The
Oaklisp Implementation Guide

November 9, 2026

DRAFT

Barak A. Pearlmutter
Dept. of Computer Science
Maynooth University
Co. Kildare
Ireland
barak+oaklisp@pearlmutter.net

Kevin J. Lang
Yahoo! Research
1961–2019

The information in this document is subject to change at any time.

Copyright ©1985, 1986, 1987, 1988, 1989 by Barak A. Pearlmutter and Kevin J. Lang.

Contents

1 Introduction **1**
1.1 Disclaimer . . . 1

2 Language **2**
2.1 Special Forms . . . 2
2.2 Macros . . . 3
2.3 Primitive Types . . . 5
2.4 Open-Coded Operations . . . 5
2.5 Subprimitives . . . 10
2.6 Defined Types . . . 12
2.7 Defined Operations . . . 13

3 Internal Data Format **14**
3.1 Tag Types . . . 14
3.2 Other Immediate Types . . . 15
3.3 Memory Structure . . . 15
3.4 Representation of Specific Types . . . 15
3.5 System Types . . . 16
3.5.1 Methods . . . 17
3.5.2 Environment Vectors . . . 17
3.5.3 Code Vectors . . . 17
3.5.4 Architectures . . . 18
3.5.5 Stack Implementation . . . 19
3.5.6 Escape Objects . . . 20
3.5.7 Types . . . 21
3.6 Storage Reclamation . . . 21

4 Stack Machine Architecture **23**
4.1 Registers in the Emulator . . . 23
4.2 Instruction Set . . . 24
4.3 Weak Pointers . . . 28

5 Stack Discipline **29**
5.1 Stack Overview . . . 29
5.2 Method Invocation/Return . . . 29
5.3 The Context Stack . . . 31

6 Methods **32**
6.0.1 Invoking Methods . . . 32
6.0.2 Adding Methods . . . 33

7 Oaklisp Level Implementation **35**
7.1 Fluid Variables . . . 35
7.2 Unwind Protection . . . 36
7.3 Catch . . . 36
7.4 Call/CC . . . 37
7.5 The Error System . . . 37
7.6 Numbers . . . 40
7.7 Vectors and Strings . . . 41
7.8 Symbols . . . 42
7.9 Variable Numbers of Arguments . . . 43

8 The Compiler **45**
8.1 File Types . . . 45
8.2 Object File Formats . . . 45
8.3 Compiler Internals . . . 45

9 Bootstrapping **46**
9.1 Building a World . . . 46
9.2 World Files . . . 47

10 Administrative Details **49**
10.1 Getting a Copy . . . 49
10.2 Bugs . . . 49
10.3 Copyright and Lack of Warranty . . . 50

Chapter 1

Introduction

This document describes the internals of the CMU implementation of Oaklisp. Although this implementation is designed for portability through the use of a bytecode interpreter written in C, the fundemental data structures and memory formats would also be suitable for a high performance implementation. In spite of the fact that Oaklisp has the potential performance penalty of being uniformly object-oriented, this implementation has proven more than competitive with other bytecode based implementations of Scheme, such at MIT's CScheme and Semantic Microsystems' MacScheme. An abbreviated version of some of the information presented here is available as a book chapter (Pearlmutter and Lang, 1991).

1.1 Disclaimer

Warning: this document may contain inaccuracies, and it lags behind the implementation as the system evolves.

Chapter 2

Language

This document is a description of one particular implementation of Oaklisp, and therefore contains information that is subject to change and may not be significant to users in any case. For a description of the language that does not contain a lot of arbitrary distinctions, refer to *The Oaklisp Language Manual*.

2.1 Special Forms

These special forms all work by magic, and can't be redefined or shadowed.

(%quote x) *Special Form*
Does what you would expect.

(%if predicate consequent alternative) *Special Form*
Does what you would expect.

(%labels ((variable value)...)form) *Special Form*
If all references to the labels are calls from tail recursive positions, this is compiled using jumps. Otherwise, it is rewritten using let and set!.

(native-catch variable . body) *Special Form*
Evaluates *body* within the lexical scope of *variable*, which is bound to a catch tag that is valid within the dynamic scope of this form. This is actually macro expanded to something pretty wierd.

(%add-method (operation (type . ivarlist). arglist)form) *Special Form*
Yields the specified method object.

(%make-locative variable) *Special Form*
Returns a locative pointing to *variable*.

(%block . forms) *Special Form*
Making this a primitive special form simplifies the compiler.

2.2 Macros

Most constructs that users think of as primitive are actually macros. This simplifies the compiler by both reducing the number of special forms to be handled and eliminating the need for the compiler to check whether special forms it encounters are syntactically correct.

(quote x) *Macro*
≡ (%quote x)

(add-method (operation (type . ivar-list). arg-list). body) *Macro*
This turns into %add-method, filling in the default type and putting a block around the body if necessary.

(lambda arglist . body) *Macro*
≡ (add-method ((make operation) . arglist) . body)
Functions are made by hanging methods off of object. There is an optimization in the compiler that expands car-position lambdas inline.

(catch var . body) *Macro*
≡ (native-catch x (let ((var (lambda (y) (throw x y)))) . body))

(define symbol value) *Macro*
≡ (set! symbol value)

(define (fluid symbol)value) *Macro*
≡ (set! (fluid symbol) value)

(define (variable . arglist). body) *Macro*
≡ (set! variable (lambda arglist . body))

(set! symbol value) *Macro*
≡ (set! (contents (make-locative symbol)) value)

(set! (op $a_1 \ldots a_n$)value) *Macro*
≡ ((setter op) $a_1 \ldots a_n$ value)

(set location value) *Macro*
An obsolete form with semantics identical to set!.

(make-locative symbol) *Macro*

≡ (%make-locative symbol)

(make-locative (op . args)) *Macro*
≡ ((locater op) . args)

(if test thenform) *Macro*
≡ (%if test thenform (undefined-value))

(if test thenform elseform) *Macro*
≡ (%if test thenform elseform)

(fluid symbol) *Macro*
≡ (%fluid (quote symbol))

(bind-error-handler) *Macro*
See the language manual for a semantic definition.

(catch-errors) *Macro*
Implemented with bind-error-handler and native-catch.

(bind (((fluid symbol) value)...). body) *Macro*
Implemented using let and set!. Hacks to native-catch and call/cc are also necessary. Essentially, the bindings are pushed onto fluid-bindings-alist for the dynamic scope of the bind. For details, see Section 7.1.

(wind-protect before form after) *Macro*
≡ (dynamic-wind (lambda () before) (lambda () form) (lambda () after))

(funny-wind-protect before abnormal-before form after abnormal-after) *Macro*
A wind-protect evaluates *before*, *form*, and *after*, returning the value of *form*. If *form* is entered or exited abnormally (due to call/cc or catch) the *before* and *after* forms, respectively, are automatically executed. funny-wind-protect is the same except that different guard forms are evaluated depending on whether the dynamic context is entered or exited normally or abnormally.

The following macro definitions may be found in *The Revised*[3] *Report on Scheme* (Rees et al., 1986).

(let) *Macro*

(let*) *Macro*

(cond) *Macro*

(or) *Macro*

(and) *Macro*

2.3 Primitive Types

The following types are *immediates*. They have no instance variables, occupy no heap storage, and are directly manipulated by the micro-engine. Their references have special tag bits. See section 3.1.

fixnum *Type*

character *Type*

locative *Type*

2.4 Open-Coded Operations

Because arithmetic on fixnums is so common, a special mechanism is used to perform operations for which byte-codes exist. When the compiler sees one of these operations in a program, it emits the corresponding byte-codes inline. At run-time, the micro-engine checks the tag-bits of the operands to verify that they are fixnums. If they are, the arithmetic is performed immediately. Otherwise, a hardware trap occurs which causes the usual search up the type hierarchy to find the appropriate method to perform the operation. The only restriction this places on the full generality of the usual method system is that new methods cannot be defined for the simple arithmetic operations on fixnums.

The operations which fall under this restriction are the following:

(zero? number) *Operation*

(!= number1 number2) *Operation*

(* number ...) *Operation*

(+ number ...) *Operation*

(- number1 number2 ...) *Operation*

(1+ number) *Operation*

(< number1 number2) *Operation*

(<= number1 number2) *Operation*

(= number1 number2) *Operation*

(> number1 number2) *Operation*

(>= number1 number2) *Operation*

(ash-left integer1 integer2) *Operation*

(ash-right integer1 integer2) *Operation*

(bit-and integer1 integer2) *Operation*

(bit-andca integer1 integer2) *Operation*

(bit-equiv integer1 integer2) *Operation*

(bit-nand integer1 integer2) *Operation*

(bit-nor integer1 integer2) *Operation*

(bit-not integer) *Operation*

(bit-or integer1 integer2) *Operation*

(bit-xor integer1 integer2) *Operation*

(object-unhash integer) *Operation*

(positive? number) *Operation*

(quotient number1 number2) *Operation*

(rot-left fixnum1 fixnum2) *Operation*

(rot-right fixnum1 fixnum2) *Operation*

(minus number) *Operation*

(modulo number1 number2) *Operation*

(negative? number) *Operation*

The following operations are also open-coded and take type-mismatch traps if necessary. They can be add-method'ed to, but only for types that are not handled by the microcode. It should be clear from the discussion below which types the bytecode expects.

(throw tag value) *Operation*
Causes control to return from the native-catch form that generated *tag*.

(contents locative) *Locatable Operation*
Dereferences *locative*. ((setter contents) locative value) puts *value* in the cell pointed to by *locative*.

(object-unhash fixnum) *Operation*
Returns the object that the weak pointer *fixnum* points to, or #f if the object has been reclaimed by the garbage collector.

The following operations are open-coded, and the microcode can handle objects of any type, so they can't be add-method'ed.

(get-type object) *Operation*
Returns the type of *object*.

(eq? x y) *Operation*
Determines whether *x* and *y* are the same object. Implemented by checking if the references are identical.

(object-hash x) *Operation*
Returns a "weak pointer" to *x*.

(cons x y) *Operation*
Conses *x* onto *y* in the usual lisp fashion.

(identity x) *Operation*
Returns *x*.

(list . args) *Operation*

Constructs a list; (list a b c) ≡ (cons a (cons b (cons c '()))).
Actually, the list operation is open coded and has backwards-args-mixin mixed into the type, so its arguments are pushed onto the stack in left to right order. The code emitted for the operation itself is just a (load-reg nil) followed by a bunch of reverse-cons instructions, one for each argument.

(list* $a_1 \ldots a_n$) *Operation*
≡ (cons $a_1 \ldots$ (cons a_{n-1} a_n) ...).
This is open coded in nearly the same way as list.

(not x) *Operation*
≡ (eq? x #f)

(null? x) *Operation*
≡ (eq? x '())

(second-arg x y . rest) *Operation*
Returns *y*. Remember, Oaklisp does not guarantee any particular order of evaluation of arguments.

The following operations are open-coded, but the microcode traps out if the arguments are not simple cons cells. They can not be add-method'ed to for the type cons-pair.

(car pair) *Locatable Operation*

(cdr pair) *Locatable Operation*

(caar pair) *Locatable Operation*

(cadr pair) *Locatable Operation*

(cdar pair) *Locatable Operation*

(cddr pair) *Locatable Operation*

(caaar pair) *Locatable Operation*

(caadr pair) *Locatable Operation*

(cadar pair) *Locatable Operation*

(caddr pair) *Locatable Operation*

(cdaar pair) *Locatable Operation*

(cdadr pair) *Locatable Operation*

(cddar pair) *Locatable Operation*

(cdddr pair) *Locatable Operation*

(caaaar pair) *Locatable Operation*

(caaadr pair) *Locatable Operation*

(caadar pair) *Locatable Operation*

(caaddr pair) *Locatable Operation*

(cadaar pair) *Locatable Operation*

(cadadr pair) *Locatable Operation*

(caddar pair) *Locatable Operation*

(cadddr pair) *Locatable Operation*

(cdaaar pair) *Locatable Operation*

(cdaadr pair) *Locatable Operation*

(cdadar pair) *Locatable Operation*

(cdaddr pair) *Locatable Operation*

(cddaar pair) *Locatable Operation*

(cddadr pair) *Locatable Operation*

(cdddar pair) *Locatable Operation*

(cddddr pair) *Locatable Operation*

2.5 Subprimitives

The following operations should be used only deep within the system. Unless otherwise noted below, when a subprimitive encounters a domain error normal Oaklisp code is not trapped to. Rather, you're lucky if the system dumps core.

(%assq object alist) *Operation*

Does the usual association list lookup, but assumes that *alist* is made out of simple cons pairs. Passing it lazy lists or things like that will crash the system.

(%big-endian?) *Operation*

Returns #t or #f depending on whether instructions are ordered starting at the high half of a reference or the low half of a reference, respectively. On all machines that I know of, this is the same as the endianity of bytes.

(%continue stack-photo) *Operation*

Resumes *stack-photo*, abandoning the current stack.

(%fill-continuation empty-stack-photo) *Operation*

Fills in the template stack snapshot *empty-stack-photo* with the appropriate information, copying sections of the stack into the heap where necessary, and returns its argument.

(%filltag empty-catch-tag) *Operation*

Fills in *empty-catch-tag* with the current stack heights.

(%crunch data tag) *Operation*

Returns a reference with the data portion *data* and a tag of *tag*. Traps if either argument is not a fixnum.

(%data x) *Operation*

Returns the non-tag field of *x* as a fixnum.

(%tag x) *Operation*

Returns the tag of *x* as a fixnum.

(%gc) *Operation*

Forces an immediate normal garbage collection.

(%full-gc) *Operation*

Forces an immediate full garbage collection. At the end of the full garbage collection, new space size is set back to its original value.

(%get-length x) *Operation*

Returns the number of storage cells occupied by *x*. Zero for immediates.

(%increment-locative locative n) *Operation*
Returns a locative to the cell *n* beyond the cell pointed to by *locative*.

(%load-bp-i n) *Locatable Operation*
Loads the contents of self's instance variable number *n*. Not for the squeamish, as who is really "self" and who would be self except that the compiler is compiling away intermediate lambdas is very implementation specific.

(%make-cell value) *Operation*
Returns a locative to a new cell containing *value*. Could be defined with (define (%make-cell x) (make-locative x)).

(%make-closed-environment $a_1 \ldots a_n$) *Operation*
Returns a new environment containing $a_1 \ldots a_n$. At least one object is required. To get an empty environment, look in %empty-environment.

(%print-digit n) *Operation*
Prints *n* as a single decimal digit to stdout. Used to indicate various error conditions during the boot process.

(%push . args) *Operation*
Pushes *args* onto the stack, returning (so to speak) the leftmost argument. This would be about the same as values, if we had multiple value return.

(%read-char) *Operation*
Returns a character read from stdin. No buffering. For use by the cold load stream.

(%return) *Operation*
Generates the return bytecode. Doesn't push anything onto the stack. Will corrupt the stack unless you really know what you are doing.

(%allocate type size) *Operation*
Allocates a block of storage *size* long, filling in the type field with *type*. *Type* should not be variable length.

(%varlen-allocate type size) *Operation*
Allocates a block of storage *size* long, filling in the type field with *type* and the size field with *size*. *Type* should be a variable length type. Using this instead of %allocate where appropriate avoids a window of gc vulnerability.

(%write-char char) *Operation*
Writes the character *char* to stdout. No buffering or anything.

(%↑super-tail type operation object) *Operation*
Generates the ↑super-tail bytecode, passing it appropriate arguments. This is used only used in the implementation of ↑super. Once the compiler is modified to handle the ↑super construct directly this will no longer be needed.

2.6 Defined Types

The following types are completely defined in Lisp.

object *Type*

This type is the top of the inheritance hierarchy. Ordinary functions are installed as methods for this type.

type *Type*

New types are generated by instantiating this type.

variable-length-mixin *Type*

This mixin allows each instance of a type to have a vector of anonymous cells tacked on the end. It also provides several low-level methods for indexed references into such vectors. Currently, the only variable-length types are vector, %code-vector and %closed-environment.

open-coded-mixin *Type*

If this is mixed in to an operation, the compiler will send it a get-byte-code-list message, and use the result instead of a regular function call whenever the operation appears in a program.

pair *Type*

cons-pair *Type*

null-type *Type*

vector *Type*

operation *Type*

settable-operation *Type*

locatable-operation *Type*

%method *Type*

%code-vector *Type*

%closed-environment *Type*

locale *Type*

general-error *Type*

foldable-mixin *Type*

2.7 Defined Operations

The methods for these operations are written in low level Oaklisp.

(apply operation $a_1 \ldots a_n$ arglist) *Operation*

Calls *operation* with arguments $a_1 \ldots a_n$ and the contents of *arglist*. For instance, (apply + 1 2 '(3 4)) $\Rightarrow$ 10.

(make type . args) *Operation*

Returns a new instance of *type* that has been initialized by sending it an initialize message with the extra arguments *args* passed along.

(%install-method-with-env type operation code-body environment) *Operation*

Adds the specified method to the search table of *type*. It returns *operation*, since this is what some instances of add-method are compiled into. Methods that don't close over anything can refer to %empty-environment, whose value is an environment object whose vector portion has length zero. It takes care of instance variable mapping conflicts.

(initialize object) *Operation*

Returns *object*. This no-op is what is shadowed when you define initialize methods for new types. (initialize type supertype-list ivar-list) does the work involved in making a new type. The list of supertypes is used to make a list of all ancestors that is searched at run time to find methods for operations. The ancestor tree is considered to be ordered from bottom to top and from left to right while constructing this list, and duplicates are removed. An error is generated if more than one top-wired type is found in the resulting ancestor list. The instance-variable map of the type is created, with any top-wired type appearing at the beginning, and variable-length-mixin appearing at the end if it is present. Any method you define to handle an initialize message should return self.

(dynamic-wind before-op main-op after-op) *Operation*

Calls the operation *before-op*, calls the operation *main-op*, calls the operation *after-op*, and returns the value returned by *main-op*. If *main-op* is exited abnormally, *after-op* is called automatically on the way out. Similarly, if *main-op* is entered abnormally, *before-op* is called automatically on the way in.

(call-with-current-continuation operation) *Operation*

Calls *operation* with one argument, the current continuation. The synonym call/cc is provided for those who feel that call-with-current-continuation is excessively verbose.

Chapter 3

Internal Data Format

This chapter describes how memory and tags are set up, and how this implements the object semantics of the language.

3.1 Tag Types

In an effort to reduce the complexity of the bytecode interpreter and to simplify the system in general, there are only four tag types. Tags are stored in the two low order bits of each reference thus simplifying tag manipulation, particularly in the presence of indexed addressing modes.

$w-1$ $w-2$ ... *11 10 9 8*	*7 6 5 4 3 2*	*1 0*	*type*
twos complement integer		0 0	fixnum
data	subtype	1 0	other immediate type
address		0 1	locative (pointer to cell)
address		1 1	reference to boxed object

Here w is the *word size*, the number of bits in a reference: 32 or 64, depending on how the emulator was built (see section 3.5.4). Fixnums thus have 30 or 62 bits.

This tagging scheme, along with our object format, does not allow for *arbitrarily* scannable heaps (in which the divisions between objects can be figured out starting the scan at any point in the heap.) In fact, if solitary cells are permitted, as they are in our implementation, scanning the heap starting at the begining is not even possible. However, our garbage collector never needs to scan the heap in such a fashion. Note that there is no extra "gc" bit in every word, but again, our garbage collector requires no such bit.

3.2 Other Immediate Types

References with a tag of 1 0 use the next six bits to specify a subtype.

31 . . . 24	*23 . . . 16*	*15 . . . 8*	*7 . . . 2*	*1 0*	*type*
reserved	font	ascii code	0 0 0 0 0 0	1 0	character

Character is currently the only "other immediate type." More may be added later, in particular Macintosh handles. (At one time weak pointers were represented as their own immediate type, but they are now represented using integers for compatibility with the Scheme standard (Rees et al., 1986).)

3.3 Memory Structure

Memory is a linear array of *cells*, aligned words of the word size. These cells are divided into two contiguous chunks: free cells and allocated cells. The *free pointer* points to the division between these two chunks, and it is incremented as memory is allocated. When allocating an object would push the free pointer beyond the limits of memory, a garbage collection is performed.

The allocated portion of memory is divided into *aggregate objects* and *solitary cells*. Each aggregate object is a contiguous chunk of cells. The first cell of an object is a reference to its type; if the type is *variable length*, the second cell holds the length of the object, including the first two cells. The remainder of the cells hold the instance variables. Solitary cells are cells that are not part of any object, but are the targets of locatives. Solitary cells are used heavily in the implementation of mutable variables.

A reference to an object consists of a pointer to that object with a tag of *boxed-object*. References to solitary cells are locatives. Furthermore, locatives may reference cells that are the instance variables of objects. If such an object is ever deallocated by the garbage collector, all of the cells making up the object are made free *except* for those cells that are referenced by locatives, which are not deallocated. These become solitary cells.

3.4 Representation of Specific Types

Consider an object of type *foo*, which is based on *bar* and *baz*. *Bar* had instance variables bar-1 and bar-2, baz has instance variables baz-1, baz-2 and baz-3, and *foo* has instance variable foo-1. *Foo* inherits the instance variables of the types it is based on, but methods defined for type *foo* can not refer to these inherited variables.

Each type's local instance variables are stored contiguously, and in order of lexical definition, in instances of that type, and of types that inherit it; this allows

variable reference to instance variables to be resolved into offsets from the start of the relevent instance variable frame at compile time. Here is an instance of *foo* as it might actually be stored in memory:

reference to type *foo*
value of foo-1
value of baz-1
value of baz-2
value of baz-3
value of bar-1
value of bar-2

Observe that instances of type *foo* are divided into contiguous chunks of instance variables, each inherited from a different supertype. When a type inherits another type through two different routes, it still only inherits the instance variables once.[1] Furthermore, if the instance variables of two types inherited by a third have the same names they are still distinct instance variables.[2] These semantics allow us to reference instance variables very quickly, once the local instance variable block has been located. It also allows us to use the same compiled code for a single method regardless of whether it is being invoked upon an instance of the type it was added to or on an instance of an inheriting type.

3.5 System Types

This section describes the format of various objects that are directly referenced by the microcode,[3] such as code vectors and catch tags.

It should be emphasized that these system objects are full-fledged objects. They have types which can be inherited and have their methods overridden, just like any other object. The only "magic" thing about these types is that their local instance variables (ie. the system ones) must live at the top of their memory representation, even when inherited. This allows the microcode to locate the values it needs without going through the type heirarchy.

The only constraint this places on the user is that a type may not inherit two types both of which are *top-wired*, for obvious reasons. For example, it is impossible to make a type whose instances are both operations and types.

[1] This aspect of the language is in flux, and should not be relied upon by users.

[2] This is in marked contrast to ZetaLisp flavors–that's why variable references in flavors go through mapping tables, resulting in considerable overhead. There are also important modularity considerations in favor of our scheme which are beyond the scope of this document, but are discussed in detail in Snyder (1986).

[3] Our microcode is C.

3.5.1 Methods

A method has two instance variables which hold the code object containing the code that implements the method and the environment vector that holds references to variables that were closed over.[4]

3.5.2 Environment Vectors

Environment vectors have a block of cells, each of which contains a locative to a cell. When the running code needs to reference a closed-over variable, it finds the location of the cell by indexing into the environment vector. This index is calculated at compile time, and such references consume only one instruction.

Just as it is possible for a number of methods to share the same code, differing only in the associated environment, it is also possible for a number of methods to share the same environment, differing only in the associated code. Currently the compiler does not generate such sophisticated constructs.

3.5.3 Code Vectors

Code lives in vectors of integers, which are interpreted as instructions by the bytecode emulator. This format allows code to be stored in the same space as all other objects, and allows the garbage collector to be ignorant of its existance, treating code vectors like any other vector. Bytecodes are 16 bits long, with the low 2 bits always 0, and several are packed into each cell: two in a 32-bit cell, and either two or four in a 64-bit one, as chosen when the emulator is built (section 3.5.4). Here is an example of some stuff taken from the middle of a code vector, for two instructions per cell.

<table>
<tr><td colspan="6">⋮</td></tr>
<tr><td colspan="2">8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td><td>8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td></tr>
<tr><td colspan="3">14 bit instruction</td><td>0 0</td><td>8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td></tr>
<tr><td colspan="3">14 bit relative address</td><td>0 0</td><td>8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td></tr>
<tr><td colspan="2">8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td><td>8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td></tr>
<tr><td colspan="3">14 bit instruction</td><td>0 0</td><td colspan="2">14 bit instruction</td><td>0 0</td></tr>
<tr><td colspan="7">arbitrary reference used by last instruction of previous word</td></tr>
<tr><td colspan="3">14 bit instruction</td><td>0 0</td><td>8 bit inline arg</td><td>6 bit opcode</td><td>0 0</td></tr>
<tr><td colspan="6">⋮</td></tr>
</table>

Note the arbitrary reference right in the middle of code. To allow the garbage collector to properly handle code vectors, as well as to allow the processor to

[4]Well, not all closed over variables. Only ones above the locale level. Locale variable references are implemented as inline references to value cells.

fetch the cell efficiently, this reference must be cell aligned. When the processor encounters an instruction that requires such an inline argument, if the pc is not currently pointing to an aligned location then the pc is suitably incremented. This means that the assembler must sometimes emit a padding instuction, which will be ignored, between instructions that require inline arguments and their arguments.

An alternative that was used earlier in the design process was to mandate that all instructions requiring inline arguments occur in a position where the following reference can be fetched without realigning the pc. This requires sometimes inserting a padding noop before an instruction that requires an inline argument, and analysis showed that the time required to process a noop instruction is much greater than the time required to check if the low bit of a register is on and increment that register if so.

3.5.4 Architectures

From Oaklisp's point of view a machine is characterized by three things:

- the *word size*, the number of bits in a reference, 32 or 64, which determines the fixnum range;
- the number of 16-bit *instructions packed into each cell* of a code vector: 2, or, with 64-bit cells, 4. With two instructions in a 64-bit cell half of the cell is unused; four fill it, halving the size of code vectors, at the cost of bytecode that 32-bit machines cannot use;
- the *byte order* of the machine, which decides the order in which the instructions in a cell lie in memory.

Instructions are packed into a cell in memory order: instruction k of a cell occupies bits $16k$ to $16k + 15$ on a little-endian machine, and bits $w - 16(k + 1)$ to $w - 16k - 1$ on a big-endian one, so that the emulator fetches successive instructions from successive 16-bit units of memory. (With two instructions in a 64-bit cell the remaining 32 bits, the high half on a little-endian machine and the low half on a big-endian one, are unused.) An inline reference in the code, such as a constant or a global variable cell, occupies a whole cell and must be cell aligned, so the assembler pads the instruction before it with noops up to the next cell boundary, and the emulator skips that padding rather than executing it.

These properties are named bc$n$-w for bytecode, where n is the number of instructions per cell and w the word size, and bc$n$-ebw for a running system or a binary world image, where b is l or b for little or big endian: bc2-32, bc2-64 and bc4-64 bytecode, and bc2-el32, bc2-eb32, bc2-el64, bc2-eb64, bc4-el64 and bc4-eb64 systems.

What is portable between architectures:

- Compiled bytecode (.oa files) is independent of byte order, and in practice of word size too, since the compiler does not fold constants whose value would depend on it; the word size in its name only records the fixnum range that its integer constants are assumed to fit, so bc2-32 bytecode can be loaded anywhere. It is specific to the instruction packing, since that decides where the padding before each inline reference goes.
- Cold world images (section 9.2) are independent of byte order but specific to word size and packing.
- Binary world images are specific to all three.

Each of these files begins with a header line naming what it is for, which the emulator, the loader and the linker check.

Within a running system, the variables %%word-size and %%instructions-per-ref, set by the linker, describe the system, and host-architecture in the language manual is derived from them. A system can generate code for another architecture, which is how a system for a new one is bootstrapped.

(%big-endian?) *Operation*

This returns the endianity of the machine that Oaklisp is running on: true if the first instruction fetched from a cell is the more significant one.

3.5.5 Stack Implementation

Although the value and context stacks are logically contiguous, they are sometimes physically discontinuous. The instructions all assume that stacks live in a designated chunk of memory called the stack buffer. They check if they are about to overflow or enderflow the stack buffer, and if so they take appropriate actions to fill or flush it, as appropriate, before proceeding.

If the stack buffer is about to overflow, most of it is copied to a *stack segment* which is allocated on the heap. These overflown segments form a linked list, so upon stack underflow the top segment is removed from this list and copied back to the stack buffer.

There is one more circumstance in which the stack buffer is flushed. The call/cc construct of Scheme (Rees et al., 1986) is implemented in terms of *stack photos*, which are snapshots of the current state of the two stacks, and which can be restored in the future. A fill-continuation instruction forces the stack buffers to be flushed and then copies references to the linked lists of overflow segments into a continuation object.

Actually, in the above treatment we have oversimplified the concept of flushing a stack buffer. The emulator constant MAX_SEGMENT_SIZE determines the maximum size of any flushed stack segment. When flushing the stack, if the buffer has more than that number of references then it is flushed into a

number of segments. This provides some hysteresis, speeding call/cc by taking advantage of coherence in its usage patterns. A possibility opened by our stack buffer scheme, which we do not currently exploit, is that of using virtual memory faults to detect stack buffer overflows, thus eliminating the overhead of explicitly checking for stack overflow and underflow.

As a historical note, an early version did not use a stack buffer but instead implemented stacks as linked lists of segments which always lived in the heap. When pushing over the top of a segment, a couple references were copied from the top of that segment onto a newly allocated segment, providing sufficient hysteresis to prevent repeated pushing and poping along a segment boundary from incurring inordinate overhead. Regretably, substantial storage is wasted by the hysteresis and the overflow and underflow limits vary dynamically wereas in the new system these limits are C link-time constants. Presumably due to these factors, in spite of its old world charm, timing experiments between the old system and the new system were definitive.

3.5.6 Escape Objects

In our implementation of Oaklisp we provide two different escape facilities: call/cc and catch. The call/cc construct is that described in the Scheme standard (Rees et al., 1986). The catch facility provides with user with a second class *catch tag*, which is valid only within the dynamic extent of the catch.

The implementation of catch tags is very simple: they contain heights for the value and context stacks. When a catch tag is thrown to, the value and context stacks are chopped off to the appropriate heights. The slot saved-wind-count is used for unwind protection and saved-fluid-binding-list is used for fluid variables. Details are given in Sections 7.3 and 7.2.

type: escape-object
value stack height: 25
context stack height: 19
saved wind count: 3
saved fluid binding list: ((print-length . #f) ...)

Actually, there are two variants of catch. In the regular variant, which is compatible with T, the escape object is invoked by calling it like a procedure, as in (catch a (+ (a 'done) 12)). In the other variant, the escape object is not called but rather thrown to using the throw operation, as in (native-catch a (+ (throw a 'done) 12)). Although the latter construct is slightly faster, the real motivation for its inclusion is to remind the user that the the escape object being thrown to is not first class. In order to ensure that an escape object is not used outside of the extent of its dynamic validity, references to them should not be retained beyond the appropriate dynamic context.

3.5.7 Types

Type objects are used when tracing up the type heirarchy in order to find appropriate methods and bp offsets. Since the types are used to find methods, they must be system objects so that reference to their instance variables can be done without sending them explicit messages. The operation-method-alist maps from operations to methods handled by the type itself, not any supertype. The type-bp-alist maps from types to offsets which are where the appropriate frame of instance variables may be found. The microengine uses a simple move-to-front heuristic in an attempt to reduce the overhead of searching these alists. The supertype-list contains a list of the immediate supertypes. Supertypes by inheritance that have instance variables are present in type-bp-alist, however.

This is a picture of the cons-pair type, as it actually appears in memory:

type	
instance-length:	3
variable-length?:	#f
supertype-list:	(pair object)
ivar-list:	(the-car the-cdr)
ivar-count:	2
type-bp-alist:	((cons-pair . 1))
operation-method-alist:	((car . meth) ...)
top-wired?:	#f

3.6 Storage Reclamation

Our garbage collector (Pearlmutter, 1996) is a variant of Baker's algorithm, a so-called "stop and copy" collector. The spaces to be reclaimed are renamed *old*, all accessible objects in the old spaces are transported to a new space, and the old spaces are reclaimed. The data present in the initial world is considered "static" and is not part of old space in normal garbage collections, only in "full" garbage collections, which also move everything not reclaimed into static space. Due to locatives, the collector makes an extra pass over the data; a paper with more complete details on this latter complication is in press. The weak pointer table is scanned at the end of garbage collection, and references to deallocated objects are discarded.

The user interface to the garbage collector is quite simple. Normally, the user need not be concerned with storage reclamation; upon the exhaustion of storage, the garbage collector is automatically invoked. The --trace-gc *level* switch makes it report what it does. The default size of new space is 128k references; it can be altered with the --size-heap *size* switch, where *size* is measured in units of 1024 references. The operations %gc and %full-gc invoke the garbage collector

explicitly. Programs that use weak pointers can be effected by garbage collection; for details, see Section 4.3.

The --predump-gc switch (on by default) indicates that if and when the world is dumped, and if Oaklisp terminates with an exit code of zero, a full garbage collection should be performed. In full garbage collections preceding world dumps, the root set does not include the stacks.

New space is resized dynamically, being expanded to RECLAIM_FRACTION times the amount of unreclaimed data if the fraction of unreclaimed data is above more than one RECLAIM_FRACTION'th of new space after a normal garbage collection, or by the minimal amount needed if there is insufficient space available in new space to fulfill the allocation request that triggered the collector. Currently RECLAIM_FRACTION is two. The next_newspace_size register says how big the next new space allocated will be, and is accessible to Oaklisp code. Its value should not be lowered casually, as the garbage collector will fail if new space is too small to hold all of the non-reclaimed storage from old space. A full garbage collection sets the size of new space back to the value originally specified by the user when Oaklisp was invoked, or the default value if none was specified.

Chapter 4

Stack Machine Architecture

4.1 Registers in the Emulator

This section describes the registers that make up the state of the bytecode emulator, called the processor below.

pc: The program counter points to a half reference address, and can not be accessed by register instructions.

val_stk: The top of the value stack. Can not be accessed by register instructions.

cxt_stk: The top of the context stack. Can not be accessed by register instructions.

bp: The base pointer points to the base of the instance variable frame of the current object.

env: The current environment object is indexed into to find locatives to lexically closed variables.

current_method: The method whose code is currently being executed. This is maintained solely to simplify garbage collection and debugging.

nargs: The number of args register is set before a function call and checked as the first action within each function.

t: Holds the cannonical truth object, #t.

nil: Holds the cannonical false object, #f, which is also used as the empty list, ().

fixnum_type: Holds the type of objects with a tag of fixnum.

loc_type: Holds the type of objects with a tag of locative.

subtype_table: Holds a table of the types of all the immediate subtypes. Currently only the first entry is used.

cons_type: Holds the *cons-pair* type, the type of simple conses which are directly manipulated by the processor.

env_type: Holds that type of environment vectors, used when making new environment objects.

object_type: Holds the type *object* which is at the root of the type hierarchy. Used when calling an operation with no parameters. This should not be necessary in the next version.

segment_type: Holds the type of stack segments, for use when the stack is being copied into the heap.

argless_tag_trap_table: Holds a table of operations to be called when various instructions fail.

arged_tag_trap_table: Holds a table of operations to be called when various instructions fail.

boot_code: Holds the method to be called first thing at boot time.

uninitialized: Holds the value that gets stuck into newly allocated storage.

free_point: Holds the point at which the next heap object will be allocated. Not accessed directly by even the most internal Oaklisp code, as the processor takes care of initialization and gc itself.

new.end: Holds the point at which we've run out of storage. An attempt to allocate past here necessitates a garbage collection. Not directly accessed by even the most internal Oaklisp code.

next_newspace_size: Holds the size in references of the next new space to be allocated by the garbage collector. This is dynamically adjusted by the garbage collector, so there is usually no need for it to be modified from the Oaklisp level.

4.2 Instruction Set

The instructions follow the same argument order conventions as the language itself. For example, (store-loc loc ref) expects to get *loc* on the top of the value stack and *ref* below it. The instruction format

8 bits	6 bits	2 bits
inline argument	opcode	0 0

leaves eight bits for an inline argument. Instructions that do not require any inline argument actually have "argless instruction" in their instruction field and use the argument field to code for the actual instruction.

Some instructions, eg. load-imm, require a complete arbitrary reference as an inline argument. This in incorporated, aligned, directly in the instruction stream. See Section 3.5.3 for details. Other instructions, in particular the long branches, require more than an eight bit inline argument but do not need an entire reference. These instructions get a 14 bit inline argument by using the space where the next instruction would normally go, with the last two bits set to zero in case the argument ends up in the low half of a word.

Arithmetic

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
plus		2 (fix,fix)	1 (fix)	
minus		1 (fix)	1 (fix)	
subtract		2 (fix,fix)	1 (fix)	
times		2 (fix,fix)	1 (fix)	
mod		2 (fix,fix)	1 (fix)	
div		2 (fix,fix)	1 (fix)	
log-op	n (4 bits)	2 (fix,fix)	1 (fix)	
bit-not		1 (fix)	1 (fix)	
rot		2 (fix,fix)	1 (fix)	
ash		2 (fix,fix)	1 (fix)	

Predicates

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
eq?		2 (ref,ref)	1 (bool)	
not		1 (ref)	1 (bool)	
<0?		1 (fix)	1 (bool)	
=0?		1 (fix)	1 (bool)	
=		2 (fix,fix)	1 (bool)	
<		2 (fix,fix)	1 (bool)	

Control

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
branch	rel-addr			
branch-nil	rel-addr	1 (ref)		
branch-t	rel-addr	1 (ref)		
long-branch				0.5
long-branch-nil	rel-addr	1 (ref)		0.5
long-branch-t	rel-addr	1 (ref)		0.5
return				

catch and call/cc Related

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
filltag		1 (tag)	1 (tag)	
throw		2 (tag,ref)	1 (ref)	
fill-continuation		1 (photo)	1 (photo)	
continue		2 (photo,ref)	1 (ref)	

Stack Manipulation

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
All stack references are zero-based. (swap 0) is a noop. (blast n) ≡(store-stack n)(pop 1).				
pop	n	n (refs)		
swap	n	n (refs)	n (refs)	
blast	n	n (refs)	n-1 (refs)	
blt-stack	n,m	n+m (refs)	n (refs)	
8 bit ref splits to 4-bit n and m, which are $1 \ldots 16$.				

Register Manipulation

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
store-reg	register	1 (ref)	1 (ref)	
load-reg	register		1 (ref)	

Addressing Modes

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
store-env	offset	1 (ref)	1 (ref)	
store-stack	offset	1 (ref)	1 (ref)	
store-bp	offset	1 (ref)	1 (ref)	
store-bp-i		2 (fix,ref)	1 (ref)	
contents		1 (loc)	1 (ref)	
set-contents		2 (loc,ref)	1 (ref)	
The next two instructions are the same.				
load-glo			1 (ref)	1 (ref)
load-imm			1 (ref)	1 (ref)
load-imm-fix	n		1 (fix)	
load-env	offset		1 (ref)	
load-stack	offset		1 (ref)	
load-bp	offset		1 (ref)	
load-bp-i		1 (fix)	1 (ref)	
Make a locative to the location $offset$ in beyond the bp register:				
make-bp-loc	offset		1 (loc)	
locate-bp-i		1 (fix)	1 (loc)	

Memory Model and Tag Cleaving

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
get-tag		1 (ref)	1 (fix)	
get-data		1 (ref)	1 (fix)	
crunch		2 (fix,fix:tag)	1 (ref)	
load-type		1 (ref)	1 (ref:type)	
load-length		1 (ref)	1 (fix)	
The next two instructions are not currently used.				
peek		1 (fix)	1 (fix:16-bit)	
poke		2 (fix,fix:16-bit)	1 (fix:16-bit)	

Misc

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
check-nargs	n	1 (op)		
check-nargs-gte	n	1 (op)		
store-nargs	n			
noop				
allocate		2 (typ,len)	1 (ref)	
vlen-allocate		2 (typ,len)	1 (ref)	
funcall-tail		2 (op,obj)	1 (op,obj)	
funcall-cxt-br	rel-addr	2 (op,obj)	1 (op,obj)	
push-cxt	rel-addr			
push-cxt-long				0.5
big-endian?			1 (bool)	
object-hash		1 (ref)	1 (fix)	
object-unhash		1 (fix)	1 (ref)	
gc			1 (ref)	
full-gc			1 (ref)	
inc-loc		2 (loc,fix)	1 (loc)	

List related instructions

instruction	*inline arg*	*initial stack*	*final stack*	*extra cell args*
cons		2 (ref,ref)	1 (ref)	
reverse-cons		2 (ref,ref)	1 (ref)	
car		1 (pair)	1 (ref)	
cdr		1 (pair)	1 (ref)	
set-car		2 (pair,ref)	1 (ref)	
set-cdr		2 (pair,ref)	1 (ref)	
locate-car		1 (pair)	1 (loc)	
locate-cdr		1 (pair)	1 (loc)	
assq		2 (ref,alist)	1 (ref:pair/nil)	

4.3 Weak Pointers

Weak pointers allow users to maintain tenuous references to objects, in the following sense. Let α be a weak pointer to the object *foo*, found by executing the code (object-hash foo). This α can be dereferenced to yield a normal reference, (object-unhash α) $\Rightarrow$ foo. However, if there is no other way to get a reference to *foo* then the system is free to invalidate α, so (object-unhash α) $\Rightarrow$ #f. In practice, when the garbage collector sees that there are no references to *foo* except for weak pointers it reclaims *foo* and invalidates any weak pointers to it.

Weak pointers are implemented directly by bytecodes because the emulator handles all details of storage allocation and reclamation directly. Weak pointers are represented by integers. Each time object-hash is called the argument is looked up in the *weak pointer hash table*. If no entry is found, a counter is incremented and the value of that counter is returned. An entry is made in the *weak pointer table* at an index corresponding to the current value of the counter, so that the weak pointer can be used to get back the original reference, and an entry is make in the weak pointer hash table to ensure that if the weak pointer to the same object is requested twice, the same number will be returned both times. After a garbage collection the weak pointer table is scanned and entries to objects which have been reclaimed are discarded, the weak pointer hash table is cleared, and the data in the weak pointer table is entered into the weak pointer hash table. Although these algorithms are poor if objects with weak pointers to them are frequently reclaimed, in practice this has not been a problem.

Chapter 5

Stack Discipline

This chapter describes how the stacks are organized at the logical level: how temporaries are allocated, how functions call and return work, how escape objects (used in the implementation of catch and throw) work, and how stack snapshots (used in the implementation of call/cc) work.

5.1 Stack Overview

The Oaklisp bytecode machine has a two-stack architecture. The *value stack* contains arbitrary references and is used for storing temporary variables, passing arguments, and returning results. The *context stack* is used for saving non-variable context when calling subroutines. Only context frames are stored on the context stack. This two stack architecture makes tail recursion particularly fast, and is in large part responsible for the speed of function call in this implementation.

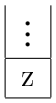
Most of the bytecodes are the usual sort of stack instructions, and use only value stack, for instance plus and $(\mathrm{swap}\ n)$. All arguments are passed on the value stack, and the value stack is *not* divided into frames. Methods consume their arguments, returning when they have replaced their arguments with their result or tail recursing when they have replaced their arguments with the appropriate arguments to the operations they are tail recursing to.

Under the current language definition there is no multiple value return, although the bytecode architecture admits such a construct. There are facilities for variable numbers of arguments, which are described in Section 7.9.

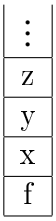
5.2 Method Invocation/Return

When a method is to be invoked, the arguments and operation are assembled on the value stack in right to left order, ie. the rightmost argument is pushed first

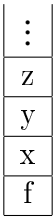
and the operation is pushed last. Let us walk through the invokation of (f x y z), where f is on operations which is being passed three arguments. Since we evaluate right to left, first we push z, thus:



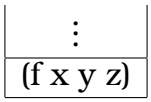
continuing, we push the rest of the arguments and the operation, until the stack is of this form.



A (store-nargs 3) instruction is now executed to place the number of arguments in the nargs register, and one of the funcall instructions is executed, which variant depending on whether this is a tail recursive call. If this is not a tail recursive call, the funcall instruction first pushes a frame containing the contents of the current_method, bp and env registers and a return pc onto the context stack. The instruction then examines the top two values, f and x, and looks f up in the operation-method-alist of the type of x, potentially also scanning the supertypes until it finds the appropriate method to be invoked. This method is placed in the current_method register, the method's environment is placed in the env register, the pc is set to the beginning of the method's code block, and the address of the appropriate instance variable frame within x is placed in the bp register. The funcall instruction leaves the value stack and nargs register unchanged:

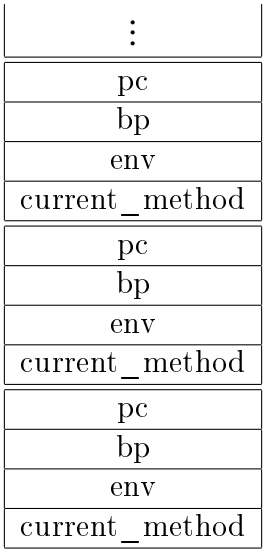


The first thing the code block of the resultant method executes is one of the check-nargs instructions, in this case perhaps (check-nargs 3). A (check-nargs n) instruction tests if nargs is n, trapping if not. After that, it pops the operation f off the stack. By leaving the operation to be popped off by the check-nargs instruction rather than the funcall instruction, when an an incorrect number of arguments is detected the operation is still available to the error system. The return instruction pops the top frame off the context stack, loads the popped context into the processor, and continues execution. Before a return is executed all of the arguments have been consumed and the result is the only thing left on the stack,



5.3 The Context Stack

The only things that can be stored on the context stack are context frames, which each have four values, as shown below. The push-cxt instruction pushes a context frame onto the context stack. It takes an inline argument, which is the relative address of the desired return point. This allows a context to be pushed whenever convenient, perhaps before the assembly of arguments begins. Earlier in the implementation process there was only one variant of the funcall instruction, which was tail recursive. Non tail recursive calls were compiled as a push-cxt followed by a funcall-tail, but because this sequence occured so frequently a combined instruction was implemented to improve code density.



Actually, the pc stored in the context stack is not a raw pointer to the next instruction but rather the offset from the beginning of the current code block, stored as a fixnum. This makes the return instruction slightly slower, as the actual return pc must be recomputed, but simplifies the garbage collector. The bp is analogously stored with a tag of locative so that the garbage collector need not treat it specially. This would cause a problem if the current object were reclaimed and afterwards had one of its instance variables refered to, as all that would be left of the object would be the solitary cell that the saved bp was pointing to, and the rest of the relevent instance variable frame would be gone. This is avoided by having the compiler ensure that a reference to the object in question is retained long enough.

Chapter 6

Methods

In this chapter we describe how methods are created, represented, and looked up. This is intimately related to instance variable reference, so we describe how that works here as well.

6.0.1 Invoking Methods

Methods are looked up by by doing a depth first search of the inheritance tree. Some Oaklisp code to find a method would look like this,

```
(define (%find-method op typ)
  (let ((here (assq op (type-operation-method-alist typ))))
    (if (null? here)
        (any? (lambda (typ) (%find-method op typ))
              (type-supertype-list typ))
        (list typ (cdr here)))))
```

Once this information is found, we need to find the offset of the appropriate block of instance variables, put a pointer to the instance variable frame in the bp register, set the other registers correctly, and branch.

```
(define (%send-operation op obj)
  (let ((typ (get-type obj)))
    (destructure (found-typ method) (%find-method op typ)
      (set! ((%register 'current-method)) method)
      (set! ((%register 'bp))
            (increment-locative
              (%crunch (%data obj) %loc-tag)
              (cdr (assq found-typ (type-bp-offset-alist typ)))))
      (set! ((%register 'env)) (method-env method))
      (set! ((%register 'pc))
            (code-body-instr (method-code (%method)))))))
```

Of course, the actual code to find a method is written in C and has a number of tricks to improve efficiency.

- Simple lambdas (operations which have only one method defined at the type object) are ubiquitous, so the overhead of method lookup is avoided for them by having a lambda? slot in each operation. This slot holds a zero if no methods are defined for the given operation. If the only method defined for the operation is for the type object then the lambda? slot holds that method, and the method is not incorporated in the operation-method-alist of type object. If neither of these conditions holds, the lambda? slot holds #f.

- To reduce the frequency of full blown method lookup, each operation has three slots devoted to a method cache. When *op* is sent to *obj*, we check if the cache-type slot of *op* is equal to the type of *obj*. If so, instead of doing a method search and finding the instance variable frame offset, we can use the cached values from cache-method and cache-offset. In addition, after each full blown method search, the results of the search are inserted into the cache.

  Giving the --trace-mcache switch to a version of the emulator compiled with FAST not defined will print an H when there is a method cache hit and an M when there is a miss. The method cache can be completely disabled by defining NO_METH_CACHE when compiling the emulator. We note in passing that we have one method cache for each operation. In contrast, the Smalltalk-80 system has an analogous cache at each call point. We know of no head to head comparison of the two techniques, but suspect that if we were to switch to the Smalltalk-80 technique we would achieve a higher average hit rate at considerable cost in storage.

- In order to speed up full blown method searches, a move to front heuristic reorders the association lists inside the types. In addition, the C code for method lookup was tuned for speed, is coded inline, and uses an internal stack to avoid recursion.

For most of this tuning we used the time required to compile compile-bench.oak as our primary benchmark for determining the speed of generic operations, since the compiler is written in a highly object-oriented style and makes extensive use of inheritance.

6.0.2 Adding Methods

A serious complication results from the fact that the type field in an add-method form is not evaluated until the method is installed at run time. Since the target type for the method is unknown at compile time the appropriate instance variable

map is also unknown, and hence the correct instance variable offsets cannot be determined. Our solution is to have the compiler guess the order[1] or simply invent one, compile the offsets accordingly, and incorporate this map in the header of the emitted code block. When the add-method form is actually executed at run time, the assumed instance variable map is compared to the actual map for the type that is the recipient of the method, and the code is copied and patched if necessary. The code only needs to be copied in the rare case when a single add-method is performed on multiple types that require different offsets.

After instance variable references in the code block have been resolved, which usually involves no work at all since the compiler almost always guesses correctly, the method can actually be created and installed. Creating the method involves pairing the code block with an appropriate environment vector containing references to variables that have been closed over. Because this environment vector is frequently empty, a special empty environment vector is kept in the global variable %empty-environment so a new one doesn't have to be created on such occations. All other environment vectors are created by pushing the elements of the environment onto the stack and executing the make-closed-environment opcode. Environment vectors are never shared in our current implementation, with the exception of the empty environment.

After the method is created it must be installed. The method cache for the involved operation is invalidated, and the method is either put in the lambda? slot of the operation or the operation-method-alist of the type it is being installed in. If there is already a value in the lambda? slot and the new method is not being installed for type object, the lambda? slot is cleared and the method that used to reside there is added to operation-method-alist of type object.

(%install-method-with-env type operation code-body environment) *Operation*
This flushes the method cache of *operation*, ensures that the instance variable maps of *code-body* and *type* agree (possibly by copying *code-body* and remapping the instance variable references), creates a method out of *code-body* and *environment*, and adds this method to the operation-method-alist of *type*, modulo the simple lambda optimization if *type* is object.

(%install-method type operation code-body) *Operation*
≡ (%install-method-with-env type operation code-body %empty-environment)

(%install-lambda-with-env code-body environment) *Operation*
≡ (%install-method-with-env object (make operation) code-body environment)
but more efficient.

(%install-lambda code-body) *Operation*
≡ (%install-method-with-env object (make operation) code-body %empty-environment)
but more efficient.

[1]The compiler guesses by attempting to evaluate the type expression at compile time.

Chapter 7

Oaklisp Level Implementation

Once the core of the language is up, the rest of the language is implemented using the language core. Some of these new language constructs require some support from the bytecode emulator along with considerable Oaklisp level support. These include such features as call/cc and its simple cousin catch. Others are implemented entirely in the core language without the use of special purpose bytecodes; in this latter class fall things like infinite precision integers (so called *bignums*), fluid variables, and the error system.

In this chapter we describe the implementation of these constructs, albeit sketchily. For more details, the source code is publicly available. We do not describe the implementation of locales or other extremely high level features; read the source for the details, which are quite straightforward.

7.1 Fluid Variables

Our implementation of fluid variables uses deep binding. A shallow bound or hybrid technology would presumably speed fluid variable reference considerably, but they are used rarely enough that we have not bothered with such optimizations. In addition, shallow binding interacts poorly with multiprocessing.

fluid-binding-list *Global Variable*

Hold an association list which associates fluid variables to their values. The bind construct simply pushes variable/value pairs onto this list before executing its body and pops them off afterwards.

It would be easy to implement fluid variables using the unwind protection facilities, but instead the abnormal control constructs (native-catch and call/cc) are careful to save and restore fluid-binding-list properly. This avoids the overhead of using the wind facilities and makes sure that (ignoring wind-protect) fluid-binding-list is only manipulated once for every abnormal exit, no matter how many bind constructs are exited and entered along the way.

(%fluid symbol) *Locatable Operation*

This looks *symbol* up on fluid-binding-list. If it is not found an error is signaled. In contrast, (setter %fluid) silently adds new fluid variables to the end of the association list, thus creating new top level fluid bindings.

7.2 Unwind Protection

In the presence of call/cc, a simple unwind-protect construct a. la. Common Lisp does not suffice. Because control can enter a dynamic context which has previously been exited, symmetry requires that if we have forms that get executed automatically when a context is abnormally exited, we must also have ones that get executed automatically when a context is abnormally entered. For this purpose the system maintains some global variables that reflect the state of the current dynamic context with respect to these automatic actions.

%windings *Global Variable*

This is a list of wind/unwind action pairs, one of which is pushed on each time we enter a dynamic-wind and poped off when we leave it. The wind/unwind action pairs are of the form (after before . saved-fluid-binding-list) where *before* and *after* are operations, guards to be called when leaving and entering this dynamic context respectively, and *saved-fluid-binding-list* is the appropriate value for fluid-binding-list when calling these guard operations.

%wind-count *Global Variable*

To reduce find-join-point's complexity from quadratic to linear, we maintain %wind-count = (length %windings).

7.3 Catch

The format of catch tags is describe in Section 3.5.6. The simplest implementation of native-catch would have the native-catch macro expand into something that executed the appropriate unwind protect actions and restored the fluid binding list before resuming execution. Regretably, the unwind protect actions can themselves potentially throw, so the stacks must not be chopped off until after the unwind protect actions have been completed. For this reason the throw operation doesn't just call the throw instruction, but first performs all the appropriate unwind protect actions. Along with stack heights, the catch tag contains saved-wind-count, which is used to compute how many elements of %windings must be popped off and called, and saved-fluid-binding-list, which is restored immediately before the stacks are actually chopped off.

7.4 Call/CC

The call/cc construct is just like native-catch, except that the saved stack state isn't just some offsets but is an entire stack photo (see Section 3.5.5), and that not only unwinding but also rewinding actions might need to be done. Because the winding actions might throw, it is necessary for the unwind actions to be executed in the stack context where the continuation is invoked, and similarly the rewind actions must be executed in the destination stack context.

%%join-count *Global Variable*

%%new-windings *Global Variable*

%%new-wind-count *Global Variable*

%%cleanup-needed *Global Variable*

These global are used to pass information about which rewind actions need to be executed by the destination of the continuation, since the normal parameter passing mechanisms are not available. This would have to be done on a per processor basis in a multithreaded implementation.

Continuations contain saved-windings and saved-wind-count instance variables, which have the values of %windings and %wind-count at the time the %call/cc was entered. Before the continuation is actually invoked and the destination stack photos restored, the highest join point between current and the destination winding lists is found, and all the unwind actions needed to get down to the join point are executed. Then the stack photo is restored, and in the destination context the rewinding actions are done to get up from the join point to the destination point.

7.5 The Error System

The error system is pretty complete, but is actually not only easy to use, but also intuitive and fun, particularly at the user level.

(error-return message . body) *Macro*

Evaluates *body* in a dynamic context in which a restart handler is available that can force the form to return. The handler is identified by *string* in the list of choices printed out by the debugger. If the handler is invoked by calling ret with an argument in addition to the handler number, the error-return form returns this additional value; otherwise it returns #f. If no error occurs, an error-return form yields the value of *body*.

(error-restart message let-clauses . body) *Macro*
Acts like a let, binding the *let-clauses* as you would expect, except that if an error occurs while evaluating *body*, the user is given the option of specifying new values for the variables of the *let-clauses* and starting *body* again. This is implemented with a native-catch and some tricky restart handlers that get pushed onto (fluid restart-handlers).

(fluid restart-handlers) *Fluid Variable*
A list of actions that the user can invoke from the debugger in order to restart the computation at various places. Not normally manipulated by user code.

(fluid debug-level) *Fluid Variable*
The number of recursive debuggers we're inside. Zero for the top level. Not normally manipulated by user code.

(catch-errors (error-type [error-lambda [non-error-lambda]]). body) *Macro*
Evaluates *body*. If an error which is a subtype of *error-type* occurs, #f is returned, unless *error-lambda* is given, in which case it is called on the error object. If no error occurs then the result of evaluating *body* is returned, unless *non-error-lambda* is provided in which case it is called on that result and the resultant value returned. Both lambdas run outside the handler this construct installs, so an error raised by either one is not caught here.

(bind-error-handler (error-type handler). body) *Macro*
This binds a handler to errors which are subtypes of *error-type*. When such an error occurs, an appropriate error object is created and *handler* is applied to it.

(invoke-debugger error) *Operation*
This error handler, when sent to an error object, invokes the debugger.

(remember-context error after-op) *Operation*
Used to make an error remember the context it occured in, so that even after the context has been exited the error can still be proceeded from, or the debugger can be entered back at the error context. This should always be called tail recursively from a handler, and after it stashes away the continuation it calls *after-op* on *error*. Of course, *after-op* should never return.

(invoke-in-error-context error operation) *Operation*
Go back to the context in which *error* occured and invoke *operation* there.

(report error stream) *Operation*

Write a human readable account of the error to *stream*. Controlled studies have shown that error messages can never be too verbose.

(proceed error value) *Operation*
Proceed from *error*, returning *value*. Of course, it is actually the call to signal that returns *value*.

(signal error-type . args) *Operation*
This signals creates an error of type *error-type* with initialization arguments *args*. It then scans down (fluid error-handlers) until it finds a type of error which is a supertype of *error-type*, at which point it sends the corresponding handler to the newly minted error object. If the handler returns, that value is returned by the call to signal. One day we'll add a way for a handler to refuse to handle an error, in which case the search for an applicable handler will proceed down the list.

(fluid error-handlers) *Fluid Variable*
An association list of mapping error types to error handlers. Users should not touch this directly.

Of course, there are a large number of types of errors used by the system. A few of the more useful to know about are:

general-error *Type*
The supertype of all errors. Abstract.

proceedable-error *Type*
The supertype of all errors that can be recovered from. Abstract.

fs-error *Type*
File system error. Abstract. It has all kinds of subtypes for all the different possible file system error conditions.

error-opening *Type*
Abstract. Signaled when a file can't be opened for some reason. Proceeding from this kind of error with a string lets you try opening a different file.

operation-not-found *Type*
Signaled when an operation is sent to an object that can't handle it. Proceeding from this kind of error will return a value from the failed call.

nargs-error *Type*
Signaled when there are an incorrect number of arguments passed to a function. Proceeding from this will return a value from the failed call. Abstract

nargs-exact-error *Type*
Signaled when there are an incorrect number of arguments passed to a method that expects a particular number of arguments.

nargs-gte-error *Type*
Signaled when there are an insufficient number of arguments passed to a method that can tolerate extra arguments.

infinite-loop *Type*
Signaled when an infinite loop is entered. User programs may wish to signal this as well.

read-error *Type*
Some kind of reader syntax error. Abstract. There are about fifty million subtypes, corresponding to all the different constructs that can be malformed, and all the different ways in which they can be malformed. We probably went a little overboard with these.

user-interrupt *Type*
Oaklisp received a DEL signal. Through a convoluted series of events in which the UNIX trap handler sets the variable _del_, which is detected by the bytecode emulator which pretends that a noop instruction failed and passes the nargs register to the Oaklisp trap handler which salts the old nargs away for restoration upon return and signals this error type, the user usually lands in the debugger after typing Control-C.

7.6 Numbers

Small integers (between -2^{29} and $2^{29}-1$ inclusive) are represented as immediates of type fixnum and handled directly by microcode. When arithmetic instructions trap out, due to either their arguments not being fixnums or to overflow, an Oaklisp operation corresponding to the bytecode is called. Most of these operations are written in terms of other bytecodes, and should never be shadowed. For instance,

```
(add-method (subtract/2 (number) x y)
  (+ x (- y)))
```

defines subtraction in terms of negation and addition. The trap code also handles fixnum overflow, promoting the operands to bignums and dispatching appropriately. The only really primitive operations, which must handle all types of numbers, are <, =, minus, negative?, plus/2, times/2, /, /r, quotient, remainder, quotientm and modulo. Whenever a new type of number is defined, methods for all of the above operations should be added for it, unless the new type is not a subtype of real, in which case methods wouldn't make sense for <, negative?, and perhaps quotient, remainder, quotientm and modulo.

7.7 Vectors and Strings

Rather than being built into the emulator, vectors are defined entirely within Oaklisp, albeit with some rather low level constructs.

variable-length-mixin *Type*

This type provides a variable amount of stuff at the end of its instances. When a type has this mixed in, whether immediately or deep down in the inheritance tree, it always takes an extra initialization argument which says has long the variable length block at the end should be. This is mixed into such system types as %code-vector, stack-segment, and %closed-environment.

In general, variable-length-mixin is used at the implementation level only and should never appear in user code. Typically if you think you want a subtype of variable-length-mixin, what you really want is an instance variable bound to a vector.

(%vref variable-length-object n) *Locatable Operation*

This is the accessor operation to get at the extra cells of subtypes of variable-length-mixin. It is used in the implementation of variable length structures, and in things like describe that look at their internals.

simple-vector *Type*

This is a subtype of vector with variable-length-mixin added and an appropriate nth method defined.

Characters are packed into strings more densely than one character per reference, so strings are not just vectors with odd print methods; they also have accessor methods which unpack characters from their internals. Unfortunately, it is not possible to pack four eight bit characters into a single 32-bit reference without violating the memory format conventions by putting something other than $\boxed{0\ 0}$ in the tag field. We could pack four seven bit characters into each reference, but some computers use eight bit fonts, and the characters within the string would not be aligned compatibly with C strings. We therefore use the following somewhat wasteful format, which packs three characters into a 32-bit reference and seven into a 64-bit one.

---

string *Type*

This is a subtype of simple-vector with the nth method shadowed by one that packs as many eight bit characters as fit into the fixnum of each word, low byte first: three into the low 24 bits of a 30-bit fixnum, seven into the low 56 bits of a 62-bit one. The bytes of the last word beyond the string's characters are padding; they are masked off by equality testing and hash key computation. Below is the string "Oaklisp Rules!" as represented in memory with 32-bit references.

31 . . . 26	25 . . . 18	17 . . . 10	9 . . . 2	1 0
string				
object length: 8				0 0
string length: 14				0 0
0 0 0 0 0 0	#\k	#\a	#\O	0 0
0 0 0 0 0 0	#\s	#\i	#\l	0 0
0 0 0 0 0 0	#\R	#\space	#\p	0 0
0 0 0 0 0 0	#\e	#\l	#\u	0 0
0 0 0 0 0 0	#\null	#\!	#\s	0 0

7.8 Symbols

We do not use any of the fancy techniques used by older dialects, like oblists or symbol buckets. Instead, the standard hash table facility is used for the symbol table.

symbol-table *Generic Hash Table*

Maps strings to symbols, using string-hash-key to compute the hash and equal? to compare strings for equality.

(intern string) *Operation*

Returns a symbol with print name *string* by looking it up in the symbol-table and making and installing a new symbol if it isn't found. Strings passed to intern should never be side effected afterwards or the symbol table could be corrupted.

(fluid print-escape) *Fluid Variable*

This flags whether symbols with weird characters in them should be with the weird characters escaped. It also applies to strings.

(fluid symbol-slashification-style) *Fluid Variable*

This flag is only relevent if (fluid print-escape) is on. With the value t-compatible then the empty symbol is printed as #[symbol ""] and all other symbols requiring escaping are printed with a \ character preceding every character of the symbol. With any other value, escaped symbols are delimited by | characters and internal characters \ and | are preceded by \.

7.9 Variable Numbers of Arguments

The formal parameter list of a method is permitted to be improper, with the terminal atom being a magic token representing the rest of the arguments. The only legal use for this magic token is as the terminal member of an improper argument list of a tail recursive call, and as an argument to the special form rest-length. Methods that accept a variable number of arguments must exit tail recursively and must pass along their magic token in their tail recursive call, unless they know that they actually received no extra arguments.

(rest-length varargs-token) *Special Form*

Returns the number of trailing arguments represented by *varargs-token*.

For example, this is legal,

```
(define (okay x y . rest)
  (if (zero? (rest-length rest))
      'nanu-nanu
      (list 'you x y 'sucker . rest)))
```

while the following are not, the first because it has an exit when there might be extra arguments which does not pass the extra arguments along tail recursively, and the second because it tries to pass along the extra arguments in a non tail recursive position.

```
(define (not-okay x y . rest)
  (if (eq? x y)
      'nanu-nanu
      (list 'you x y 'sucker . rest)))

(define (also-bad x y . rest)
  (append (list 'you x 'sucker . rest) y))
```

The implementation behind this is very simple: extra arguments are ignored by the compiler, except that it emits a check-nargs-gte in place of a chech-nargs at the top of the method code body and does a little computation to figure out what the value to put in the nargs register when it sees rest argument at the tail of a call. When all the user wishes to do is pass the extra arguments along in the way that the make method passes extra args along to initialize, this mechanism is both convenient and efficient. Sometimes the user needs to actually get into the extra arguments though, so some operations are provided to make handling variable numbers of arguments easier.

(consume-args value . extra) *Operation*

Returns *value*.

(listify-args operation . args) *Operation*

Calls *operation* with a single argument, a list of *args*.

There is also a macro package that implements optional and keyword arguments using these facilities, and the Scheme compatiblity package redefines add-method so that, as required by the Scheme standard (Rees et al., 1986), extra arguments are made into a list.

Chapter 8

The Compiler

8.1 File Types

There are a number of different kinds of object files, distinguished by extension.

extension	file type
.oak	Oaklisp source file
.omac	Macroexpanded Oaklisp source file
.ou	Assembly file, not peephole optimized
.oc	Assembly file, peephole optimized
.oa	Assembled object file

compiler-from-extension *Global Variable*
The extension of the input files the compiler will read. Default ".oak". This variable is in the compiler locale.

compiler-to-extension *Global Variable*
The extension the the output files the compiler will produce. Default ".oa". This variable is in the compiler locale.

compiler-noisiness *Global Variable*
The amount of noise the compiler should produce; zero for none, 1 for a little, and 2 for a lot. Default value is 1, but the oakliszt batch file compiler sets it to zero. This variable is in the compiler locale.

8.2 Object File Formats

8.3 Compiler Internals

Some compiler internals documentation. Very sketchy, just enough to give people a vague idea of what the internal program representation is and what the various passes are for.

Chapter 9

Bootstrapping

In this chapter we describe how new versions of Oaklisp are created. Oaklisp is self-hosting: the compiler and most of the runtime are written in Oaklisp, so building a world from source requires a running Oaklisp, or a stand-in for one, for two steps: compiling the .oak source files to .oa object files, and linking the object files of the *cold world* into a cold world image. Everything after that is done by the emulator being built.

9.1 Building a World

The build is much like that of a C program. First the Oaklisp sources which make up the cold world load are compiled to produce object files. Then a linker, tool.oak, an Oaklisp program, takes these object files and lays them all out in memory, resolving references to global variables and laying out quoted constants referred to in the code, and puts a map of where it allocated various globals in memory. At this point the cold world, new.cold, is booted by the emulator, and the files that the linker laid out in memory are thereby executed, sequentially. These files gradually build all the infrastructure required for a full Oaklisp world. The first files are written at an extremely low level, and make things like make and cons work. Later files bring up more advanced constructs, until finally there is enough for object files to be loaded. At this point the world is dumped, and then it is booted and has the remaining files loaded into it using the normal file loading mechanisms, in stages: first the rest of the runtime (macros, bignums, rationals, development tools), then the compiler into compiler-locale, then the Scheme compatibility files into scheme-locale, until the full Oaklisp world, oakworld.bin, is built.

The two steps that need a running Oaklisp can each be done in three ways, and the build system (see BUILD.md) picks the first that is possible from what is at hand:

- with an *old world*: an existing world image, run by the emulator just built,

compiles the sources and runs tool.oak. The old world may be older than the sources: the freshly compiled assembler, and anything else the sources need that it lacks, is loaded into it first. It may also be for another architecture, since a system can generate code for any architecture (section 3.5.4), although what is loaded into it is compiled for it.

- from *prebuilt bytecode*: object files compiled earlier, which are portable between architectures of the same instruction packing, linked by tool.oak running in the host below;
- from source alone, with a *Guile-hosted* Oaklisp: enough of Oaklisp implemented in Guile Scheme to load the world's own macros, runtime, compiler and linker from their sources and run them. Because it is the real compiler that runs, its output is byte for byte what a native Oaklisp produces.

Whichever way it starts, the result is the same, and the world is then rebuilt with itself until it reaches a fixpoint: make rebuild-world saves the world just built and builds everything again with it, and make bootstrap does that twice and checks that the world reproduces its own object files exactly. The compiler is deterministic, and the linker lays symbols and data out in the order it first meets them, so all three routes, and both linkers (an optional C reimplementation of tool.oak exists as an independent check), produce identical worlds.

Bootstrapping a system for a new architecture is done the same way from an existing one: the existing system compiles the sources and links the cold world for the new architecture (--target), and the new emulator boots it.

9.2 World Files

The formats of these files is very simple. Each begins with a line naming the architecture it is for:

```
;oaklisp-bytecode word-size=64 instructions-per-ref=2
;oaklisp-world format=cold word-size=64 instructions-per-ref=4 chars-per-word=7
;oaklisp-world format=binary endian=little word-size=64 instructions-per-ref=2 chars-per-word=7
```

World files also record how many characters a string packs into each word (7.7): seven with 64-bit references, three with 32-bit ones. A world image then contains a header which gives the length of the various segments and the values of some registers, followed by a memory image with pointers given as offsets from the beginning of the image, followed by the weak pointer table.

The cold world is in a hexadecimal format, with each reference represented as a space followed by a sequence of hexadecimal digits. Newlines may optionally precede spaces. Actually, the space referred to above can be either a space

character or the ↑ character. The latter indicates that the following reference contains instructions, written as one number with the first instruction most significant; since the instructions in a cell are ordered in memory differently depending on the endianity of the machine, the loader puts them into memory order as it reads them, reversing the 16-bit fields on a little-endian machine. This keeps the cold load file independent of endianity.

Binary worlds are memory images and are specific to byte order, word size and packing; the emulator refuses one whose header does not match it.

To make Oaklisp dump itself upon exiting use the --dump *filename* switch when invoking the emulator. A running system can also save itself with dump-world, and replace itself with a saved image with load-world.

Chapter 10

Administrative Details

10.1 Getting a Copy

See https://github.com/barak/oaklisp/.

10.2 Bugs

The following are known serious problems and inadequacies of the current implementation. People are invited to work on remedying them. None of these are fundamental; they're simply due to lack of either effort or motivation.

- Floating point numbers are not supported. Rationals can be used to make up for this lack.
- In contrast to the error handling system, which is Industrial Strength, the debugger barely exists.
- There is no foreign function interface for loading and calling C routines from a running Oaklisp.

Bug reports, enhancements, and the like should be posted using the facilities on https://github.com/barak/oaklisp/; queries can also be sent to barak+oaklisp@pearlmutter.n

We appreciate enhancements (especially in the form of patch files), bug fixes, and bug reports. We are particularly grateful for porting problem fixes. In a bug report, please include the precise version of Oaklisp, which is indicated by the date at the end of the tar file. And please try to make sure that it's really a bug and not a feature, and pretty please, if at all possible, find a *very short* program that manifests your bug. In any case please be aware that we are under no obligation to respond to bug reports in any way whatsoever.

10.3 Copyright and Lack of Warranty

The Oaklisp copyright belongs to its authors. It is authorized for distribution under the GNU General Public License, version 2, copies of which are readily obtainable from the Free Software Foundation. There is no warranty; use at your own risk. For more precise information, see the COPYING file in the Oaklisp source distribution.

Bibliography

Barak A. Pearlmutter. Garbage collection with pointers to individual cells. *Communications of the ACM*, 39(12):202–6, December 1996. doi: 10.1145/272682.272712.

Barak A. Pearlmutter and Kevin J. Lang. The implementation of Oaklisp. In Peter Lee, editor, *Topics in Advanced Language Implementation*, pages 189–215. MIT Press, 1991. ISBN 0262121514.

Jonathan A. Rees, William Clinger, et al. The revised^3 report on the algorithmic language Scheme. *SIGPLAN Notices*, 21(12):37–79, December 1986.

Alan Snyder. Encapsulation and inheritance in object-oriented programming languages. In *ACM Conference on Object-Oriented Systems, Programming, Languages and Applications*, pages 38–45, September 1986. Special issue of *ACM SIGPLAN Notices* 21(11).

Index

swap, **29**
(store-nargs 3), 30
-, 18
-e, 18
.oa, 19, 46
.oak, 46
.oak|hyperpage, 45
.oa|hyperpage, 45
/, 40
/r, 40
<, 25, 40
<0?, 25
=, 25, 40
=0?, 25
BUILD.md, 46
FAST, 33
MAX_SEGMENT_SIZE, 19
NO_METH_CACHE, 33
RECLAIM_FRACTION, 22
#f, 7, 33, 37, 38
%%instructions-per-ref, 19
%%word-size, 19
%add-method, 3
%allocate, 11
%call/cc, 37
%closed-environment, 12, 41
%code-vector, 12, 41
%empty-environment, 11, 13, 34
%full-gc, 21
%gc, 21
%wind-count, 36, 37
%windings, 36, 37
del, 40
add-method, 7, 8, 13, 33, 34, 44
allocate, 27
ash, 25
assq, 27
b, 18
backwards-args-mixin, 8
bc, 18
bc2-32, 18, 19
bc2-64, 18
bc2-eb32, 18
bc2-eb64, 18
bc2-el32, 18
bc2-el64, 18
bc4-64, 18
bc4-eb64, 18
bc4-el64, 18
big-endian?, 27
bignum, 40
bind, 4, 35
bind-error-handler, 4
bit-not, 25
blast, 26
blt-stack, 26
bp, 26, 30–32
branch, 25
branch-nil, 25
branch-t, 25
cache-method, 33
cache-offset, 33
cache-type, 33
call-with-current-continuation, 13
call/cc, 4, 13, 19, 20, 26, 35–37
car, 27
catch, 4, 20, 26, 35
cdr, 27
chech-nargs, 43
check-nargs, 27, 30

check-nargs-gte, 27, 43
compile-bench.oak, 33
compiler-locale, 46
cons, 27, 46
cons-pair, 8, 21
contents, 26
continue, 26
crunch, 27
current_method, 30, 31
describe, 41
div, 25
dump-world, 48
dynamic-wind, 36
env, 30, 31
eq?, 25
equal?, 42
error-return, 37
fill-continuation, 19, 26
filltag, 26
find-join-point, 36
fixnum, 5, 40
fluid-binding-list, 35, 36
fluid-bindings-alist, 4
full-gc, 27
funcall, 30, 31
funcall-cxt-br, 27
funcall-tail, 27, 31
funny-wind-protect, 4
gc, 27
get-byte-code-list, 12
get-data, 27
get-tag, 27
host-architecture, 19
inc-loc, 27
initialize, 13, 43
intern, 42
l, 18
lambda?, 33, 34
let, 2, 4, 38
list, 8
load-bp, 26
load-bp-i, 26
load-env, 26
load-glo, 26
load-imm, 25, 26
load-imm-fix, 26
load-length, 27
load-reg, 26
load-stack, 26
load-type, 27
load-world, 48
locate-bp-i, 26
locate-car, 27
locate-cdr, 27
locative, 31
log-op, 25
long-branch, 25
long-branch-nil, 25
long-branch-t, 25
make, 43, 46
make bootstrap, 47
make rebuild-world, 47
make-bp-loc, 26
make-closed-environment, 34
minus, 25, 40
mod, 25
modulo, 40
nargs, 30, 40, 43
native-catch, 4, 7, 35–38
negative?, 40
new.cold, 46
next_newspace_size, 22
noop, 18, 27, 40
not, 25
nth, 41, 42
oakliszt, 45
oakworld.bin, 46
object, 3, 33, 34
object-hash, 27, 28
object-unhash, 27
operation-method-alist, 21, 30, 33, 34
pc, 30, 31
peek, 27
plus, 25, 29

plus/2, 40
poke, 27
pop, 26
push-cxt, 27, 31
push-cxt-long, 27
quotient, 40
quotientm, 40
real, 40
remainder, 40
rest-length, 43
ret, 37
return, 11, 25, 30, 31
reverse-cons, 8, 27
rot, 25
saved-fluid-binding-list, 20, 36
saved-wind-count, 20, 36, 37
saved-windings, 37
scheme-locale, 46
self, 13
set-car, 27
set-cdr, 27
set-contents, 26
set!, 2–4
signal, 39
simple-vector, 42
stack-segment, 41
stdin, 11
stdout, 11
store-bp, 26
store-bp-i, 26
store-env, 26
store-loc, 24
store-nargs, 27
store-reg, 26
store-stack, 26
string-hash-key, 42
subtract, 25
supertype-list, 21
swap, 26
symbol-table, 42
t-compatible, 42
throw, 20, 26, 36, 37
times, 25
times/2, 40
tool.oak, 46, 47
type-bp-alist, 21
unwind-protect, 36
variable-length-mixin, 13, 41
vector, 12, 41
vlen-allocate, 27
wind-protect, 4, 35
↑super, 11
↑super-tail, 11
*
    Operation, 5
+
    Operation, 6
-
    Operation, 6
1+
    Operation, 6
<=
    Operation, 6
<
    Operation, 6
=
    Operation, 6
>=
    Operation, 6
>
    Operation, 6
%%cleanup-needed
    Global Variable, 37
%%join-count
    Global Variable, 37
%%new-wind-count
    Global Variable, 37
%%new-windings
    Global Variable, 37
%add-method
    Special Form, 2
%allocate
    Operation, 11
%assq

Operation, 10
%big-endian?
Operation, 10, 19
%block
Special Form, 2
%closed-environment
Type, 12
%code-vector
Type, 12
%continue
Operation, 10
%crunch
Operation, 10
%data
Operation, 10
%fill-continuation
Operation, 10
%filltag
Operation, 10
%fluid
Locatable Operation, 35
%full-gc
Operation, 10
%gc
Operation, 10
%get-length
Operation, 10
%if
Special Form, 2
%increment-locative
Operation, 11
%install-lambda-with-env
Operation, 34
%install-lambda
Operation, 34
%install-method-with-env
Operation, 13, 34
%install-method
Operation, 34
%labels
Special Form, 2
%load-bp-i
Locatable Operation, 11
%make-cell
Operation, 11
%make-closed-environment
Operation, 11
%make-locative
Special Form, 2
%method
Type, 12
%print-digit
Operation, 11
%push
Operation, 11
%quote
Special Form, 2
%read-char
Operation, 11
%return
Operation, 11
%tag
Operation, 10
%varlen-allocate
Operation, 11
%vref
Locatable Operation, 41
%wind-count
Global Variable, 36
%windings
Global Variable, 36
%write-char
Operation, 11
%↑super-tail
Operation, 11
add-method
Macro, 3
and
Macro, 5
apply
Operation, 13
ash-left
Operation, 6
ash-right

Operation, 6
bind-error-handler
Macro, 4, 38
bind
Macro, 4
bit-andca
Operation, 6
bit-and
Operation, 6
bit-equiv
Operation, 6
bit-nand
Operation, 6
bit-nor
Operation, 6
bit-not
Operation, 6
bit-or
Operation, 6
bit-xor
Operation, 6
caaaar
Locatable Operation, 9
caaadr
Locatable Operation, 9
caaar
Locatable Operation, 8
caadar
Locatable Operation, 9
caaddr
Locatable Operation, 9
caadr
Locatable Operation, 8
caar
Locatable Operation, 8
cadaar
Locatable Operation, 9
cadadr
Locatable Operation, 9
cadar
Locatable Operation, 8
caddar
Locatable Operation, 9
cadddr
Locatable Operation, 9
caddr
Locatable Operation, 8
cadr
Locatable Operation, 8
call-with-current-continuation
Operation, 13
car
Locatable Operation, 8
catch-errors
Macro, 4, 38
catch
Macro, 3
cdaaar
Locatable Operation, 9
cdaadr
Locatable Operation, 9
cdaar
Locatable Operation, 9
cdadar
Locatable Operation, 9
cdaddr
Locatable Operation, 9
cdadr
Locatable Operation, 9
cdar
Locatable Operation, 8
cddaar
Locatable Operation, 9
cddadr
Locatable Operation, 9
cddar
Locatable Operation, 9
cdddar
Locatable Operation, 9
cddddr
Locatable Operation, 9
cdddr
Locatable Operation, 9
cddr

Locatable Operation, 8
cdr
Locatable Operation, 8
character
Type, 5
compiler-from-extension
Global Variable, 45
compiler-noisiness
Global Variable, 45
compiler-to-extension
Global Variable, 45
cond
Macro, 5
cons-pair
Type, 12
consume-args
Operation, 43
cons
Operation, 7
contents
Locatable Operation, 7
debug-level
Fluid Variable, 38
define
Macro, 3
dynamic-wind
Operation, 13
eq?
Operation, 7
error-handlers
Fluid Variable, 39
error-opening
Type, 39
error-restart
Macro, 38
error-return
Macro, 37
fixnum
Type, 5
fluid-binding-list
Global Variable, 35
fluid
Macro, 4
foldable-mixin
Type, 12
fs-error
Type, 39
funny-wind-protect
Macro, 4
general-error
Type, 12, 39
get-type
Operation, 7
identity
Operation, 7
if
Macro, 4
infinite-loop
Type, 40
initialize
Operation, 13
intern
Operation, 42
invoke-debugger
Operation, 38
invoke-in-error-context
Operation, 38
lambda
Macro, 3
let*
Macro, 5
let
Macro, 5
list*
Operation, 8
listify-args
Operation, 44
list
Operation, 7
locale
Type, 12
locatable-operation
Type, 12
locative

Type, 5
make-locative
Macro, 3, 4
make
Operation, 13
minus
Operation, 7
modulo
Operation, 7
nargs-error
Type, 39
nargs-exact-error
Type, 40
nargs-gte-error
Type, 40
native-catch
Special Form, 2
negative?
Operation, 7
not
Operation, 8
null-type
Type, 12
null?
Operation, 8
object-hash
Operation, 7
object-unhash
Operation, 6, 7
object
Type, 12
open-coded-mixin
Type, 12
operation-not-found
Type, 39
operation
Type, 12
or
Macro, 5
pair
Type, 12
positive?
Operation, 6
print-escape
Fluid Variable, 42
proceedable-error
Type, 39
proceed
Operation, 39
quote
Macro, 3
quotient
Operation, 6
read-error
Type, 40
remember-context
Operation, 38
report
Operation, 38
rest-length
Special Form, 43
restart-handlers
Fluid Variable, 38
rot-left
Operation, 7
rot-right
Operation, 7
second-arg
Operation, 8
set!
Macro, 3
settable-operation
Type, 12
set
Macro, 3
signal
Operation, 39
simple-vector
Type, 41
string
Type, 41
symbol-slashification-style
Fluid Variable, 42
symbol-table

Generic Hash Table, 42
throw
Operation, 7
type
Type, 12
user-interrupt
Type, 40
variable-length-mixin
Type, 12, 41
vector
Type, 12
wind-protect
Macro, 4
zero?
Operation, 5
--dump
switch, 48
--predump-gc
switch, 22
--size-heap
switch, 21
--target
switch, 47
--trace-gc
switch, 21
--trace-mcache
switch, 33
!=
Operation, 5

Smalltalk-80, 33