

# LL System Design

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# Introduction

- Motivation
- Language
  - Scheme but not just Scheme
- Implementation
  - Still buggy and slow after 10 years :)
  - Similar to Oaklisp:
    - but has flonum, but no bignum.
    - all method invocations are by C function pointer call.

*«Because LL is self-referential, concepts and constructs to be illuminated later will be marked with “☀”.»*

# Why Bother?

- Wanted an embeddable Scheme:
  - with clean C name-space
  - with proper tail-calls
  - with object-oriented foundation
  - with introspection
- Platform for ideas:
  - Interpreter multiplicity, self-referential systems
  - Tagging, memory, GC, linkage, compilation, FFI.
- Another plate of hubris? :)

# Language

- LL is an pure object-oriented, lexically-scoped Scheme
- Supports multiple inheritance and mixins
- R4RS compliance is built on object-oriented core
- Based on Oaklisp and Dylan syntax and semantics
- Extensible and embedded in C
- Introspection

# Constructs

- Objects → #<<type> <object>>
- Types → #<<type> <type>>
- Operations → #<<type> <operation>>
- Messages → #<<type> <message>>
- Methods → #<<type> <method>>
- Locatives → #<<type> <locative>>

# Objects

- Have a type.
- Have a fixed number of slots.
- Immediate objects have no slots:
  - fixnum, flonum, locative ☼
- Are created by sending the **make** operation to a type object with arguments for a type-specific initialize method.

# <object>

- (get-type 5) ; => <fixnum>
- (get-type 5.5) ; => <flonum>
- (get-type <fixnum>) ; => <type>
- (get-type <type>) ; => <object>
- (make <pair> 1 2) ; => (1 . 2)
- (eq? (make <symbol> "foo") 'foo)  
; => #t
- (%slot (make <pair> 1 2) 1) ;;; unsafe! ☀  
; => 1

# Types

- Are subtypes of <object>.
- Are named **<something>** by convention.
- Can be anonymous.
- Can be subtyped (meta-types).
- Have a list of supertypes.
- Have a list of slots.
- Have a mapping of operations and methods.
- Core LL types have analogous C structs.



# <type>

- (type-supers <object>) ; => ()
- (type-supers <type>) ; => (<object>)
- (type-supers <pair>) ; => (<list> <object>)
- (type-slots <object>) ; => ((isa 0)) ☀
- (type-slots (get-type '(1 2))  
; => ((car 0) (cdr 4)) ☀
- (define <my-cons>  
 (make <type>  
 (list <object>) ; supertypes  
 (list 'car 'cdr))) ; slots

# Mutable .vs. Immutable

- By convention mutable types are subtypes of immutable types.
  - (define x (cons 1 2))  
(get-type x) ; => #<<type> <mutable-pair>>  
x ; => (1 . 2)  
(set-car! x 'a)  
x ; => (a . 2)
  - (make-immutable x)  
(get-type x) ; => #<<type> <pair>>  
(set-car! x "foo") ; => *ERROR*

# Operations

- Are objects.
- Can be anonymous.
- Can be subtyped.
- Contain a method lookup cache. ☀
- Associate the receiver type (the first argument or <object>) and an implementation method.
- Are the only objects that can be “applied”. ☀

# <operation>

- (define my-car (make <operation>))
- (define my-cdr (make <operation>))
- (define my-func  
    (lambda (x) ; ☀  
        (+ (my-car x) (my-cdr x))))

# Settable Operations

- Are operations that have a setter operation.
  - `car` ; => `#<locatable-operation car>` ☀
  - `(type-supers (get-type car))`  
; => `(<settable-operation>)`
  - `(setter car)` ; => `#<operation set-car!>`
  - `(define x (cons 1 2))`  
`x` ; => `(1 . 2)`  
`(car x)` ; => `1`  
`((setter car) x 'a)`  
`x` ; => `(a . 2)`

# (set! (op . op-args) value)

- Syntax is transformed into the application of a setter of a <settable-operation>:
  - (set! (op . op-args) value) =>  
((setter op) . op-args value)
- (define x (car 1 2))  
(set! (car x) 'b)  
x ; => (b . 2)
- (define v (make <vector> 4 'a))  
(set! (vector-ref v 2) 'b)  
v ; => #(a a b a)

# Messages

- Are objects.
- Are created by the application of an operation to a receiver and some arguments.
- Lookup is based on the <type> of the receiver.
- Without arguments are messages to a non-existent <object>. ☀
- Implementation:
  - Created on a message stack. ☀
  - Arguments and results are on a separate value stack. ☀

# Message Lookup

- `(cons 1 2) =>`
  - Receiver type => `<fixnum>`
  - Implementation type => `<object>`
- `(newline) => ...`
  - Receiver type => `<object>`
  - Implementation type => `<object>`
- `(+ 1 2) => ...`
  - Receiver type => `<fixnum>`
  - Implementation type => `<fixnum>`



# Methods

- Are objects.
- Are anonymous.
- Can be subtyped.
- Can close-over globals, formal arguments or object slots.
- Give lexical scope to slots in an object of a particular type.
- Are resolved at run-time by operation and type.  
Implementation: a primitive C function pointer. ☀

# (add-method ...)

- The primitive closure syntax is:  
(%method slots formals . body) ☼
- (add-method (op (type . slots) . formals) . body)  
; =>  
(%add-method type op  
(%method slots formals . body))

# <method>

- (add-method  
 (initialize (<my-cons> car cdr) self a d)  
 (set! car a)  
 (set! cdr d)  
 self))
- (define my-car (make <settable-operation>))  
 (add-method  
 (my-car (<my-cons> car) self)  
 car)  
 (add-method  
 ((setter my-car) (<my-cons> car) self value)  
 (set! car value)))

# Operation Overloading

- (define add (make <operation>))  
(add-method (add (<string>) a b))  
  (string-concat a b))  
(add-method (add (<number>) a b))  
  (+ a b))
- (add "foo" "bar")       ; => "foobar"  
  (add 2 3)               ; => 5  
  (add "foo" 3)          ; => ERROR:

# Lambda

- Lambdas are anonymous operations.
- The anonymous lambda <operation> is implemented by a <method> defined on <object>.
- Lambda operations can be overloaded for other receiver (first argument) types.

# (lambda formals . body)

- (define (foo bar)  
  (+ bar 5))  
=>  
(define foo (lambda (bar)  
  (+ bar 5)))
- =>  
(define foo  
  (add-method ((make <operation>) (<object>)  
    bar)  
  (+ bar 5)))

# Locatives

- Locatives are language-level pointers to value locations, such as:
  - arguments, global bindings or object slots.
- Simplify closures, great for mutable object slots.
- <method> environment vectors contain locatives to closed-over formals and slots which have been moved to the heap.
- $(\text{contents } (\text{make-locative } x)) \Rightarrow x$
- $(\text{make-locative } (\text{contents } x)) \Rightarrow x$

# <locative>

- (define x 5)  
(define l (make-locative x))  
x ; => 5  
(contents l) ; => 5  
(set-contents! l 10)  
(contents l) ; => 10  
x ; => 10
- (define x (cons 1 2))  
(define l ((locater car) x))  
(set-contents! l 'foo)  
x ; => (foo . 2)



# Locatable Operation

- A <locatable-operation> is a <settable-operation> that has a locator <operation>.
- (locator op) returns an <operation> that returns a <locative> to a value:
  - car ; => #<locatable-operation car>
  - (setter car) ; => #<operation set-car!>
  - (locator car) ; => #<operation locative-car>
  - (define x (cons 1 2))  
(define f (locator car))  
(f x) ; => #<locative (car x)>  
(contents (f x)) ; => 1

# (make-locative (op . args))

- (make-locative (op . args) =>  
((locator op) . args)
- (define x (cons 1 2))  
(define l (make-locative (car x)))  
x ; => (1 . 2)  
(set-locative! l 'a)  
x ; => (a . 2)

# `(set! (contents . args) x)`

- `(set! (contents . args) x) =>`  
`((setter contents) . args x)`
- `(define x (cons 1 2))`  
`(define l (make-locative (car x)))`  
`(set! (contents l) 'a)`  
`x ; => (a . 2)`

# Messaging

- Message Object
  - Operation
  - Receiver and Type
  - Arguments
- Method Lookup
  - Method
  - Implementation type
  - Type offset ☀
- Method Application

# Message Object

- Message objects have:
  - An operation
  - An argument list (including the receiver in car)
- Method lookup computes:
  - The receiver type
  - The method implementing the operation for the receiver type
  - The type that implemented the method
- Method application:
  - Calls the method with the message.

# Mutual Tail Recursion

- ```
(define (f a)
  (write (cons 'f a)) (newline)
  (g (+ a 1)))          ; tail call
```

  

```
(define (g b)
  (write (cons 'g b)) (newline)
  (f (* b 2)))          ; tail call
```

  

```
(f 0)                   ; normal call
```

# Message Protocol

- <message> objects are created.
- Two explicit stacks:
  - <message> stack.
  - Value stack for arguments and results.
- Both stacks use stack buffers for call-cc. ☀
- Dual stacks simplify tail-calls. ☀
- Avoid passing arguments to lookup primitives, use global stack pointers. ☀

# Operation Application

- `(operation . arguments) =>`  
    `(apply operation arguments)`
- Pseudo-code to implement `(apply ...)` =>
  - `(define *value-stack* ())`
  - `(define *method-stack* ())`
  - `(define (%call operation . arguments) ...)`
  - `(define (%call-tail operation . arguments) ...)`
  - `(define (%return result) ...)`



# (%call operation . arguments)

- (define (%call operation . arguments)  
 (%push-each \*value-stack\* arguments)  
 (%push \*message-stack\*  
 (make <message>  
 operation (%length arguments)))  
 (while (%lookup-and-apply))  
 (%pop \*value-stack\*))

# (%lookup-and-apply)

- (define (%lookup-and-apply)  
 (%call  
 (%method-function  
 (%lookup (%top \*message-stack\*)))))

# (%lookup message)

- (define (%lookup message)  
 (let\* ((type (%receiver-type message))  
 (meth (assq (%operation message)  
 (%op-meth-alist type))))  
 (if meth  
 (begin  
 (%set-method! message meth)  
 (%set-method-impl! message type)  
 meth  
 )  
 (%lookup-super message))))

# (%return result)

- (define (%return result))  
 (%pop-arguments)  
 (%pop \*message-stack\*)  
 (%push \*value-stack\* result)  
 #f)
- #f tells caller's %apply (while ...) loop to stop.

# (%call-tail operation . arguments)

- (define (%call-tail operation . arguments)  
 (let ((message (%top \*message-stack\*)))  
 (%pop-arguments)  
 (%push-each \*value-stack\* arguments)  
 (%set-operation! message operation)  
 (%set-arguments! message  
 (make-locative (%top \*value-stack\*)))  
 #t)
- #t tells caller's %apply (while ...) loop to keep going.

# Interpreter Implementation

- Values, Boxing and Tagging
- Object Layouts
- Runtime Bootstrapping
- Messaging
- Continuations, Catch/Throw
- Evaluation
- Performance

# Values, Boxing and Tagging

- Values are machine words:
  - 32-bit words => 4 byte alignment.
  - Defined in C as **typedef unsigned int ll\_v**.
- Boxing Values
  - Some objects cannot fit in a machine word.
- Tagging Values
  - Not all values are pointers.
  - Tagging takes up space in machine words.
- Tagging Schemes
  - Some schemes are better than others.

# Boxing and Tagging

- Most CPUs do not support latent typing in microcode.
- Some interpreter objects can fit in machine words, many cannot.
- Allocating memory for every object (including integers, floats) is expensive, if not impossible.
- Trade off space, precision, performance and complexity.
- Play nice with C but don't give the good fight.



# Allocated Object Layout

- Each slot is a word.
- Each ancestor type is given one block of slots.
- Offsets of each ancestor type is stored in each type.
- Mixins have no slots.
- Core types are defined by C macros:
  - Define C structures with inheritance.
  - Create interpreter <type> objects for introspection.

|                                       |            |           |
|---------------------------------------|------------|-----------|
| <i>&lt;object&gt; : #&lt;anon&gt;</i> |            |           |
| 0+0                                   | isa        | <binding> |
| <i>&lt;properties-mixin&gt;</i>       |            |           |
| <i>&lt;binding&gt;</i>                |            |           |
| 4+0                                   | name       | 'x        |
| 4+4                                   | value      | ...       |
| 4+8                                   | readonly?  | #f        |
| 4+12                                  | properties | (...)     |

```
(define x (cons 'foo "bar")) =>
'(foo . "bar") =>
```

|                                      |               |                                                   |
|--------------------------------------|---------------|---------------------------------------------------|
| <i>&lt;object&gt; : &lt;pair&gt;</i> |               |                                                   |
| 0+0                                  | isa           | <type>                                            |
| <i>&lt;properties-mixin&gt;</i>      |               |                                                   |
| <i>&lt;type&gt;</i>                  |               |                                                   |
| 4+0                                  | supers        | (<object> <list>)                                 |
| 4+4                                  | slots         | '((car . 0) (cdr . 4))                            |
| 4+8                                  | op-meth-alist | ((car . #<meth>) ...)                             |
| 4+12                                 | type-offset   | ((<object> . 0) (<list> . 4)<br>(<pair> . 4) ...) |
| 4+16                                 | properties    | (...)                                             |
| 4+20                                 | size          | 12                                                |

|                             |     |                |
|-----------------------------|-----|----------------|
| <i>&lt;object&gt; : x</i>   |     |                |
| 0+0                         | isa | <mutable-pair> |
| <i>&lt;sequence&gt;</i>     |     |                |
| <i>&lt;list&gt;</i>         |     |                |
| <i>&lt;pair&gt;</i>         |     |                |
| 4+0                         | car | 'foo           |
| 4+4                         | cdr | "bar"          |
| <i>&lt;mutable-pair&gt;</i> |     |                |

|                                      |               |                         |
|--------------------------------------|---------------|-------------------------|
| <i>&lt;object&gt; : &lt;list&gt;</i> |               |                         |
| 0+0                                  | isa           | <type>                  |
| <i>&lt;properties-mixin&gt;</i>      |               |                         |
| <i>&lt;type&gt;</i>                  |               |                         |
| 4+0                                  | supers        | (<sequence>)            |
| 4+4                                  | slots         | '()                     |
| 4+8                                  | op-meth-alist | ((list? . #<meth>) ...) |
| 4+12                                 | type-offset   | ((<sequence> . 0))      |
| 4+16                                 | properties    | (...)                   |
| 4+20                                 | size          | 12                      |

# <pair> type definition

- (get-type (cons car cdr)) => <mutable-pair> ☼
  - <pair> C definition
  - <pair> C struct (generated)
  - <pair> LL <type> definition (generated)

# <pair> C definition

- ll\_define\_type(object, type)  
    ll\_define\_type\_slot(object, type, ll\_v, isa)  
ll\_define\_type\_end(object, type)
- ll\_define\_type(pair, type)  
    ll\_define\_type\_super(pair, type, object)  
    ll\_define\_type\_slot(pair, type, ll\_v, car)  
    ll\_define\_type\_slot(pair, type, ll\_v, cdr)  
ll\_define\_type\_end(pair, type)
- ll\_define\_type(mutable\_pair, type)  
    ll\_define\_type\_super(pair, type, pair)  
ll\_define\_type\_end(pair, type)

# <pair> C struct generated

/\* type slot blocks \*/

```
struct ll_ts_object { ll_v isa; };  
struct ll_ts_pair { ll_v car; ll_v cdr; };  
struct ll_ts_mutable_pair { /* empty */ };
```

/\* type actual structure \*/

```
struct ll_tsa_object {  
    ll_v isa;  
};  
struct ll_tsa_pair {  
    struct ll_ts_object    super_object;  
    struct ll_ts_pair      super_cons;  
};  
struct ll_tsa_mutable_pair {  
    struct ll_tsa_pair      super_pair;  
};
```

# <pair> LL definition generated

- (define <object>  
 (make <type>  
 '() ; supers  
 '(isa) )) ; slots
- (define <pair>  
 (make <type>  
 (list <object>) ; supers  
 '(car cdr) )) ; slots
- (define <mutable-pair>  
 (make <type>  
 (list <pair>) ; supers  
 '() )) ; slots

# Tagging

- **Tagging** is a compromise between the **statically-typed** world of the hardware and the **latently-typed** world of the interpreter under the performance constraints of the machine.
- After tagging most native machine object values can fit in machine words; objects that cannot fit in machine words must be allocated.
- Tagging schemes effect:
  - GC, memory layout, code size, FFI, performance.

# Tagging Schemes

- Trade off word precision for indirection and storage reduction.
  - High-bit tags
  - Low-bit tags
  - Variable-width tags
  - Fixed-width tags
  - Dedicated tags:
    - Lisp machines.
    - Some experimental HW with dedicated GC support.



# High Bit Tagging

- Requires special memory management: mmap(), etc.
- Presumes small type domain and limited object frequency.
- Complicate GC.
- Older Common Lisp Implementation.

# Low Bit Tagging

- Requires no special memory management.
- Open-ended type domain and object frequency.
- Compatible with off-the-shelf conservative GCs.
- Use tag bits normally unused due to machine alignment.
- Most new language implementations.

# II\_TAG(II\_v)

- Tags are low-bit tags: ( $\log_2(\text{sizeof}(\text{int}))$ )
  - 32-bit words => 2-bit tags; 64 bits => 3-bit tags
- From ll/value.h:
  - ```
3322222222222211111111111000000000000
10987654321098765432109876543210
-----
fixnum          (immediate) | 00
locative        (address)  | 01
flonum          (immediate) | 10
boxed object    (address)  | 11
```

# Tagging

- Values converted from statically-typed values (CPU) to latently-typed values (interpreter).
- Lower 2-bit tags for all values:
  - $\text{ll\_BOX\_fixnum}(x) \Rightarrow$   
 $x \gg 2 ==$   
 $x * 4$
  - $\text{ll\_UNBOX\_fixnum}(x) \Rightarrow$   
 $x \ll 2 ==$   
 $x / 4$
- Some C integer values cannot be tagged, must be dynamically allocated as boxed object.

# Fixnum Tagging/Boxing

- `ll_BOX_fixnum(int)`
  - `ll_BOX_fixnum(0) => 0 << 2 => (ll_v) 0`
  - `ll_BOX_fixnum(1) => 1 << 2 => (ll_v) 4`
  - `ll_BOX_fixnum(-5) => -5 << 2 => (ll_v) -20`
- `ll_UNBOX_fixnum(ll_v)`
  - `ll_UNBOX_fixnum(0) => (int) 0`
  - `ll_UNBOX_fixnum(4) => (int) 1`
  - `ll_UNBOX_fixnum(-20) => (int) -5`

# Why `ll_TAG(fixnum) == 0`?

- Fixnum addition, subtraction and vector element offset are common.
- $X \gg 2 == X * 4$
- `sizeof(ll_v) == sizeof(int) == 4`
- $0 \gg 2 == 0 * 4 == 0$
- Overflow/underflow still an issue but uncommon in practice.

# If `ll_TAG(fixnum) != 0`

- Scheme: `(+ x y) =>`  
C: `ll_BOX_fixnum(  
    ll_UNBOX_fixnum(x) +  
    ll_UNBOX_fixnum(y))`
- Scheme: `(+ x y) =>`  
C: `ll_BOX_fixnum(  
    ll_UNBOX_fixnum(x) -  
    ll_UNBOX_fixnum(y))`
- Scheme: `(vector-ref v i) =>`  
C: `*(ll_v*) (((char*) ll_vector_ptr(v)) +  
    ll_UNBOX_fixnum(i) * 4)`

# If `ll_TAG(fixnum) == 0`

- Scheme: `(+ x y)`  $\Rightarrow$  C: `(x + y)`
- Scheme: `(- x y)`  $\Rightarrow$  C: `(x - y)`
- Scheme: `(vector-ref v i)`  $\Rightarrow$  C:  
`*(ll_v*) (((char*) ll_vector_ptr(v)) + i)`
- Scheme: `(string-ref s i)`  $\Rightarrow$  C:  
`*(ll_v*) (((char*) ll_string_ptr(s)) + (i >> 2))`
- Still need to check for underflow/overflow, but checks can be done in a separate pipeline.



# Allocated Reference Tagging/Boxing

- First slot in all allocated objects is the object's <type>.
- Lowest 2 bit of 32-bit word addresses are 00 due to C compiler alignment and performance concerns.
- Offset object address with `ll_TAG_ref`:
  - `ll_BOX_ref(x) => (((char*) x) + ll_TAG_ref)`
  - `ll_UNBOX_ref(x) => ((void*)((x) - ll_TAG_ref))`

# Why II\_TAG\_ref == 3

- Most slot access will be an offset from C pointer to allocated structure.
- C:  $((\text{type}^*) \text{ptr}) \rightarrow \text{slot} \Rightarrow$   
 $*(\text{typeof}(\text{type}, \text{slot}))(\text{ptr} + \text{offsetof}(\text{type}, \text{slot}))$
- Most slot accesses are unaffected by **subtracting** tag bits after C compiler optimizations.
- Getting the object's type (object slot 0) is more complex at the expense of making <fixnum> tagging faster.

# If `ll_TAG_ref == 0`

- `(car x) =>`
  - `*(ll_v*)(ll_UNBOX_ref(x) +  
offsetof(ll_ts_pair, car)) =>`  
`*(ll_v*)(x + 0 + 4) =>`  
`*(ll_v*)(x + 4)`
  - Non-zero offset has cost.
- `(get-type x) =>`
  - `*(ll_v*)(ll_UNBOX_ref(x) +  
offsetof(ll_ts_object, isa)) =>`  
`*(ll_v*)(x + 0 + 0) =>`  
`*(ll_v*)(x)`
  - Zero offset has no cost.

# If `ll_TAG_ref == 3`

- `(car x) =>`
  - `*(ll_v*)(ll_UNBOX_ref(x) +  
offsetof(ll_ts_pair, car)) =>`  
`*(ll_v*)(x - 3 + 4) =>`  
`*(ll_v*)(x + 1)`
  - Tag removal has no additional cost with offset.
- `(get-type x) =>`
  - `*(ll_v*)(ll_UNBOX_ref(x) +  
offsetof(ll_ts_object, isa)) =>`  
`*(ll_v*)(x - 3 + 0) =>`  
`*(ll_v*)(x - 3)`
  - Tag removal and offset has a unified cost.

# II\_TAG(float)

- Trade lower 2-bits of C float mantissa precision for tag bits instead of allocating objects.
- C inline functions II\_BOX\_float(float) and II\_UNBOX\_float(II\_v) use a i386 C union.
- Some C float values cannot be represented.
- Reasonable trade-off since operations on floats are often inexact anyway.
- Does not prevent creation of full precision float or double boxed values using a new <type>.

# Runtime Bootstrapping

- The runtime itself is accessible by the user as a `<%runtime>` object.
- Some objects are statically allocated in the `ll_tsa__runtime` C structure:
  - Symbols
  - Global bindings
  - Character objects, `nil`, `#f`, `#t`.
- `nil != ll_BOX_ref(0)`
- The runtime system can be modified by itself.

# Bootstrapping

- Because LL is self-referential, bootstrapping requires very controlled object allocation and initialization:
- Type layout and initialization is implemented in **C and LL**.
- At a certain point, the core constants, types, bindings, operations and methods are complete enough allow `ll_send()` to be usable for the remainder the initialization.
- `LL_DEBUG_INIT=1 ./llt`

# `nil != II_BOX_ref(0)`

- If nil was a boxed reference to NULL, the entire interpreter would need NULL checks.
- There is a single object instance of the <null> type.
- The nil symbol has a read-only global binding and is specially recognized by the compiler.
- This complicates bootstrapping the runtime but this simplifies the interpreter by not introducing special cases in the very lowest levels of the message protocol.



# Messaging in C

- C macros
  - Normal calls:  
**`ll_v ll_call(op, _N(arg1, ... argN))`**
  - Tail calls:  
**`void ll_call_tail(op, _N(arg1, ... argN))`**
  - Return from call:  
**`void ll_return(val)`**
  - Manipulate stacks inline.
  - Allocate and use inline lookup caches. ☀

# Tail-calls in C

- `ll_call()` puts a new `<message>` on the message stack and loops while the return value of method function is true (non-zero).
- `ll_call_tail()` removes current arguments from value stack and replaces current `<message>` with new message operation and arguments and returns true (non-zero).
- `ll_return()` pops the current arguments, pushes the result onto the value stack and returns 0.

# Mutual Tail Recursion : C

- `/*pseudo-C: vs is the value stack, ms is the method stack*/`  
`int f( /* a = vs.top() */ ) { /* (g (+ a 1)) */`  
    `ll_v temp = vs.pop() + 1;`  
    `vs.push(temp); ms.top().operation = ll_o(g);`  
    `return 1;`  
}
- `int g( /* b = vs.top() / ) { /* (f (* b 2)) */`  
    `ll_v temp = vs.pop() * 2;`  
    `vs.push(temp); ms.top().operation = ll_o(f);`  
    `return 1;`  
}
- `int temp_func() {`  
    `vs.push(0); ms.push(f); /* f(0) */`  
    `while ( ms.top().lookup()->func() );`  
}

# Method Lookup Performance

- Lambda operation
- Operation lookup cache
- Call site lookup cache
- Move-to-front Heuristic
- Supertypes lookup

# Lambda Operations

- Each <operation> object has a lambda cache for operations with methods defined on only one <type>.
  - <object> is a pinned global and its operation-method association lists is also pinned.
  - This allows lambdas to be GCed if the anonymous <operation> is no longer accessible.
- The lambda <method> is moved into <object> if a <method> on another <type> is added.

# Operation lookup cache

- Each <operation> object has a lookup cache.
  - Cache is invalidated when a <method> is added or removed from the <operation>.
- Each <operation> object has a version number.
  - Version number is incremented when a <method> is added or removed from the <operation>.

# Call site lookup cache

- Each call site has a multi-entry lookup cache table.
  - Each entry keeps track of the operation version at time of cache fill.
  - If the operation version has changed, the entry is refilled.
  - Most-popular entries are moved to the front of the table.
  - Caveats: inaccessible operations may be stuck in caches.

# Move-to-front Heuristic

- The <type>'s op-meth-alist is scanned if the previous caches are not filled.
- The matched association of the op-meth-alist is moved to the front of the list.
- Commonly-applied methods are at the front of the list.
- Consider making op-meth associations weak.



# Supertype Lookup

- Supertype lookup routines:
  - Are recursive.
  - Do not pass the <message> object.
  - Return 1 if match is found.
  - Return 0 if more searching is required.
  - Could be changed to use an explicit stack.

# Catch/Throw

- Catch/Throw
  - Lighter than call/cc
  - `ll_CATCH(type)`
    - C `setjmp()`
    - Creates an anonymous `<operation>` with a `<method>` that references the C `jmpbuf`.
  - `<catch-method>` subtype of `<method>`
    - C func invokes `longjmp()`.

# Continuations

- Save/restore C stack segments since last continuation (see ccont library).
- Flush <message> and value stack buffers.
- Save/restore <message> and value stack pointers.
- Save/restore fluid variable bindings.
- Save/restore current catch.

# Interpreter Evaluation

- All (eval) expressions are byte-compiled
  - Phase 1: macro-expansion
    - Simple quasiquote expander.
  - Phase 2: intermediate representation
    - `(lambda ...) => (%add-method <object> ... (%method ...))`
    - `(%method slots formals ...) => <%ir ...>`
  - Phase 3: semantics
    - car-position lambda inlining
    - closure generation and environment planning
    - constant-folding
  - Phase 4: assembly generation

# <method>

- Slots:
  - func: Primitive method function points to primitive C function.
  - formals: parameter list (for debugging)
  - code: code value (for debugging)
  - properties: alist  
i.e.: ((no-side-effect? . #t))

# <byte-code-method>

- Supers: <method>
- Slots:
  - Primitive method function points to byte-code VM function.
  - A byte-code <string>
  - A constants <vector>
    - Contents be shared between multiple methods defined in an expression:
      - A <vector> of global symbols.
      - A <vector> of global <bindings> for each global symbol.
      - Other (quote)'ed expressions or constants.

# Constant Folding

- (constant-fold symbol scope) =>
  - If symbol is a <symbol> AND
  - If symbol is bound to a global AND
  - If (readonly? binding) THEN
    - (value binding) ELSE op
- (constant-fold (op . args) scope) =>
  - If (constant-fold op scope) is constant? AND
  - If all (map constant-fold args) are constant? AND
  - If (%lookup op rcvr) has no-side-effect? THEN
    - (eval-no-constant-fold (cons op args)) ELSE
    - (cons op args)

# Without Constant Folding

- (define x (cons 1 2))  
(lambda (y . args) (set! (car x) y))
- |                 |                |      |
|-----------------|----------------|------|
| ( (probe 0)     | ; value stack  |      |
| (nargs-rest- 1) | ; temps        | args |
| (probe 3)       | ;              | y    |
| (arg 0 y)       | ; &y           | y    |
| (contents)      | ; y            | y    |
| (glo 2 x)       | ; x y          | y    |
| (probe 2)       | ; x y          | y    |
| (glo 1 car)     | ; car x y      | y    |
| (glo 0 setter)  | ; setter x y   | y    |
| (call 1)        | ; set-car! x y | y    |
| (call-tail 2)   | ;              |      |
| (rtn))          |                |      |



# With Constant Folding

- (define x (cons 1 2))  
(lambda (y . args) (set! (car x) y))
- |                                 |                |      |
|---------------------------------|----------------|------|
| ( (probe 0)                     | ; value stack  |      |
| (nargs-rest- 1)                 | ; temps        | args |
| (probe 3)                       | ;              | y    |
| (arg 0 y)                       | ; &y           | y    |
| (contents)                      | ; y            | y    |
| (glo 2 x)                       | ; x y          | y    |
| (const 4 #<operation set-car!>) | ; set-car! x y | y    |
| (call-tail 2)                   | ;              |      |
| (rtn))                          |                |      |

# Tak Benchmark

- Recursion, Fixnum +, -

- ```
(define (tak x y z)
  (if (not (< y x))
      z
      (tak (tak (- x 1) y z)
            (tak (- y 1) z x)
            (tak (- z 1) x y)))))
```

# Performance Comparision

- (tak 18 12 6) (tak 30 15 9)  
(tak 33 15 9) (tak 40 15 9)
  - ikarus 0.25 sec
  - chicken 1.41 sec (precompiled)
  - oaklisp 2.63 sec
  - mzscheme 2.65 sec
  - scheme-r5rs 5.89 sec
  - guile 7.91 sec
  - larceny 10.35 sec
  - LL 12.93 sec

# Future Work

- Re-implement LL as a library of Scheme procedures and syntax using Ikarus?
- Vary levels of self-reference to improve performance?
- Imbed TinyCC C compiler?

# Conclusion

- Q & A
- Discussion

# Resources

- <http://kurtstephens.com/page/article.html/5>
- <http://www2.lib.uchicago.edu/~keith/crisis/benchmarks/tak/>
- <http://www.cs.indiana.edu/~aghuloum/ikarus/>
- The Art of The Metaobject Protocol - Gregor Kiczales
- <http://www.amazon.com/Brain-Makers-HP-Newquist/dp/0672304120>
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