)

- self-describing, self-implementing, self-bootstrapping dynamic syntax
- memoisation
- analytic treatments (predictive parsing)

synergy:

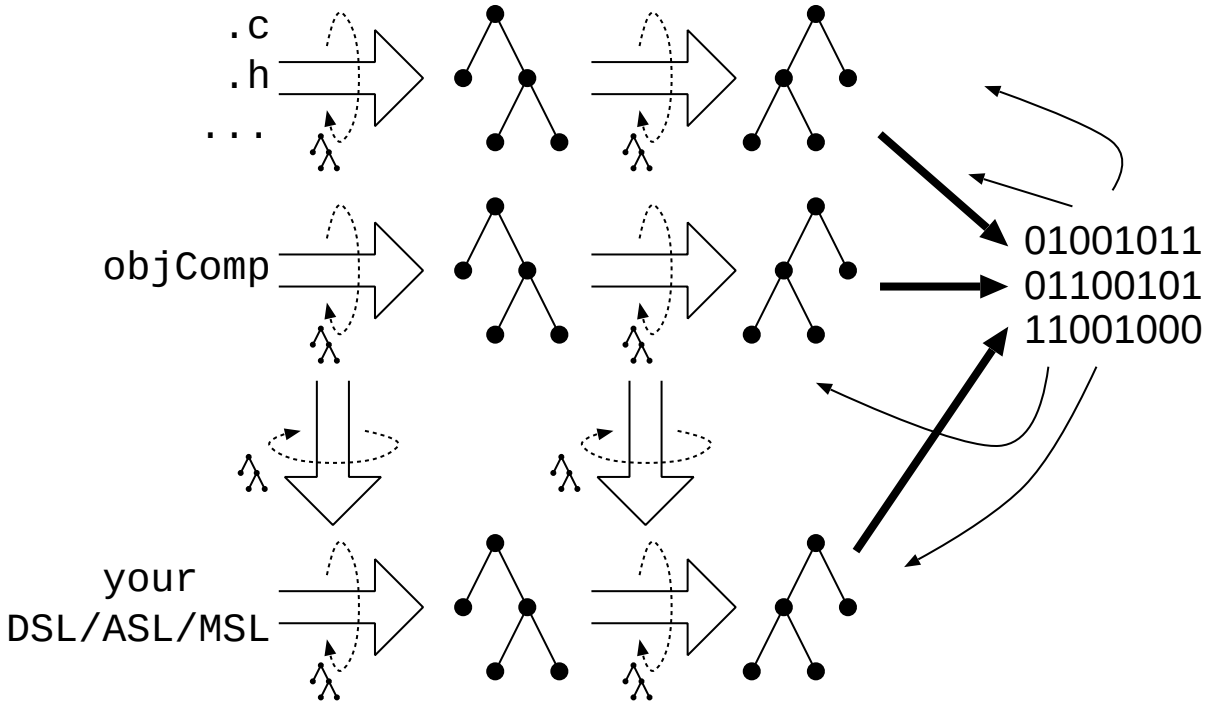
- TEX (Donald Knuth, 1981)

demo:

- active parsing $\Rightarrow$ input
- dynamic postfix operator syntax in a prefix language $\Rightarrow$ array

everything is self-describing structure

downwards, sideways



& upwards

- lexical, syntactic, semantic, IR analysis as pattern-directed transformation

scorecard (so far)

- √ extend the program's code during execution
- √ extend objects and definitions during execution
- √ a program analyzing its own structure, code, types or data
- √ executable data structures
- √ offline and online compilation
- √ VM, just-in-time compilation
- √ ability to directly modify machine code
- √ generating new objects from a runtime definition
- √ runtime alteration of object or type system
- √ changing the inheritance or type tree
- √ closures, continuations, introspection
- √ new language constructs, optimisations, grammar

object comp	s-expr comp	VPU + 2 arch	total
2199	620	714	3533

topics not discussed #1

implicit types

- tagged immediates
- NULL pointer as nil object

pragmatics

- primitive function `_dlsym`, primitive constant `_RTLD_DEFAULT`
- platform header parsing $\longrightarrow$ dynamic interface generation

lazy coercions

- impedance mismatch between object and primitive type
- compiler-introduced message send to covert value
- ‘primitive methods’ become unnecessary
  - all ‘primitive’ behaviour subsumed by dynamic interfaces and coercions

selector-directed compilation

topics not discussed #2

reduction of compilation process to smallest number of ‘fundamental’ algorithms

- generic inference engine:parsing, compilation, codegen

```
ri4 :: (indiri4 (addp ri4 li2))                    => $0 := $1   [ lwz  r$1, $2(r$1)  ]
ri4 :: (addp ri4 li2)                              => $0 := $1   [ addi r$1, $2       ]
ri4 :: (addi4 ri4 ri4)                             => $0 := $1   [ add  r$1, r$1, r$2 ]
ri4 :: (cvtu4 ri4)                                 => $0 := $1
ri4 :: (indiri4 (vregp))                           => $0 := $1.1
li2 :: (cnstu4)          ? -32768 <= $1 <= 32767   => $0 := $1
```

```
reduce(tree, startSymbol) =
  foreach rule in startSets[startSymbol]
    if match(tree, rule.pattern)
      invoke rule.action
      return startSymbol
```

```
match(tree, pattern) =
  if (isSymbol(pattern)) return reduce(tree, pattern)
  if (tree.first ~= pattern.first) return false
  return foreach treeElement, patternElement in tree.tail, pattern.tail
    match(treeElement, patternElement)
```

```
(addi4
    (indiri4 (vregp 1))                    =>    lwz  r3, 12(r5)
    (indiri4 (addp (indirp (vregp 2)))           addi r3, r3, r4
                   (cnstu4 12)))
```

putting it all together: parser

```
Stmt ::=
    "{" Stmt*:s "}"                                  => ‘(begin ,@s)
  | "var" Binding:first ("," Binding)*:rest ";"      => ‘(begin ,first ,@rest)
  | "if" "(" Expr:c ")" Stmt:t ("else" Stmt |
                                Empty => ’0):f       => ‘(if (js-bool ,c) ,t ,f)
  | "while" "(" Expr:c ")" Stmt:s                    => ‘(while (js-bool ,c) ,s)
  | "do" Stmt:stmt "while" "(" Expr:cond ")" ";"     => ‘(while (begin ,stmt ,cond
  | "for" "(" ("var" Binding | Expr):init ";"
              Expr:cond ";" Expr:upd ")" Stmt:s      => ‘(begin ,init
                                                          (while ,cond
                                                            (begin ,s ,upd)))
  | "break" ";"                                      => ’(break)
  | "continue" ";"                                   => ’(continue)
  | "return" (Expr:e => ‘(#return ,e) |
              Empty => ’(#return)):r ";"             => r
  | Expr:e ";"                                       => e
```

JavaScript parser:86 LOC

putting it all together: semantics

```
(define js-set
  (lambda (lhs val)
    (match lhs
      ((js-get (js-get :c :n) :p)      `[(js-get ,c ,n) bind: ,p to: ,val])
      ((js-get (js-arr-get :a :i) :p)  `[(js-arr-get ,a ,i) bind: ,p to: ,val])
      ((js-get :c :n)                  `[,c set: ,n to: ,val])
      ((js-arr-get :a :i)              `(js-arr-set ,a ,i ,val))
      (:otherwise                      (error "%o is not assignable" lhs)))))
```

JavaScript semantics:100 LOC

putting it all together: library

```
function Array()
{
  var l = arguments.length == 1 ? arguments[0] : 0;
  this.__array__ = #[Array new: (js-get _ctxt 'l)];
  this.length = l;
  for (var idx = 0; idx < l; idx++)
    this[idx] = null;
}
```

JavaScript library:102 LOC

(minimal Object, String, Date, Number, etc...)

putting it all together: JavaScript

- semantics:100
- parser:86
- library:102 (minimal Object, String, Date, Number, etc.)
- graphics:136

⇒ js repl

⇒ cairo-app.js

just over 400 LOC

with no serious attempt at optimisation, runs a little faster than FireFox

(and a *lot* faster than WebKit aka Safari)

conclusion #1

objects

- five ‘essential’ methods
- one semantic primitive (dynamic bind in the method cache)
- $\approx$ 2200 LOC for self-hosting object compiler (Smalltalk-like syntax)
- infinitely extensible/reusable object framework

conclusion #2

functions

- tightly integrated with object model $\Rightarrow$ dynamic objects
- compatible with platform ABI
- $\approx$ 1300 LOC for self-hosting dynamic function $\longrightarrow$ native code compiler
- infinitely extensible/reusable semantic framework

conclusion #3

take away:

- ‘dynamic’ can apply to everything (data, code, types, ...)
- ‘language’ can mean all of it (syntax, semantics, implementation, pragmatics, ...)
- it can be made very, very simple
- it can be made very, very general
- it can free you from a multitude of pedantries
- it is a *lot* of fun

attractive implementation vehicle

- active protocols, extensible/configurable systems
- programming/scripting languages

conclusion #4

ideal testbed for new language and systems ideas

- if you aren't using dynamic languages this way, you should be

ideal for teaching language and systems principles

- if you aren't teaching languages this dynamic, you should be

go home and innovate!

- built your own and share it with us
- or use ours:release in a month or two

Form follows function — that has been misunderstood. Form and function should be one, joined in a spiritual union.

Frank Lloyd Wright, 1908

It is the grand object of all theory to make these irreducible elements as simple and as few in number as possible, without having to renounce the adequate representation of any empirical content whatever.

Albert Einstein, *Mein Weltbild*, 1934

On the contrary, most of our systems are much more complicated than can be considered healthy, and are too messy and chaotic to be used in comfort and confidence.

Edsger W. Dijkstra, CACM 44(3), 2001