

A No-Frills Introduction to Lua 5.1 VM Instructions

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1 Introduction

This is a no-frills introduction to the instruction set of the Lua 5.1 virtual machine. Compared to Perl or Python, the compactness of Lua makes it relatively easier for someone to peek under the hood and understand its internals. I think that one cannot completely grok a scripting language, or any complex system for that matter, without slitting the animal open and examining the entrails, organs and other yucky stuff that isn't normally seen. So this document is supposed to help with the "peek under the hood" bit.

This introductory guide covers Lua 5.1 only. Please see the older document for the guide to Lua 5.0.2 virtual machine instructions. This is intentional; the internals of Lua is not fixed or standardized in any way, so users *must not* expect compatibility from one version of Lua to another as far as internals are concerned.

Output from ChunkSpy (URL: <http://luaforge.net/projects/chunkspy/>), a Lua 5 binary chunk disassembler which I wrote while studying Lua internals, was used to generate the examples shown in this document. The brief disassembly mode of ChunkSpy is very similar to the output of the listing mode of `luac`, so you do not need to learn a new listing syntax. ChunkSpy can be downloaded from LuaForge (URL: <http://luaforge.net/>); it is licensed under the same type of MIT-style license as Lua 5 itself.

ChunkSpy has an interactive mode: you can enter a source chunk and get an immediate disassembly. This allows you to use this document as a tutorial by entering the examples into ChunkSpy and seeing the results yourself. The interactive mode is also very useful when you are exploring the behaviour of the Lua code generator on many short code snippets.

This is a quick introduction, so it isn't intended to be a comprehensive or expert treatment of the Lua virtual machine (from this point on, "Lua" refers to "Lua 5" unless otherwise stated) or its instructions. It is intended to be a simple, easy-to-digest beginner's guide to the Lua virtual machine instruction set – it won't do cartwheels or blow smoke rings.

The objective of this introduction is to cover all the Lua virtual machine instructions and the structure of Lua 5 binary chunks with a minimum of fuss. Then, if you want more detail, you can use `luac` or ChunkSpy to study non-trivial chunks of code, or you can dive into the Lua source code itself for the real thing.

This is currently a draft, and I am not a Lua internals expert. So feedback is welcome. If you find any errors, or if you have anything to contribute please send me an e-mail (to khman AT users.sf.net or mkh AT pl.jaring.my) so that I can correct it. Thanks.

2 Lua Instruction Basics

The Lua virtual machine instruction set we will look at is a particular *implementation* of the Lua language. It is by no means the only way to skin the chicken. The instruction set just happens to be the way the authors of Lua chose to implement version 5 of Lua. The following sections are based on the instruction set used in Lua 5.1. The instruction set might change in the future – do not expect it to be set in stone. This is because the implementation details of virtual machines are not a concern to most users of scripting languages. For most applications, there is no need to specify how bytecode is generated or how the virtual machine runs, as long as the language works as advertised. So remember that there is no official specification of the Lua virtual machine instruction set, there is no need for one; the only official specification is of the Lua language.

In the course of studying disassemblies of Lua binary chunks, you will notice that many generated instruction sequences aren't as perfect as you would like them to be. This is perfectly normal from an engineering standpoint. The canonical Lua implementation is not meant to be an optimizing bytecode compiler or a JIT compiler. Instead it is supposed to load, parse and run Lua source code efficiently. It is the totality of the implementation that counts. If you really need the performance, you are supposed to drop down into native C functions anyway.

Lua instructions have a fixed size, using a 32 bit unsigned integer data type by default. In binary chunks, endianness is significant, but while in memory, an instruction can be portably decoded or encoded in C using the usual integer shift and mask operations. The details can be found in `lopcodes.h`, while the `Instruction` type definition is defined in `llimits.h`.

There are three instruction types and 38 opcodes (numbered 0 through 37) are currently in use as of Lua 5.1. The instruction types are enumerated as `iABC`, `iABx`, `iAsBx`, and may be visually represented as follows:

	31	24 23	16 15	8 7	0
iABC	B:9		C:9		Opcode:6
iABx	Bx:18			A:8	Opcode:6
iAsBx	sBx:18			A:8	Opcode:6

Lua 5 Instruction Formats

Instruction fields are encoded as simple unsigned integer values, except for `sBx`. Field `sBx` can represent negative numbers, but it doesn't use 2s complement. Instead, it has a bias equal to half the maximum integer that can be represented by its unsigned counterpart, `Bx`. For a field size of 18 bits, `Bx` can hold a maximum unsigned integer value of 262143, and so the bias is 131071 (calculated as $262143 \gg 1$). A value of -1 will be encoded as $(-1 + 131071)$ or 131070 or 1FFFE in hexadecimal.

Fields A, B and C usually refers to register numbers (I'll use the term "register" because of its similarity to processor registers). Although field A is the target operand in arithmetic operations, this rule isn't always true for other instructions. A register is really an index into the current stack frame, register 0 being the bottom-of-stack position.

Unlike the Lua C API, negative indices (counting from the top of stack) are not supported. For some instructions, where the top of stack may be required, it is encoded as a special operand value, usually 0. Local variables are equivalent to certain registers in the current stack frame, while dedicated opcodes allow read/write of globals and upvalues. For some instructions, a value in fields B or C may be a register or an encoding of the number of a constant in the constant pool. This will be described further in the section on instruction notation.

By default, Lua has a maximum stack frame size of 250. This is encoded as `MAXSTACK` in `llimits.h`. The maximum stack frame size in turn limits the maximum number of locals per function, which is set at 200, encoded as `LUAI_MAXVARS` in `luaconf.h`. Other limits found in the same file include the maximum number of upvalues per function (60), encoded as `LUAI_MAXUPVALUES`, call depths, the minimum C stack size, etc. Also, with an `sBx` field of 18 bits, jumps and control structures cannot exceed a jump distance of about 131071.

A summary of the Lua 5.1 virtual machine instruction set is as follows:

Opcode	Name	Description
0	MOVE	Copy a value between registers
1	LOADK	Load a constant into a register
2	LOADBOOL	Load a boolean into a register
3	LOADNIL	Load nil values into a range of registers
4	GETUPVAL	Read an upvalue into a register
5	GETGLOBAL	Read a global variable into a register
6	GETTABLE	Read a table element into a register
7	SETGLOBAL	Write a register value into a global variable
8	SETUPVAL	Write a register value into an upvalue
9	SETTABLE	Write a register value into a table element
10	NEWTABLE	Create a new table
11	SELF	Prepare an object method for calling
12	ADD	Addition operator
13	SUB	Subtraction operator
14	MUL	Multiplication operator
15	DIV	Division operator
16	MOD	Modulus (remainder) operator
17	POW	Exponentiation operator
18	UNM	Unary minus operator
19	NOT	Logical NOT operator
20	LEN	Length operator
21	CONCAT	Concatenate a range of registers
22	JMP	Unconditional jump
23	EQ	Equality test
24	LT	Less than test
25	LE	Less than or equal to test
26	TEST	Boolean test, with conditional jump
27	TESTSET	Boolean test, with conditional jump and assignment
28	CALL	Call a closure
29	TAILCALL	Perform a tail call
30	RETURN	Return from function call
31	FORLOOP	Iterate a numeric for loop
32	FORPREP	Initialization for a numeric for loop
33	TFORLOOP	Iterate a generic for loop
34	SETLIST	Set a range of array elements for a table
35	CLOSE	Close a range of locals being used as upvalues
36	CLOSURE	Create a closure of a function prototype
37	VARARG	Assign vararg function arguments to registers

3 Really Simple Chunks

Before heading into binary chunk and virtual machine instruction details, this section will demonstrate briefly how ChunkSpy can be used to explore Lua 5 code generation. All the examples in this document were produced using the Lua 5.1 version of ChunkSpy found in the ChunkSpy 0.9.8 distribution.

First, start ChunkSpy in interactive mode (user input is set in bold):

```
$ lua ChunkSpy.lua --interact
ChunkSpy: A Lua 5.1 binary chunk disassembler
Version 0.9.8 (20060307) Copyright (c) 2004-2006 Kein-Hong Man
The COPYRIGHT file describes the conditions under which this
software may be distributed (basically a Lua 5-style license.)

Type 'exit' or 'quit' to end the interactive session. 'help' displays
this message. ChunkSpy will attempt to turn anything else into a
binary chunk and process it into an assembly-style listing.
A '\' can be used as a line continuation symbol; this allows multiple
lines to be strung together.

>
```

We'll start with the shortest possible binary chunk that can be generated:

```
>do end
; source chunk: (interactive mode)
; x86 standard (32-bit, little endian, doubles)

; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
[1] return 0 1
; end of function
```

ChunkSpy will treat your keyboard input as a small chunk of Lua source code. The library function `string.dump()` is first used to generate a binary chunk string, then ChunkSpy will disassemble that string and give you a brief assembly language-style output listing.

Some features of the listing: Comment lines are prefixed by a semicolon. The header portion of the binary chunk is not displayed with the brief style. Data or header information that isn't an instruction is shown as an assembler directive with a dot prefix. `luac`-style comments are generated for some instructions, and the instruction location is in square brackets.

A “do end” generates a single RETURN instruction and does nothing else. There are no parameters, locals, upvalues or globals. For the rest of the disassembly listings shown in this document, we will omit some common header comments and show only the function disassembly part. Instructions will be referenced by its marked position, e.g. line [1]. Here is another very short chunk:

```
>return
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
[1] return 0 1
[2] return 0 1
; end of function
```

A RETURN instruction is generated for every **return** in the source. The first RETURN (line [1]) is generated by the **return** keyword, while the second RETURN (line [2]) is always added by the code generator. This isn't a problem, because the second RETURN never gets executed anyway, and only 4 bytes is wasted. Perfect generation of RETURN instructions requires basic block analysis, and it is not done because there is no performance penalty for an extra RETURN during execution, only a negligible memory penalty.

Notice in these examples, the minimum stack size is 2, even when the stack isn't used. The next snippet assigns a constant value of 6 to the global variable **a**:

```
>a=6
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.const "a" ; 0
.const 6 ; 1
[1] loadk 0 1 ; 6
[2] setglobal 0 0 ; a
[3] return 0 1
; end of function
```

All string and number constants are pooled on a per-function basis, and instructions refer to them using an index value which starts from 0. Global variable names need a constant string as well, because globals are maintained as a table. Line [1] loads the value 6 (with an index to the constant pool of 1) into register 0, then line [2] sets the global table with the constant "a" (constant index 0) as the key and register 0 (holding the number 6) as the value.

If we write the variable as a local, we get:

```
>local a="hello"
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const "hello" ; 0
[1] loadk 0 0 ; "hello"
[2] return 0 1
; end of function
```

Local variables reside in the stack, and they occupy a stack (or register) location for the duration of their existence. The scope of a local variable is specified by a starting program counter location and an ending program counter location; this is not shown in a brief disassembly listing.

The local table in the function tells the user that register 0 is variable **a**. This information doesn't matter to the VM, because it needs to know register numbers only – register allocation was supposed to have been properly done by the code generator. So LOADK in line [1] loads constant 0 (the string "hello") into register 0, which is the local variable **a**. A stripped binary chunk will not have local variable names for debugging.

Some examples in the following sections have been further annotated with additional comments in parentheses. Please note that ChunkSpy will not generate such comments, nor will it indent functions that are at different nesting levels. Next we will take a look at the structure of Lua 5.1 binary chunks.

4 Lua Binary Chunks

Lua can dump functions as binary chunks, which can then be written to a file, loaded and run. Binary chunks behave exactly like the source code from which they were compiled.

A binary chunk consist of two parts: a header block and a top-level function. The header portion contains 12 elements:

Header block of a Lua 5 binary chunk	
Default values shown are for a 32-bit little-endian platform with IEEE 754 doubles as the number format. The header size is always 12 bytes.	
4 bytes	Header signature: ESC, "Lua" or 0x1B4C7561 <ul style="list-style-type: none">• Binary chunk is recognized by checking for this signature
1 byte	Version number, 0x51 (81 decimal) for Lua 5.1 <ul style="list-style-type: none">• High hex digit is major version number• Low hex digit is minor version number
1 byte	Format version, 0=official version
1 byte	Endianness flag (default 1) <ul style="list-style-type: none">• 0=big endian, 1=little endian
1 byte	Size of int (in bytes) (default 4)
1 byte	Size of size_t (in bytes) (default 4)
1 byte	Size of Instruction (in bytes) (default 4)
1 byte	Size of lua_Number (in bytes) (default 8)
1 byte	Integral flag (default 0) <ul style="list-style-type: none">• 0=floating-point, 1=integral number type
On an x86 platform, the default header bytes will be (in hex): 1B4C7561 51000104 04040800	

A Lua 5.1 binary chunk header is always 12 bytes in size. Since the characteristics of a Lua virtual machine is hard-coded, the Lua undump code checks all 12 of the header bytes to determine whether the binary chunk is fit for consumption or not. All 12 header bytes of the binary chunk must exactly match the header bytes of the platform, otherwise Lua 5.1 will refuse to load the chunk. The header is also not affected by endianness; the same code can be used to load the main header of little-endian or big-endian binary chunks. The data type of `lua_Number` is determined by the size of `lua_Number` byte and the integral flag together.

In theory, a Lua binary chunk is portable; in real life, there is no need for the undump code to support such a feature. If you need undump to load all kinds of binary chunks, you are probably doing something wrong. If however you somehow need this feature, you can try `ChunkSpy`'s `rewrite` option, which allows you to convert a binary chunk from one profile to another.

Anyway, most of the time there is little need to seriously scrutinize the header, because since Lua source code is usually available, a chunk can be readily compiled into the native binary chunk format.

The header block is followed immediately by the top-level function or chunk:

Function block of a Lua 5 binary chunk

Holds all the relevant data for a function. There is one top-level function.

String	source name
Integer	line defined
Integer	last line defined
1 byte	number of upvalues
1 byte	number of parameters
1 byte	is_vararg flag (see explanation further below) <ul style="list-style-type: none">• 1=VARARG_HASARG• 2=VARARG_ISVARARG• 4=VARARG_NEEDSARG
1 byte	maximum stack size (number of registers used)
List	list of instructions (code)
List	list of constants
List	list of function prototypes
List	source line positions (optional debug data)
List	list of locals (optional debug data)
List	list of upvalues (optional debug data)

A function block in a binary chunk defines the prototype of a function. To actually execute the function, Lua creates an instance (or *closure*) of the function first. A function in a binary chunk consist of a few header elements and a bunch of lists. Debug data can be stripped.

A **String** is defined in this way:

All strings are defined in the following format:

Size_t	String data size
Bytes	String data, includes a NUL (ASCII 0) at the end

The string data size takes into consideration a NUL character at the end, so an empty string ("") has 1 as the size_t value. A size_t of 0 means zero string data bytes; the string does not exist. This is often used by the source name field of a function.

The **source name** is usually the name of the source file from which the binary chunk is compiled. It may also refer to a string. This source name is specified only in the top-level function; in other functions, this field consists only of a **Size_t** with the value 0.

The **line defined** and **last line defined** are the line numbers where the function prototype starts and ends in the source file. For the main chunk, the values of both fields are 0. The next two fields, the **number of upvalues** and the **number of parameters**, are self-explanatory, as is the **maximum stack size** field. The **is_vararg** field is a bit more complicated, though. These are all byte-sized fields.

The **is_vararg** flag comprise 3 bitfields. By default, Lua 5.1 defines the constant `LUA_COMPAT_VARARG`, allowing the table **arg** to be used in functions that are defined with a variable number of parameters (*vararg* functions.) The table **arg** itself is not counted in the number of parameters. For old style code that uses **arg**, **is_vararg** is 7. If the code within the vararg function uses `...` instead of **arg**, then **is_vararg** is 3 (the `VARARG_NEEDSARG` field is 0.) If 5.0.2 compatibility is compiled out, then **is_vararg** is 2.

To summarize, the flag `VARARG_ISVARARG` (2) is always set for vararg functions. If `LUA_COMPAT_VARARG` is defined, `VARARG_HASARG` (1) is also set. If `...` is not used within the function, then `VARARG_NEEDSARG` (4) is set. A normal function always has an **is_vararg** flag value of 0, while the main chunk always has an **is_vararg** flag value of 2.

After the function header elements comes a number of lists that store the information that makes up the body of the function. Each list starts with an **Integer** as a list size count, followed by a number of list elements. Each list has its own element format. A list size of 0 has no list elements at all.

In the following boxes, a data type in square brackets, e.g. **[Integer]** means that there are multiple numbers of the element, in this case an integer. The count is given by the list size. Names in parentheses are the ones given in the Lua sources; they are data structure fields.

The first list is the instruction list, or the actual code to the function. This is the list of instructions that will actually be executed:

Instruction list	
Holds list of instructions that will be executed.	
Integer	size of code (sizecode)
[Instruction]	virtual machine instructions

The format of the virtual machine instructions was given in the last chapter. A `RETURN` instruction is always generated by the code generator, so the size of the instruction list should be at least 1. Next is the list of constants:

Constant list	
Holds list of constants referenced in the function (it's a constant pool.)	
Integer	size of constant list (sizek)
[
1 byte	type of constant (value in parentheses):
	• 0=LUA_TNIL, 1=LUA_TBOOLEAN,
	• 3=LUA_TNUMBER, 4=LUA_TSTRING
Const	the constant itself: this field does not exist if the constant type is 0; it is 0 or 1 for type 1; it is a Number for type 3, or a String for type 4.
]	

Number is the Lua number data type, normally an IEEE 754 64-bit double. **Integer**, **Size_t** and **Number** are all endian-sensitive; Lua 5.1 will not load a chunk whose endianness is different from that of the platform. Their sizes and formats are of course specified in the binary chunk header. The data type of **Number** is determined by its size byte and the integral flag. Boolean values are encoded as either 0 or 1.

The function prototype list comes after the constant list:

Function prototype list	
Holds function prototypes defined within the function.	
Integer	size of function prototypes (sizep)
[Functions]	function prototype data, or function blocks

Function prototypes or function blocks have the exact same format as the top-level function or chunk. However, function prototypes that isn't the top-level function do not have the source name field defined. In this way, function prototypes at different lexical scoping levels are defined and nested. In a complex binary chunk, the nesting may be several levels deep. A closure will refer to a function by its number in the list.

The lists following the list of prototypes are optional. They contain debug information and can be stripped to save space. First comes the source line position list:

Source line position list	
Holds the source line number for each corresponding instruction in a function. This information is used by error handlers or debuggers. In a stripped binary, the size of this list is zero. The execution of a function does not depend on this list.	
Integer	size of source line position list (sizelineinfo)
[Integer]	list index corresponds to instruction position; the integer value is the line number of the Lua source where the instruction was generated

Next up is the local list. Each local variable entry has 3 fields, a string and two integers:

Local list	
Holds list of local variable names and the program counter range in which the local variable is active.	
Integer	size of local list (sizelocvars)
[
String	name of local variable (varname)
Integer	start of local variable scope (startpc)
Integer	end of local variable scope (endpc)
]	

The final list is the upvalue list:

Upvalue list Holds list of upvalue names.	
Integer	size of upvalue list (sizeupvalues)
[String]	name of upvalue

All the lists are not shared or re-used: Locals, upvalues, constants and prototypes referenced in the code must be specified in the respective lists in the same function. In addition, locals, upvalues, constants and the function prototypes are indexed using numbers starting from 0. In disassembly listings, both the source line position list and the instruction list are indexed starting from 1. Note that the latter is by convention only; the indices does not matter to the virtual machine itself, since all jump-related instructions use only signed displacements. However, for debug information, the scope of local variables is encoded using absolute program counter positions, and these positions are based on a starting index of 1. This is also consistent with the output listing from luac.

How does it all fit in? You can easily generate a detailed binary chunk disassembly using ChunkSpy. Enter the following short bit of code and name the file `simple.lua`:

```
local a = 8
function b(c) d = a + c end
```

Next, run ChunkSpy from the command line to generate the listing:

```
$ lua ChunkSpy.lua --source simple.lua > simple.lst
```

The following is a description of the generated listing (`simple.lst`), split into segments.

Pos	Hex Data	Description or Code
0000		** source chunk: simple.lua
		** global header start **
0000	1B4C7561	header signature: "\27Lua"
0004	51	version (major:minor hex digits)
0005	00	format (0=official)
0006	01	endianness (1=little endian)
0007	04	size of int (bytes)
0008	04	size of size_t (bytes)
0009	04	size of Instruction (bytes)
000A	08	size of number (bytes)
000B	00	integral (1=integral)
		* number type: double
		* x86 standard (32-bit, little endian, doubles)
		** global header end **

This is an example of a binary chunk header. ChunkSpy calls this the global header to differentiate it from a function header. For binary chunks specific to a certain platform, it is easy to match the entire header at one go instead of testing each field. As described previously, the header is 12 bytes in size, and needs to be exactly compatible with the platform or else Lua 5.1 won't load the binary chunk.

The global header is followed by the function header of the top-level function:

```

000C                                ** function [0] definition (level 1)
                                ** start of function **
000C 0B000000                      string size (11)
0010 73696D706C652E6C+           "simple.l"
0018 756100                        "ua\0"
                                source name: simple.lua
001B 00000000                      line defined (0)
001F 00000000                      last line defined (0)
0023 00                            nups (0)
0024 00                            numparams (0)
0025 02                            is_vararg (2)
0026 02                            maxstacksize (2)

```

A function's header is always variable in size, due to the **source name** string. The source name is only present in the top-level function. A top-level chunk does not have a line number on which it is defined, so both the line defined fields are 0. There are no upvalues or parameters. A top-level chunk can always take a variable number of parameters; **is_vararg** is always 2 for the top-level chunk. The stack size is set at the minimum of 2 for this very simple chunk.

Next we come to the various lists, starting with the code listing of the main chunk:

```

                                * code:
0027 05000000                      sizecode (5)
002B 01000000                      [1] loadk      0  0      ; 8
002F 64000000                      [2] closure   1  0      ; 1 upvalues
0033 00000000                      [3] move      0  0
0037 47400000                      [4] setglobal 1  1      ; b
003B 1E008000                      [5] return    0  1

```

The first line of the source code compiles to a single instruction, line [1]. Local **a** is register 0 and the number 8 is constant 0. In line [2], an instance of function prototype 0 is created, and the closure is temporarily placed in register 1. The MOVE instruction in line [3] is actually used by the CLOSURE instruction to manage the upvalue **a**; it is not really executed. This will be explained in detail in Chapter 14. The closure is then placed into the global **b** in line [4]; “b” is constant 1 while the closure is in register 1. Line [5] returns control to the calling function. In this case, it exits the chunk.

The list of constants follow the instructions:

```

                                * constants:
003F 02000000                      sizek (2)
0043 03                            const type 3
0044 000000000000002040           const [0]: (8)
004C 04                            const type 4
004D 02000000                      string size (2)
0051 6200                          "b\0"
                                const [1]: "b"

```

The top-level function requires two constants, the number 8 (which is used in the assignment on line 1) and the string “b” (which is used to refer to the global variable **b** on line 2.)

This is followed by the function prototype list of the main chunk. On line 2 of the source, a function prototype was declared within the main chunk. This function is instantiated and the closure is assigned to global **b**.

The function prototype list holds all the relevant information, a function block within a function block. ChunkSpy reports it as function prototype number 0, at level 2. Level 1 is the top-level function; there is only one level 1 function, but there may be more than one function prototype at other levels.

```

0053 01000000      * functions:
                        sizep (1)

0057                                ** function [0] definition (level 2)
                        ** start of function **

0057 00000000      string size (0)
                        source name: (none)
005B 02000000      line defined (2)
005F 02000000      last line defined (2)
0063 01                                nups (1)
0064 01                                numparams (1)
0065 00                                is_vararg (0)
0066 02                                maxstacksize (2)
                        * code:
0067 04000000      sizecode (4)
006B 44000000      [1] getupval  1  0          ; a
006F 4C008000      [2] add       1  1  0
0073 47000000      [3] setglobal 1  0          ; d
0077 1E008000      [4] return   0  1

```

Above is the first section of function **b**'s prototype. It has no name string; it is defined on line 2 (both values point to line 2); there is one upvalue; there is one parameter, **c**; it is not a vararg function; and its maximum stack size is 2. Parameters are located from the bottom of the stack, so the single parameter **c** of the function is at register 0.

The prototype has 4 instructions. Most Lua virtual machine instructions are easy to decipher, but some of them have details that are not immediately evident. This example however should be quite easy to understand. In line [1], 0 is the upvalue **a** and 1 is the target register, which is a temporary register. Line [2] is the addition operation, with register 1 holding the temporary result while register 0 is the function parameter **c**. In line [3], the global **d** (so named by constant 0) is set, and in the next line, control is returned to the caller.

```

                                * constants:
007B 01000000      sizek (1)
007F 04                                const type 4
0080 02000000      string size (2)
0084 6400                                "d\0"
                        const [0]: "d"
                                * functions:
0086 00000000      sizep (0)

```

The constant list for the function has one entry, the string "d" is used to look up the global variable of that name. This is followed by the source line position list:

```

                                * lines:
008A 04000000      sizelineinfo (4)
                        [pc] (line)
008E 02000000      [1] (2)
0092 02000000      [2] (2)
0096 02000000      [3] (2)
009A 02000000      [4] (2)

```

All four instructions that were generated came from line 2 of the source code.

The last two lists of the function prototype are the local list and the upvalue list:

```

                                * locals:
009E  01000000    sizelocvars (1)
00A2  02000000    string size (2)
00A6  6300        "c\0"
                                local [0]: c
00A8  00000000        startpc (0)
00AC  03000000        endpc  (3)
                                * upvalues:
00B0  01000000    sizeupvalues (1)
00B4  02000000    string size (2)
00B8  6100        "a\0"
                                upvalue [0]: a
                                ** end of function **
```

There is one local variable, which is parameter **c**. For parameters, the `startpc` value is 0. Normal locals that are defined within a function have a `startpc` value of 1. There is also an upvalue, **a**, which refers to the local **a** in the parent (top) function.

After the end of the function prototype data for function **b**, the chunk resumes with the debug information for the top-level chunk:

```

                                * lines:
00BA  05000000    sizelineinfo (5)
                                [pc] (line)
00BE  01000000    [1] (1)
00C2  02000000    [2] (2)
00C6  02000000    [3] (2)
00CA  02000000    [4] (2)
00CE  02000000    [5] (2)
                                * locals:
00D2  01000000    sizelocvars (1)
00D6  02000000    string size (2)
00DA  6100        "a\0"
                                local [0]: a
00DC  01000000        startpc (1)
00E0  04000000        endpc  (4)
                                * upvalues:
00E4  00000000    sizeupvalues (0)
                                ** end of function **

00E8                                ** end of chunk **
```

From the source line list, we can see that there are 5 instructions in the top-level function. The first instruction came from line 1 of the source, while the other 4 instructions came from line 2 of the source.

The top-level function has one local variable, named “a”, active from program counter location 1 to location 4, and it refers to register 0. There are no upvalues, so the size of that table is 0. The binary chunk ends after the debug information of the main chunk is listed.

Now that we’ve seen a binary chunk in detail, we will proceed to look at each Lua 5.1 virtual machine instruction.

5 Instruction Notation

Before looking at some Lua virtual machine instructions, here is a little something about the notation used for describing instructions. Instruction descriptions are given as comments in the Lua source file `lopcodes.h`. The instruction descriptions are reproduced in the following chapters, with additional explanatory notes. Here are some basic symbols:

R(A)	Register A (specified in instruction field A)
R(B)	Register B (specified in instruction field B)
R(C)	Register C (specified in instruction field C)
PC	Program Counter
Kst(n)	Element n in the constant list
Upvalue[n]	Name of upvalue with index n
Gbl[sym]	Global variable indexed by symbol sym
RK(B)	Register B or a constant index
RK(C)	Register C or a constant index
sBx	Signed displacement (in field sBx) for all kinds of jumps

The notation used to describe instructions is a little like pseudo-C. The operators used in the notation are largely C operators, while conditional statements use C-style evaluation. Booleans are evaluated C-style. Thus, the notation is a loose translation of the actual C code that implements an instruction.

The operation of some instructions cannot be clearly described by one or two lines of notation. Hence, this guide will supplement symbolic notation with detailed descriptions of the operation of each instruction. Having described an instruction, examples will be given to show the instruction working in a short snippet of Lua code. Using ChunkSpy's interactive mode, you can try out the examples yourself and get instant feedback in the form of disassembled code. If you want a disassembled listing plus the byte values of data and instructions, you can use ChunkSpy to generate a normal, verbose, disassembly listing.

The program counter of the virtual machine (PC) always points to the next instruction. This behaviour is standard for most microprocessors. The rule is that once an instruction is read in to be executed, the program counter is immediately updated. So, to skip a single instruction following the current instruction, add 1 (the displacement) to the PC. A displacement of -1 will theoretically cause a JMP instruction to jump back onto itself, causing an infinite loop. Luckily, the code generator is not supposed to be able to make up stuff like that.

As previously explained, registers and local variables are roughly equivalent. Temporary results are always held in registers. Instruction fields B and C can point to a constant instead of a register for some instructions, this is when the field value has its MSB (most significant bit) set. For example, a field B value of 256 will point to the constant at index 0, if the field is 9 bits wide. For most instructions, field A is the target register. Disassembly listings preserve the A, B, C operand field order for consistency.

6 Loading Constants

Loads and moves are the starting point of pretty much all processor or virtual machine instruction sets, so we'll start with primitive loads and moves:

MOVE **A B** R(A) := R(B)

Copies the value of register R(B) into register R(A). If R(B) holds a table, function or userdata, then the *reference* to that object is copied. MOVE is often used for moving values into place for the next operation.

The opcode for MOVE has a second purpose – it is also used in creating closures, always appearing *after* the CLOSURE instruction; see CLOSURE for more information.

The most straightforward use of MOVE is for assigning a local to another local:

```
>local a,b = 10; b = a
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.local "b" ; 1
.const 10 ; 0
[1] loadk 0 0 ; 10
[2] loadnil 1 1
[3] move 1 0
[4] return 0 1
; end of function
```

Line [3] assigns (*copies*) the value in local **a** (register 0) to local **b** (register 1).

You won't see MOVE instructions used in arithmetic expressions because they are not needed by arithmetic operators. All arithmetic operators are in 2- or 3-operand style: the entire local stack frame is already visible to operands R(A), R(B) and R(C) so there is no need for any extra MOVE instructions.

Other places where you will see MOVE are:

- When moving parameters into place for a function call.
- When moving values into place for certain instructions where stack order is important, e.g. GETTABLE, SETTABLE and CONCAT.
- When copying return values into locals after a function call.
- After CLOSURE instructions (discussed in Chapter 14.)

There are 3 fundamental instructions for loading constants into local variables. Other instructions, for reading and writing globals, upvalues and tables are discussed in the following chapters. The first constant loading instruction is LOADNIL:

LOADNIL **A B** R(A) := ... := R(B) := nil

Sets a range of registers from R(A) to R(B) to **nil**. If a single register is to be assigned to, then R(A) = R(B). When two or more consecutive locals need to be assigned **nil** values, only a single LOADNIL is needed.

LOADNIL uses the operands A and B to mean a *range* of register locations. The example for MOVE in the last page shows LOADNIL used to set a single register to **nil**.

```
>local a,b,c,d,e = nil,nil,0
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
.local "d" ; 3
.local "e" ; 4
.const 0 ; 0
[1] loadk      2  0      ; 0
[2] loadnil   3  4
[3] return    0  1
; end of function
```

Line [2] **nils** locals **d** and **e**. A LOADNIL instruction is not needed for locals **a** and **b** because the instruction has been optimized away. Local **c** is explicitly initialized with the value 0. The LOADNIL for locals **a** and **b** can be optimized away as the Lua virtual machine always sets all locals to **nil** prior to executing a function. The optimization rule is a simple one: If no other instructions have been generated, then a LOADNIL as the first instruction can be optimized away.

In the example, although the LOADNIL on line [2] is redundant, it is still generated as there is already an instruction that is not LOADNIL on line [1]. Ideally, one should put all locals that are initialized to **nil** at the top of the function, before anything else. In the above case, we can rearrange the locals to take advantage of the optimization rule:

```
>local a,b,d,e local c=0
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.local "a" ; 0
.local "b" ; 1
.local "d" ; 2
.local "e" ; 3
.local "c" ; 4
.const 0 ; 0
[1] loadk      4  0      ; 0
[2] return    0  1
; end of function
```

Now, we save one LOADNIL instruction. In other parts of a function, an explicit assignment of **nil** to a local variable will of course require a LOADNIL instruction.

LOADK **A Bx** R(A) := Kst(Bx)

Loads constant number Bx into register R(A). Constants are usually numbers or strings. Each function has its own constant list, or pool.

LOADK loads a constant from the constant list into a register or local. Constants are indexed starting from 0. Some instructions, such as arithmetic instructions, can use the constant list without needing a LOADK. Constants are pooled in the list, duplicates are eliminated. The list can hold **nils**, booleans, numbers or strings.

```

>local a,b,c,d = 3,"foo",3,"foo"
; function [0] definition (level 1)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 2 4
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
.local "d" ; 3
.const 3 ; 0
.const "foo" ; 1
[1] loadk 0 0 ; 3
[2] loadk 1 1 ; "foo"
[3] loadk 2 0 ; 3
[4] loadk 3 1 ; "foo"
[5] return 0 1
; end of function

```

The constant 3 and the constant “foo” are both written twice in the source snippet, but in the constant list, each constant has a single location. The constant list contains the names of global variables as well, since GETGLOBAL and SETGLOBAL makes an implied LOADK operation in order to get the name string of a global variable first before looking it up in the global table.

The final constant-loading instruction is LOADBOOL, for setting a boolean value, and it has some additional functionality.

LOADBOOL A B C R(A) := (Bool)B; if (C) PC++

Loads a boolean value (**true** or **false**) into register R(A). **true** is usually encoded as an integer 1, **false** is always 0. If C is non-zero, then the next instruction is skipped (this is used when you have an assignment statement where the expression uses relational operators, e.g. M = K>5.)

You can use any non-zero value for the boolean **true** in field B, but since you cannot use booleans as numbers in Lua, it’s best to stick to 1 for **true**.

LOADBOOL is used for loading a boolean value into a register. It’s also used where a boolean result is supposed to be generated, because relational test instructions, for example, do not generate boolean results – they perform conditional jumps instead. The operand C is used to optionally skip the next instruction (by incrementing PC by 1) in order to support such code. For simple assignments of boolean values, C is always 0.

```

>local a,b = true,false
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.local "b" ; 1
[1] loadbool 0 1 0 ; true
[2] loadbool 1 0 0 ; false
[3] return 0 1
; end of function

```

This example is straightforward: Line [1] assigns **true** to local **a** (register 0) while line [2] assigns **false** to local **b** (register 1). In both cases, field C is 0, so PC is not incremented and the next instruction is not skipped.

```

>local a = 5 > 2
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const 5 ; 0
.const 2 ; 1
[1] lt      1    257 256 ; 2 5, to [3] if false
[2] jmp     1                ; to [4]
[3] loadbool 0 0 1 ; false, to [5]
[4] loadbool 0 1 0 ; true
[5] return  0 1
; end of function

```

This is an example of an expression that gives a boolean result and is assigned to a variable. Notice that Lua does not optimize the expression into a **true** value; Lua 5.1 does not perform compile-time constant evaluation for relational operations, but it can perform simple constant evaluation for arithmetic operations.

Since the relational operator LT (which will be covered in greater detail later) does not give a boolean result but performs a conditional jump, LOADBOOL uses its C operand to perform an unconditional jump in line [3] – this saves one instruction and makes things a little tidier. The reason for all this is that the instruction set is simply optimized for **if...then** blocks. Essentially, `local a = 5 > 2` is executed in the following way:

```

local a
if 2 < 5 then
  a = true
else
  a = false
end

```

In the disassembly listing, when LT tests `2 < 5`, it evaluates to **true** and doesn't perform a conditional jump. Line [2] jumps over the false result path, and in line [4], the local **a** (register 0) is assigned the boolean **true** by the instruction LOADBOOL. If 2 and 5 were reversed, line [3] will be followed instead, setting a **false**, and then the true result path (line [4]) will be skipped, since LOADBOOL has its field C set to non-zero.

So the true result path goes like this (additional comments in parentheses):

```

[1] lt      1    257 256 ; 2 5, to [3] if false (if 2 < 5)
[2] jmp     1                ; to [4]
[4] loadbool 0 1 0 ; true (a = true)
[5] return  0 1

```

and the false result path (which never executes in this example) goes like this:

```

[1] lt      1    257 256 ; 2 5, to [3] if false (if 2 < 5)
[3] loadbool 0 0 1 ; false, to [5] (a = false)
[5] return  0 1

```

The true result path looks longer, but it isn't, due to the way the virtual machine is implemented. This will be discussed further in the section on relational and logic instructions.

7 Upvalues and Globals

When the Lua virtual machine needs an upvalue or a global, there are dedicated instructions to load the value into a register. Similarly, when an upvalue or a global needs to be written to, dedicated instructions are used.

GETGLOBAL A Bx $R(A) := \text{Gbl}[\text{Kst}(\text{Bx})]$

Copies the value of the global variable whose name is given in constant number Bx into register R(A). The name constant must be a string.

SETGLOBAL A Bx $\text{Gbl}[\text{Kst}(\text{Bx})] := R(A)$

Copies the value from register R(A) into the global variable whose name is given in constant number Bx. The name constant must be a string.

The GETGLOBAL and SETGLOBAL instructions are very straightforward and easy to use. The instructions require that the global variable name be a constant, indexed by instruction field Bx. R(A) is either the source or target register. The names of the global variables used by a function will be part of the constant list of the function.

```
>a = 40; local b = a
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "b" ; 0
.const "a" ; 0
.const 40 ; 1
[1] loadk 0 1 ; 40
[2] setglobal 0 0 ; a
[3] getglobal 0 0 ; a
[4] return 0 1
; end of function
```

From the example, you can see that “b” is the name of the local variable while “a” is the name of the global variable. Line [1] loads the number 40 into register 0 (functioning as a temporary register, since local **b** hasn’t been defined.) Line [2] assigns the value in register 0 to the global variable with name “a” (constant 0). By line [3], local **b** is defined and is assigned the value of global **a**.

GETUPVAL A B $R(A) := \text{UpValue}[\text{B}]$

Copies the value in upvalue number B into register R(A). Each function may have its own upvalue list. This upvalue list is internal to the virtual machine; the list of upvalue name strings in a prototype is not mandatory.

The opcode for GETUPVAL has a second purpose – it is also used in creating closures, always appearing *after* the CLOSURE instruction; see CLOSURE for more information.

SETUPVAL A B $\text{UpValue}[\text{B}] := R(A)$

Copies the value from register R(A) into the upvalue number B in the upvalue list for that function.

GETUPVAL and SETUPVAL uses internally-managed upvalue lists. The list of upvalue name strings that are found in a function prototype is for debugging purposes; it is not used by the Lua virtual machine and can be stripped by `luac`.

During execution, upvalues are set up by a CLOSURE, and maintained by the Lua virtual machine. In the following example, function `b` is declared inside the main chunk, and is shown in the disassembly as a function prototype within a function prototype. The indentation, which is not in the original output, helps to visually separate the two functions.

```
>local a; function b() a = 1 return a end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const "b" ; 0

; function [0] definition (level 2)
; 1 upvalues, 0 params, 2 stacks
.function 1 0 0 2
.upvalue "a" ; 0
.const 1 ; 0
[1] loadk 0 0 ; 1
[2] setupval 0 0 ; a
[3] getupval 0 0 ; a
[4] return 0 2
[5] return 0 1
; end of function

[1] closure 1 0 ; 1 upvalues
[2] move 0 0
[3] setglobal 1 0 ; b
[4] return 0 1
; end of function
```

In the main chunk (function 0, level 1), local `a` starts as a `nil`. The CLOSURE in line [1] then instantiates function prototype 0 (function 0, level 2) with a single upvalue, `a`. Line [2] is part of the closure, it links local `a` in the current scope to upvalue `a` in the closure. Finally the closure is assigned to global `b`.

In function `b`, there is a single upvalue, `a`. In Pascal, a variable in an outer scope is found by traversing stack frames. However, instantiations of Lua functions are first-class values, and they may be assigned to a variable and referenced elsewhere. Moreover, a single prototype may have multiple instantiations. Managing upvalues thus becomes a little more tricky than traversing stack frames in Pascal. The Lua virtual machine solution is to provide a clean interface to access upvalues via GETUPVAL and SETUPVAL, while the management of upvalues is handled by the virtual machine itself.

Line [2] in function `b` sets upvalue `a` (upvalue number 0 in the upvalue table) to a number value of 1 (held in temporary register 0.) In line [3], the value in upvalue `a` is retrieved and placed into register 0, where the following RETURN instruction will use it as a return value. The RETURN in line [5] is unused.

8 Table Instructions

Accessing table elements is a little more complex than accessing upvalues and globals:

GETTABLE **A B C** R(A) := R(B)[RK(C)]

Copies the value from a table element into register R(A). The table is referenced by register R(B), while the index to the table is given by RK(C), which may be the value of register R(C) or a constant number.

SETTABLE **A B C** R(A)[RK(B)] := RK(C)

Copies the value from register R(C) or a constant into a table element. The table is referenced by register R(A), while the index to the table is given by RK(B), which may be the value of register R(B) or a constant number.

All 3 operand fields are used, and some of the operands can be constants. A constant is specified by setting the MSB of the operand to 1. If RK(C) need to refer to constant 1, the encoded value will be (256 | 1) or 257, where 256 is the value of bit 8 of the operand. Allowing constants to be used directly reduces considerably the need for temporary registers.

```
>local p = {}; p[1] = "foo"; return p["bar"]
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "p" ; 0
.const 1 ; 0
.const "foo" ; 1
.const "bar" ; 2
[1] newtable 0 0 0 ; array=0, hash=0
[2] settable 0 256 257 ; 1 "foo"
[3] gettable 1 0 258 ; "bar"
[4] return 1 2
[5] return 0 1
; end of function
```

In line [1], a new empty table is created and the reference placed in local **p** (register 0). Creating and populating new tables is a little involved so it will only be discussed later.

Table index 1 is set to “foo” in line [2] by the SETTABLE instruction. Both the index and the value for the table element are encoded constant numbers; 256 is constant 0 (the number 1) while 257 is constant 1 (the string “foo”). The R(A) value of 0 points to the new table that was defined in line [1].

In line [3], the value of the table element indexed by the string “bar” is copied into temporary register 1, which is then used by RETURN as a return value. 258 is constant 2 (the string “bar”) while 0 in field B is the reference to the table.

RK(B) and RK(C) type operands are also used in virtual machine instructions that implement binary arithmetic operators and relational operators.

9 Arithmetic and String Instructions

The Lua virtual machine's set of arithmetic instructions looks like 3-operand arithmetic instructions on a RISC processor. 3-operand instructions allow arithmetic expressions to be translated into machine instructions pretty efficiently.

ADD	A B C	$R(A) := RK(B) + RK(C)$
SUB	A B C	$R(A) := RK(B) - RK(C)$
MUL	A B C	$R(A) := RK(B) * RK(C)$
DIV	A B C	$R(A) := RK(B) / RK(C)$
MOD	A B C	$R(A) := RK(B) \% RK(C)$
POW	A B C	$R(A) := RK(B) ^ RK(C)$

Binary operators (arithmetic operators with two inputs.) The result of the operation between $RK(B)$ and $RK(C)$ is placed into $R(A)$. These instructions are in the classic 3-register style. $RK(B)$ and $RK(C)$ may be either registers or constants in the constant pool.

ADD is addition. SUB is subtraction. MUL is multiplication. DIV is division. MOD is modulus (remainder). POW is exponentiation.

The source operands, $RK(B)$ and $RK(C)$, may be constants. If a constant is out of range of field B or field C, then the constant will be loaded into a temporary register in advance.

```
>local a,b = 2,4; a = a + 4 * b - a / 2 ^ b % 3
; function [0] definition (level 1)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 2 4
.local "a" ; 0
.local "b" ; 1
.const 2 ; 0
.const 4 ; 1
.const 3 ; 2
[1] loadk 0 0 ; 2
[2] loadk 1 1 ; 4
[3] mul 2 257 1 ; 4 (loc2 = 4 * b)
[4] add 2 0 2 (loc2 = A + loc2)
[5] pow 3 256 1 ; 2 (loc3 = 2 ^ b)
[6] div 3 0 3 (loc3 = a / loc3)
[7] mod 3 3 258 ; 3 (loc3 = loc3 % 3)
[8] sub 0 2 3 (a = loc2 - loc3)
[9] return 0 1
; end of function
```

In the disassembly shown above, parts of the expression is shown as additional comments in parentheses. Each arithmetic operator translates into a single instruction. This also means that while the statement “`count = count + 1`” is verbose, it translates into a single instruction if **count** is a local. If **count** is a global, then two extra instructions are required to read and write to the global (GETGLOBAL and SETGLOBAL), since arithmetic operations can only be done on registers (locals) only.

As of Lua 5.1, the parser and code generator can perform limited constant expression folding or evaluation. Constant folding only works for binary arithmetic operators and the unary minus operator (UNM, which will be covered next.) There is no equivalent optimization for relational, boolean or string operators.

The optimization rule is simple: If both terms of a subexpression are numbers, the subexpression will be evaluated at compile time. However, there are exceptions. One, the code generator will not attempt to divide a number by 0 for DIV and MOD, and two, if the result is evaluated as a NaN (Not a Number) then the optimization will not be performed.

Also, constant folding is not done if one term is in the form of a string that need to be coerced. In addition, expression terms are not rearranged, so not all optimization opportunities can be recognized by the code generator. This is intentional; the Lua code generator is not meant to perform heavy duty optimizations, as Lua is a lightweight language. Here are a few examples to illustrate how it works (additional comments in parentheses):

```
>local a = 4 + 7 + b; a = b + 4 * 7; a = b + 4 + 7
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const "b" ; 0
.const 11 ; 1
.const 28 ; 2
.const 4 ; 3
.const 7 ; 4
[1] getglobal 0 0 ; b
[2] add 0 257 0 ; 11 (a = 11 + b)
[3] getglobal 1 0 ; b
[4] add 0 1 258 ; 28 (a = b + 28)
[5] getglobal 1 0 ; b
[6] add 1 1 259 ; 4 (loc1 = b + 4)
[7] add 0 1 260 ; 7 (a = loc1 + 7)
[8] return 0 1
; end of function
```

For the first assignment statement, **4+7** is evaluated, thus 11 is added to **b** in line [2]. Next, in line [3] and [4], **b** and 28 are added together and assigned to **a** because multiplication has a higher precedence and **4*7** is evaluated first. Finally, on lines [5] to [7], there are two addition operations. Since addition is left-associative, code is generated for **b+4** first, and only after that, 7 is added. So in the third example, Lua performs no optimization. This can be fixed using parentheses to explicitly change the precedence of a subexpression:

```
>local a = b + (4 + 7)
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const "b" ; 0
.const 11 ; 1
[1] getglobal 0 0 ; b
[2] add 0 0 257 ; 11
[3] return 0 1
; end of function
```

Now, the **4+7** subexpression can be evaluated at compile time. If the statement is written as:

```
local a = 7 + (4 + 7)
```

the code generator will generate a single LOADK instruction; Lua first evaluates **4+7**, then 7 is added, giving a total of 18. The arithmetic expression is completely evaluated in this case, thus no arithmetic instructions are generated.

In order to make full use of constant folding in Lua 5.1, the user just need to remember the usual order of evaluation of an expression's elements and apply parentheses where necessary. The following are two expressions which will not be evaluated at compile time:

```
>local a = 1 / 0; local b = 1 + "1"
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.local "b" ; 1
.const 1 ; 0
.const 0 ; 1
.const "1" ; 2
[1] div      0   256 257 ; 1 0
[2] add      1   256 258 ; 1 "1"
[3] return   0   1
; end of function
```

The first is due to a divide-by-0, while the second is due to a string constant that needs to be coerced into a number. In both cases, constant folding is not performed, so the arithmetic instructions needed to perform the operations at run time are generated instead.

Next are instructions for performing unary minus and logical NOT:

UNM	A B	R(A) := -R(B)
Unary minus (arithmetic operator with one input.) R(B) is negated and the value placed in R(A). R(A) and R(B) are always registers.		

NOT	A B	R(A) := not R(B)
Applies a boolean NOT to the value in R(B) and places the result in R(A). R(A) and R(B) are always registers.		

Here is an example of both unary operations:

```
>local p,q = 10,false; q,p = -p,not q
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "p" ; 0
.local "q" ; 1
.const 10 ; 0
[1] loadk    0   0 ; 10
[2] loadbool 1   0 0 ; false
[3] unm      2   0
[4] not      0   1
[5] move     1   2
[6] return   0   1
; end of function
```

Both UNM and NOT do not accept a constant as a source operand, making the LOADK on line [1] and the LOADBOOL on line [2] necessary. When an unary minus is applied to a constant number, the unary minus is optimized away. Similarly, when a **not** is applied to **true** or **false**, the logical operation is optimized away.

In addition to this, constant folding is performed for unary minus, if the term is a number. So, the expression in the following is completely evaluated at compile time:

```
>local a = - (7 / 4)
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const -1.75 ; 0
[1] loadk 0 0 ; -1.75
[2] return 0 1
; end of function
```

Constant folding is performed on **7/4** first. Then, since the unary minus operator is applied to the constant 1.75, constant folding can be performed again, and the code generated becomes a simple LOADK (on line [1].)

LEN **A B** R(A) := length of R(B)

Returns the length of the object in R(B). For strings, the string length is returned, while for tables, the table size (as defined in Lua) is returned. For other objects, the metamethod is called. The result, which is a number, is placed in R(A).

This instruction is new in Lua 5.1, implementing the # operator. If # operates on a constant, then the constant is loaded in advance using LOADK. The LEN instruction is currently not optimized away using compile time evaluation, even if it is operating on a constant string or table.

```
>local a,b; a = #b; a = #"foo"
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.const "foo" ; 0
[1] len 0 1
[2] loadk 2 0 ; "foo"
[3] len 0 2
[4] return 0 1
; end of function
```

In the above example, LEN operates on local **b** in line [1], leaving the result in local **a**. Since LEN cannot operate directly on constants, line [2] first loads the constant “foo” into a temporary local, and only then LEN is executed.

CONCAT **A B C** R(A) := R(B)..R(C)

Performs concatenation of two or more strings. In a Lua source, this is equivalent to one or more concatenation operators (‘..’) between two or more expressions. The source registers must be consecutive, and C must always be greater than B. The result is placed in R(A).

Like LOADNIL, CONCAT accepts a range of registers. Doing more than one string concatenation at a time is faster and more efficient than doing them separately.

```

>local x,y = "foo","bar"; return x..y..x..y
; function [0] definition (level 1)
; 0 upvalues, 0 params, 6 stacks
.function 0 0 2 6
.local "x" ; 0
.local "y" ; 1
.const "foo" ; 0
.const "bar" ; 1
[1] loadk 0 0 ; "foo"
[2] loadk 1 1 ; "bar"
[3] move 2 0
[4] move 3 1
[5] move 4 0
[6] move 5 1
[7] concat 2 2 5
[8] return 2 2
[9] return 0 1
; end of function

```

In this example, strings are moved into place first (lines [3] to [6]) in the concatenation order before a single CONCAT instruction is executed in line [7]. The result is left in temporary local 2, which is then used as a return value by the RETURN instruction on line [8].

```

>local a = "foo".."bar".."baz"
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.const "foo" ; 0
.const "bar" ; 1
.const "baz" ; 2
[1] loadk 0 0 ; "foo"
[2] loadk 1 1 ; "bar"
[3] loadk 2 2 ; "baz"
[4] concat 0 0 2
[5] return 0 1
; end of function

```

In the second example, three strings are concatenated together. Note that there is no string constant folding. Lines [1] through [3] loads the three constants in the correct order for concatenation; the CONCAT on line [4] performs the concatenation itself and assigns the result to local **a**.

10 Jumps and Calls

Lua does not have any unconditional jump feature in the language itself, but in the virtual machine, the unconditional jump is used in control structures and logical expressions.

JMP **sBx** PC += sBx

Performs an unconditional jump, with sBx as a signed displacement. sBx is added to the program counter (PC), which points to the next instruction to be executed. E.g., if sBx is 0, the VM will proceed to the next instruction.

JMP is used in loops, conditional statements, and in expressions when a boolean **true/false** need to be generated.

For example, since a relational test instruction makes conditional jumps rather than generate a boolean result, a JMP is used in the code sequence for loading either a **true** or a **false**:

```
>local m, n; return m >= n
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "m" ; 0
.local "n" ; 1
[1] le      1 1 0 ; to [3] if false (n <= m)
[2] jmp     1 ; to [4]
[3] loadbool 2 0 1 ; false, to [5] (false path)
[4] loadbool 2 1 0 ; true (true path)
[5] return  2 2
[6] return  0 1
; end of function
```

Line[1] performs the relational test. In line [2], the JMP skips over the false path (line [3]) to the true path (line [4]). The result is placed into temporary local 2, and returned to the caller by RETURN in line [5]. More examples where JMP is used will be covered in later chapters.

Next we will look at the CALL instruction, for calling instantiated functions:

CALL **A B C** R(A), ... ,R(A+C-2) := R(A)(R(A+1), ... ,R(A+B-1))

Performs a function call, with register R(A) holding the reference to the function object to be called. Parameters to the function are placed in the registers following R(A). If B is 1, the function has no parameters. If B is 2 or more, there are (B-1) parameters.

If B is 0, the function parameters range from R(A+1) to the top of the stack. This form is used when the last expression in the parameter list is a function call, so the number of actual parameters is indeterminate.

Results returned by the function call is placed in a range of registers starting from R(A). If C is 1, no return results are saved. If C is 2 or more, (C-1) return values are saved. If C is 0, then multiple return results are saved, depending on the called function.

CALL always updates the top of stack value. CALL, RETURN, VARARG and SETLIST can use multiple values (up to the top of the stack.)

Generally speaking, for fields B and C, a zero means that multiple results or parameters (up to the top of stack) are expected. If the number of results or parameters are fixed, then the actual number is one less than the encoded field value. Here is the simplest possible call:

```
>z()
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.const "z" ; 0
[1] getglobal 0 0 ; z
[2] call 0 1 1
[3] return 0 1
; end of function
```

In line [2], the call has zero parameters (field B is 1), zero results are retained (field C is 1), while register 0 temporarily holds the reference to the function object from global **z**. Next we see a function call with multiple parameters or arguments:

```
>z(1,2,3)
; function [0] definition (level 1)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 2 4
.const "z" ; 0
.const 1 ; 1
.const 2 ; 2
.const 3 ; 3
[1] getglobal 0 0 ; z
[2] loadk 1 1 ; 1
[3] loadk 2 2 ; 2
[4] loadk 3 3 ; 3
[5] call 0 4 1
[6] return 0 1
; end of function
```

Lines [1] to [4] loads the function reference and the arguments in order, then line [5] makes the call with an operand B value of 4, which means there are 3 parameters. Since the call statement is not assigned to anything, no return results need to be retained, hence field C is 1. Here is an example that uses multiple parameters and multiple return values:

```
>local p,q,r,s = z(y())
; function [0] definition (level 1)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 2 4
.local "p" ; 0
.local "q" ; 1
.local "r" ; 2
.local "s" ; 3
.const "z" ; 0
.const "y" ; 1
[1] getglobal 0 0 ; z
[2] getglobal 1 1 ; y
[3] call 1 1 0
[4] call 0 0 5
[5] return 0 1
; end of function
```

First, the function references are retrieved (lines [1] and [2]), then function **y** is called first (temporary register 1). The CALL has a field C of 0, meaning multiple return values are accepted. These return values become the parameters to function **z**, and so in line [4], field B

of the CALL instruction is 0, signifying multiple parameters. After the call to function **z**, 4 results are retained, so field C in line [4] is 5. Finally, here is an example with calls to standard library functions:

```
>print(string.char(64))
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.const "print" ; 0
.const "string" ; 1
.const "char" ; 2
.const 64 ; 3
[1] getglobal 0 0 ; print
[2] getglobal 1 1 ; string
[3] gettable 1 1 258 ; "char"
[4] loadk 2 3 ; 64
[5] call 1 2 0
[6] call 0 0 1
[7] return 0 1
; end of function
```

When a function call is the last parameter to another function call, the former can pass multiple return values, while the latter can accept multiple parameters.

Complementing CALL is RETURN:

RETURN A B return R(A), ... ,R(A+B-2)

Returns to the calling function, with optional return values. If B is 1, there are no return values. If B is 2 or more, there are (B-1) return values, located in consecutive registers from R(A) onwards.

If B is 0, the set of values from R(A) to the top of the stack is returned. This form is used when the last expression in the return list is a function call, so the number of actual values returned is indeterminate.

RETURN also closes any open upvalues, equivalent to a CLOSE instruction. See the CLOSE instruction for more information.

Like CALL, a field B value of 0 signifies multiple return values (up to top of stack.)

```
>local e,f,g; return f,g
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.local "e" ; 0
.local "f" ; 1
.local "g" ; 2
[1] move 3 1
[2] move 4 2
[3] return 3 3
[4] return 0 1
; end of function
```

In line [3], 2 return values are specified (field B value of 3.) The return values are placed in consecutive registers starting from register 3 by the MOVEs on line [1] and [2]. The RETURN in line [4] is redundant; it is always generated by the Lua code generator.

TAILCALL **A B C** return R(A)(R(A+1), ... ,R(A+B-1))

Performs a tail call, which happens when a **return** statement has a *single* function call as the expression, e.g. `return foo(bar)`. A tail call is effectively a *goto*, and avoids nesting calls another level deeper. Only Lua functions can be tailcalled.

Like CALL, register R(A) holds the reference to the function object to be called. B encodes the number of parameters in the same manner as a CALL instruction.

C isn't used by TAILCALL, since all return results are significant. In any case, Lua always generates a 0 for C, to denote multiple return results.

A TAILCALL is used only for one specific **return** style, described above. Multiple return results are always produced by a tail call. Here is an example:

```
>return x("foo", "bar")
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.const "x" ; 0
.const "foo" ; 1
.const "bar" ; 2
[1] getglobal 0 0 ; x
[2] loadk 1 1 ; "foo"
[3] loadk 2 2 ; "bar"
[4] tailcall 0 3 0
[5] return 0 0
[6] return 0 1
; end of function
```

Arguments for a tail call are handled in exactly the same way as arguments for a normal call, so in line [3], the tail call has a field B value of 3, signifying 2 parameters. Field C is 0, for multiple returns; this due to the constant `LUA_MULTRET` in `lua.h`. In practice, field C is not used by the virtual machine (except as an assert) since the syntax guarantees multiple return results.

Line [5] is a RETURN instruction specifying multiple return results. This is required when the function called by TAILCALL is a C function. In the case of a C function, execution continues to line [5] upon return, thus the RETURN is necessary. Line [6] is redundant. When Lua functions are tailcalled, the virtual machine does not return to line [5] at all.

The other instructions covered in this section are SELF and VARARG. Both instructions are covered here because they are closely tied to function calls. We will start with VARARG:

VARARG **A B** R(A), R(A+1), ..., R(A+B-1) = vararg

VARARG implements the vararg operator `'...'` in expressions. VARARG copies B-1 parameters into a number of registers starting from R(A), padding with `nils` if there aren't enough values. If B is 0, VARARG copies as many values as it can based on the number of parameters passed. If a fixed number of values is required, B is a value greater than 1. If any number of values is required, B is 0.

The use of VARARG will become clear with the help of a few examples:

```
>local a,b,c = ...
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
[1] vararg    0    4
[2] return    0    1
; end of function
```

Note that the main or top-level chunk is a vararg function, as the **is_vararg** flag is set (the third number of the `.function` directive) in the example above. In this example, the left hand side of the assignment statement needs three values (or objects.) So in line [1], the operand B of the VARARG instruction is (3+1), or 4. VARARG will copy three values into **a**, **b** and **c**. If there are less than three values available, **nils** will be used to fill up the empty places.

```
>local a = function(...) local a,b,c = ... end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0

; function [0] definition (level 2)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 3 4
.local "arg" ; 0
.local "a" ; 1
.local "b" ; 2
.local "c" ; 3
[1] vararg    1    4
[2] return    0    1
; end of function

[1] closure    0    0    ; 0 upvalues
[2] return    0    1
; end of function
```

Here is an alternate version where a function is instantiated and assigned to local **a**. The old-style **arg** is retained for compatibility purposes, but is unused in the above example.

```
>local a; a(...)
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
[1] move      1    0
[2] vararg    2    0
[3] call      1    0    1
[4] return    0    1
; end of function
```

When a function is called with `'...'` as the argument, the function will accept a variable number of parameters or arguments. On line [2], a VARARG with a B field of 0 is used. The VARARG will copy all the parameters passed on to the main chunk to register 2 onwards, so that the CALL in the next line can utilize them as parameters of function **a**. The function call is set to accept a multiple number of parameters and returns zero results.


```

>local a = {...}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
[1] newtable 0 0 0 ; array=0, hash=0
[2] vararg 1 0
[3] setlist 0 0 1 ; index 1 to top
[4] return 0 1
; end of function

>return ...
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
[1] vararg 0 0
[2] return 0 0
[3] return 0 1
; end of function

```

Above are two other cases where VARARG needs to copy all passed parameters over to a set of registers in order for the next operation to proceed. Both the above forms of table creation and **return** accepts a variable number of values or objects.

SELF A B C R(A+1) := R(B); R(A) := R(B)[RK(C)]

For object-oriented programming using tables. Retrieves a function reference from a table element and places it in register R(A), then a reference to the table itself is placed in the next register, R(A+1). This instruction saves some messy manipulation when setting up a method call.

R(B) is the register holding the reference to the table with the method. The method function itself is found using the table index RK(C), which may be the value of register R(C) or a constant number.

Finally, we have an instruction, SELF, which is used for object-oriented programming. A SELF instruction saves an extra instruction and speeds up the calling of methods in object-oriented programming. It is only generated for method calls that use the colon syntax. In the following example:

```

>foo:bar("baz")
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.const "foo" ; 0
.const "bar" ; 1
.const "baz" ; 2
[1] getglobal 0 0 ; foo
[2] self 0 0 257 ; "bar"
[3] loadk 2 2 ; "baz"
[4] call 0 3 1
[5] return 0 1
; end of function

```

The method call is equivalent to: `foo.bar(foo, "baz")`, except that the global `foo` is only looked up *once*. This is significant if metamethods have been set. The SELF in line [2] is equivalent to a GETTABLE lookup (the table is in register 0 and the index is constant 1) and a MOVE (copying the table reference from register 0 to register 1.)

Without SELF, a GETTABLE will write its lookup result to register 0 (which the code generator will normally do) and the table reference will be overwritten before a MOVE can be done. Using SELF saves roughly one instruction and one temporary register slot.

After setting up the method call using SELF, the call is made with the usual CALL instruction in line [4], with two parameters. The equivalent code for a method lookup is compiled in the following manner:

```
>foo.bar(foo, "baz")
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.const "foo" ; 0
.const "bar" ; 1
.const "baz" ; 2
[1] getglobal 0 0 ; foo
[2] gettable 0 0 257 ; "bar"
[3] getglobal 1 0 ; foo
[4] loadk 2 2 ; "baz"
[5] call 0 3 1
[6] return 0 1
; end of function
```

The alternative form of a method call is one instruction longer, and the user must take note of any metamethods that may affect the call. The SELF in the previous example replaces the GETTABLE on line [2] and the GETGLOBAL on line [3]. If **foo** is a local variable, then the equivalent code is a GETTABLE and a MOVE.

Next we will look at more complicated instructions.

11 Relational and Logic Instructions

Relational and logic instructions are used in conjunction with other instructions to implement control structures or expressions. Instead of generating boolean results, these instructions conditionally perform a jump over the next instruction; the emphasis is on implementing control blocks. Instructions are arranged so that there are two paths to follow based on the relational test.

EQ	A B C	if ((RK(B) == RK(C)) ~= A) then PC++
LT	A B C	if ((RK(B) < RK(C)) ~= A) then PC++
LE	A B C	if ((RK(B) <= RK(C)) ~= A) then PC++

Compares RK(B) and RK(C), which may be registers or constants. If the boolean result is not A, then skip the next instruction. Conversely, if the boolean result equals A, continue with the next instruction.

EQ is for equality. LT is for “less than” comparison. LE is for “less than or equal to” comparison. The boolean A field allows the full set of relational comparison operations to be synthesized from these three instructions. The Lua code generator produces either 0 or 1 for the boolean A.

For the fall-through case, a JMP is always expected, in order to optimize execution in the virtual machine. In effect, EQ, LT and LE must always be paired with a following JMP instruction.

By comparing the result of the relational operation with A, the sense of the comparison can be reversed. Obviously the alternative is to reverse the paths taken by the instruction, but that will probably complicate code generation some more. The conditional jump is performed if the comparison result is not A, whereas execution continues normally if the comparison result matches A. Due to the way code is generated and the way the virtual machine works, a JMP instruction is always expected to follow an EQ, LT or LE. The following JMP is optimized by executing it in conjunction with EQ, LT or LE.

```
>local x,y; return x ~= y
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 0 3
.local "x" ; 0
.local "y" ; 1
[1] loadnil 0 1
[2] eq 0 0 1 ; to [4] if true (x ~= y)
[3] jmp 1 ; to [5]
[4] loadbool 2 0 1 ; false, to [6] (false result path)
[5] loadbool 2 1 0 ; true (true result path)
[6] return 2 2
[7] return 0 1
; end of function
```

In the above example, the equality test is performed in line [2]. However, since the comparison need to be returned as a result, LOADBOOL instructions are used to set a register with the correct boolean value. This is the usual code pattern generated if the expression requires a boolean value to be generated and stored in a register as an intermediate value or a final result.

It is easier to visualize the disassembled code as:

```
if x ~= y then
  return true
else
  return false
end
```

The true result path (when the comparison result matches A) goes like this:

```
[1] loadnil    0  1
[2] eq         0  0  1    ; to [4] if true    (x ~= y)
[3] jmp       1
[5] loadbool  2  1  0    ; true        (true path)
[6] return    2  2
```

while the false result path (when the comparison result does not match A) goes like this:

```
[1] loadnil    0  1
[2] eq         0  0  1    ; to [4] if true    (x ~= y)
[4] loadbool  2  0  1    ; false, to [6]    (false path)
[6] return    2  2
```

ChunkSpy comments the EQ in line [2] by letting the user know when the conditional jump is taken. The jump is taken when “the value in register 0 equals to the value in register 1” (the comparison) is not **false** (the value of operand A). If the comparison is **x == y**, everything will be the same except that the A operand in the EQ instruction will be 1, thus reversing the sense of the comparison. Anyway, these are just the Lua code generator’s conventions; there are other ways to code **x ~= y** in terms of Lua virtual machine instructions.

For conditional statements, there is no need to set boolean results. Lua is optimized for coding the more common conditional statements rather than conditional expressions.

```
>local x,y; if x ~= y then return "foo" else return "bar" end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "x" ; 0
.local "y" ; 1
.const "foo" ; 0
.const "bar" ; 1
[1] eq      1  0  1    ; to [3] if false    (x ~= y)
[2] jmp     3
[3] loadk   2  0      ; "foo"            (true block)
[4] return  2  2
[5] jmp     2          ; to [8]
[6] loadk   2  1      ; "bar"            (false block)
[7] return  2  2
[8] return  0  1
; end of function
```

In the above conditional statement, the same inequality operator is used in the source, but the sense of the EQ instruction in line [1] is now reversed. Since the EQ conditional jump can only skip the next instruction, additional JMP instructions are needed to allow large blocks of code to be placed in both true and false paths. In contrast, in the previous example, only a single instruction is needed to set a boolean value. For **if** statements, the true block comes first followed by the false block in code generated by the code generator. To reverse the positions of the true and false paths, the value of operand A is changed.

The true path (when $x \sim y$ is true) goes from [1] to [3]–[5] and on to [8]. Since there is a RETURN in line [4], the JMP in line [5] and the RETURN in [8] are never executed at all; they are redundant but does not adversely affect performance in any way. The false path is from [1] to [2] to [6]–[8] onwards. So in a disassembly listing, you should see the true and false code blocks in the same order as in the Lua source.

The following is another example, this time with an **elseif**:

```
>if 8 > 9 then return 8 elseif 5 >= 4 then return 5 else return 9 end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.const 8 ; 0
.const 9 ; 1
.const 5 ; 2
.const 4 ; 3
[01] lt      0   257 256 ; 9 8, to [3] if true   (9 < 8)
[02] jmp     3           ; to [6]
[03] loadk   0   0      ; 8           (1st true block)
[04] return  0   2
[05] jmp     7           ; to [13]
[06] le      0   259 258 ; 4 5, to [8] if true   (4 <= 5)
[07] jmp     3           ; to [11]
[08] loadk   0   2      ; 5           (2nd true block)
[09] return  0   2
[10] jmp     2           ; to [13]
[11] loadk   0   1      ; 9           (2nd false block)
[12] return  0   2
[13] return  0   1
; end of function
```

This example is a little more complex, but the blocks are structured in the same order as the Lua source, so interpreting the disassembled code should not be too hard.

Next are the two instructions used for performing boolean tests and implementing Lua's logic operators:

TEST	A C	if not (R(A) <=> C) then PC++
TESTSET	A B C	if (R(B) <=> C) then R(A) := R(B) else PC++

Used to implement **and** and **or** logical operators, or for testing a single register in a conditional statement.

For TESTSET, register R(B) is coerced into a boolean and compared to the boolean field C. If R(B) matches C, the next instruction is skipped, otherwise R(B) is assigned to R(A) and the VM continues with the next instruction. The **and** operator uses a C of 0 (false) while **or** uses a C value of 1 (true).

TEST is a more primitive version of TESTSET. TEST is used when the assignment operation is not needed, otherwise it is the same as TESTSET except that the operand slots are different.

For the fall-through case, a JMP is always expected, in order to optimize execution in the virtual machine. In effect, TEST and TESTSET must always be paired with a following JMP instruction.

TEST and TESTSET are used in conjunction with a following JMP instruction, while TESTSET has an additional conditional assignment. Like EQ, LT and LE, the following JMP instruction is compulsory, as the virtual machine will execute the JMP together with TEST or TESTSET. The two instructions are used to implement short-circuit LISP-style logical operators that retains and propagates operand values instead of booleans. First, we'll look at how **and** and **or** behaves:

```
>local a,b,c; c = a and b
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
[1] testset 2 0 0 ; to [3] if true
[2] jmp 1 ; to [4]
[3] move 2 1
[4] return 0 1
; end of function
```

An **and** sequence exits on *false operands* (which can be **false** or **nil**) because any **false** operands in a string of **and** operations will make the whole boolean expression **false**. If operands evaluates to **true**, evaluation continues. When a string of **and** operations evaluates to true, the result is the *last* operand value.

In line [1], the first operand (the local **a**) is set to local **c** when the test is **false** (with a field C of 0), while the jump to [3] is made when the test is **true**, and then in line [3], the expression result is set to the second operand (the local **b**). This is equivalent to:

```
if a then
  c = b      -- executed by MOVE on line [3]
else
  c = a      -- executed by TESTSET on line [1]
end
```

The **c = a** portion is done by TESTSET itself, while MOVE performs **c = b**. Now, if the result is already set with one of the possible values, a TEST instruction is used instead:

```
>local a,b; a = a and b
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.local "b" ; 1
[1] test 0 0 ; to [3] if true
[2] jmp 1 ; to [4]
[3] move 0 1
[4] return 0 1
; end of function
```

The TEST instruction does not perform an assignment operation, since **a = a** is redundant. This makes TEST a little faster. This is equivalent to:

```
if a then
  a = b
end
```

Next, we will look at the **or** operator:

```

>local a,b,c; c = a or b
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
[1] testset 2 0 1 ; to [3] if false
[2] jmp 1 ; to [4]
[3] move 2 1
[4] return 0 1
; end of function

```

An **or** sequence exits on *true operands*, because any operands evaluating to **true** in a string of **or** operations will make the whole boolean expression **true**. If operands evaluates to **false**, evaluation continues. When a string of **or** operations evaluates to **false**, all operands must have evaluated to **false**.

In line [1], the local **a** value is set to local **c** if it is **true**, while the jump is made if it is **false** (the field C is 1). Thus in line [3], the local **b** value is the result of the expression if local **a** evaluates to **false**. This is equivalent to:

```

if a then
  c = a      -- executed by TESTSET on line [1]
else
  c = b      -- executed by MOVE on line [3]
end

```

Like the case of **and**, TEST is used when the result already has one of the possible values, saving an assignment operation:

```

>local a,b; a = a or b
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.local "b" ; 1
[1] test 0 1 ; to [3] if false
[2] jmp 1 ; to [4]
[3] move 0 1
[4] return 0 1
; end of function

```

Short-circuit logical operators also means that the following Lua code does not require the use of a boolean operation:

```

>local a,b,c; if a > b and a > c then return a end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
[1] lt 0 1 0 ; to [3] if true
[2] jmp 3 ; to [6]
[3] lt 0 2 0 ; to [5] if true
[4] jmp 1 ; to [6]
[5] return 0 2
[6] return 0 1
; end of function

```

With short-circuit evaluation, **a > c** is never executed if **a > b** is **false**, so the logic of the Lua statement can be readily implemented using the normal conditional structure. If both **a > b** and **a > c** are **true**, the path followed is [1] (the **a > b** test) to [3] (the **a > c** test) and finally to [5], returning the value of **a**. A TEST instruction is not required. This is equivalent to:

```

if a > b then
  if a > c then
    return a
  end
end
end

```

For a single variable used in the expression part of a conditional statement, TEST is used to boolean-test the variable:

```

>if Done then return end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.const "Done" ; 0
[1] getglobal 0 0 ; Done
[2] test 0 0 ; to [4] if true
[3] jmp 1 ; to [5]
[4] return 0 1
[5] return 0 1
; end of function

```

In line [2], the TEST instruction jumps to the true block if the value in temporary register 0 (from the global **Done**) is **true**. The JMP at line [3] jumps over the true block, which is the code inside the **if** block (line [4].)

If the test expression of a conditional statement consist of purely boolean operators, then a number of TEST instructions will be used in the usual short-circuit evaluation style:

```

>if Found and Match then return end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.const "Found" ; 0
.const "Match" ; 1
[1] getglobal 0 0 ; Found
[2] test 0 0 ; to [4] if true
[3] jmp 4 ; to [8]
[4] getglobal 0 1 ; Match
[5] test 0 0 ; to [7] if true
[6] jmp 1 ; to [8]
[7] return 0 1
[8] return 0 1
; end of function

```

In the last example, the true block of the conditional statement is executed only if both **Found** and **Match** evaluates to **true**. The path is from [2] (test for **Found**) to [4] to [5] (test for **Match**) to [7] (the true block, which is an explicit **return** statement.)

If the statement has an **else** section, then the JMP on line [6] will jump to the false block (the **else** block) while an additional JMP will be added to the true block to jump over this new block of code. If **or** is used instead of **and**, the appropriate C operand will be adjusted accordingly.

Finally, here is how Lua's ternary operator (:? in C) equivalent works:

```
>local a,b,c; a = a and b or c
; function [0] definition (level 1)
; 0 upvalues, 0 params, 3 stacks
.function 0 0 2 3
.local "a" ; 0
.local "b" ; 1
.local "c" ; 2
[1] test      0      0      ; to [3] if true
[2] jmp       2      ; to [5]
[3] testset   0      1      1      ; to [5] if false
[4] jmp       1      ; to [6]
[5] move      0      2
[6] return    0      1
; end of function
```

The TEST in line [1] is for the **and** operator. First, local **a** is tested in line [1]. If it is **false**, then execution continues in [2], jumping to line [5]. Line [5] assigns local **c** to the end result because since if **a** is **false**, then **a and b** is **false**, and **false or c** is **c**.

If local **a** is **true** in line [1], the TEST instruction makes a jump to line [3], where there is a TESTSET, for the **or** operator. If **b** evaluates to **true**, then the end result is assigned the value of **b**, because **b or c** is **b** if **b** is not **false**. If **b** is also **false**, the end result will be **c**.

For the instructions in line [1], [3] and [5], the target (in field A) is register 0, or the local **a**, which is the location where the result of the boolean expression is assigned. The equivalent Lua code is:

```
if a then
  if b then
    a = b
  else
    a = c
  end
else
  a = c
end
```

The two **a = c** assignments are actually the same piece of code, but are repeated here to avoid using a **goto** and a label. Normally, if we assume **b** is not **false** and not **nil**, we end up with the more recognizable form:

```
if a then
  a = b      -- assuming b ~= false
else
  a = c
end
```

12 Loop Instructions

Lua has dedicated instructions to implement the two types of **for** loops, while the other two types of loops uses traditional test-and-jump.

FORPREP	A sBx	R(A) -= R(A+2); PC += sBx
FORLOOP	A sBx	R(A) += R(A+2) if R(A) <?= R(A+1) then { PC += sBx; R(A+3) = R(A) }

FORPREP initializes a numeric **for** loop, while FORLOOP performs an iteration of a numeric **for** loop.

A numeric for loop requires 4 registers on the stack, and each register must be a number. R(A) holds the initial value and doubles as the internal loop variable (the *internal index*); R(A+1) is the limit; R(A+2) is the stepping value; R(A+3) is the actual loop variable (the *external index*) that is local to the **for** block.

FORPREP sets up a **for** loop. Since FORLOOP is used for initial testing of the loop condition as well as conditional testing during the loop itself, FORPREP performs a *negative step* and jumps unconditionally to FORLOOP so that FORLOOP is able to correctly make the initial loop test. After this initial test, FORLOOP performs a loop step as usual, restoring the initial value of the loop index so that the first iteration can start.

In FORLOOP, a jump is made back to the start of the loop body if the limit has not been reached or exceeded. The sense of the comparison depends on whether the stepping is negative or positive, hence the “<?” operator. Jumps for both instructions are encoded as signed displacements in the sBx field. An empty loop has a FORLOOP sBx value of -1.

FORLOOP also sets R(A+3), the external loop index that is local to the loop block. This is significant if the loop index is used as an upvalue (see below.) R(A), R(A+1) and R(A+2) are not visible to the programmer.

The loop variable ends with the last value before the limit is reached (unlike C) because it is not updated unless the jump is made. However, since loop variables are local to the loop itself, you should not be able to use it unless you cook up an implementation-specific hack.

Loop indices behave a little differently in Lua 5.1 compared to Lua 5.0.2. Consider the following, where loop index **i** is used as an upvalue in the instantiation of 10 functions:

```
local a = {}
for i = 1, 10 do
  a[i] = function() return i end
end
print(a[5]())
```

Lua 5.0.2 will print out 10, while Lua 5.1 will print out 5. In Lua 5.0.2, the scope of the loop index encloses the **for** loop, resulting in the creation of a single upvalue. In Lua 5.1, the loop index is truly local to the loop, resulting in the creation of 10 separate upvalues.

For the sake of efficiency, FORLOOP contains a lot of functionality, so when a loop iterates, only *one* instruction, FORLOOP, is needed. Here is a simple example:

```
>local a = 0; for i = 1,100,5 do a = a + i end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.local "a" ; 0
.local "(for index)" ; 1
.local "(for limit)" ; 2
.local "(for step)" ; 3
.local "i" ; 4
.const 0 ; 0
.const 1 ; 1
.const 100 ; 2
.const 5 ; 3
[1] loadk 0 0 ; 0
[2] loadk 1 1 ; 1
[3] loadk 2 2 ; 100
[4] loadk 3 3 ; 5
[5] forprep 1 1 ; to [7]
[6] add 0 0 4
[7] forloop 1 -2 ; to [6] if loop
[8] return 0 1
; end of function
```

In the above example, notice that the **for** loop causes three additional local pseudo-variables (or internal variables) to be defined, apart from the external loop index, **i**. The three pseudo-variables, named (**for index**), (**for limit**) and (**for step**) are required to completely specify the state of the loop, and are not visible to Lua source code. They are arranged in consecutive registers, with the external loop index given by R(A+3) or register 4 in the example.

The loop body is in line [6] while line [7] is the FORLOOP instruction that steps through the loop state. The sBx field of FORLOOP is negative, as it always jumps back to the beginning of the loop body.

Lines [2]–[4] initializes the three register locations where the loop state will be stored. If the loop step is not specified in the Lua source, a constant 1 is added to the constant pool and a LOADK instruction is used to initialize the pseudo-variable (**for step**) with the loop step.

FORPREP in lines [5] makes a negative loop step and jumps to line [7] for the initial test. In the example, at line [5], the internal loop index (at register 1) will be (1-5) or -4. When the virtual machine arrives at the FORLOOP in line [7] for the first time, one loop step is made prior to the first test, so the initial value that is actually tested against the limit is (-4+5) or 1. Since 1 < 100, an iteration will be performed. The external loop index **i** is then set to 1 and a jump is made to line [6], thus starting the first iteration of the loop.

The loop at line [6]–[7] repeats until the internal loop index exceeds the loop limit of 100. The conditional jump is not taken when that occurs and the loop ends. Beyond the scope of the loop body, the loop state ((**for index**), (**for limit**), (**for step**) and **i**) is not valid. This is determined by the parser and code generator. The range of PC values for which the loop state variables are valid is located in the locals list. The brief assembly listings generated by ChunkSpy that you are seeing does not give the **startpc** and **endpc** values contained in the locals list. In theory, these rules can be broken if you write Lua assembly directly.

```

>for i = 10,1,-1 do if i == 5 then break end end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 4 stacks
.function 0 0 2 4
.local "(for index)" ; 0
.local "(for limit)" ; 1
.local "(for step)" ; 2
.local "i" ; 3
.const 10 ; 0
.const 1 ; 1
.const -1 ; 2
.const 5 ; 3
[1] loadk 0 0 ; 10
[2] loadk 1 1 ; 1
[3] loadk 2 2 ; -1
[4] forprep 0 3 ; to [8]
[5] eq 0 3 259 ; 5, to [7] if true
[6] jmp 1 ; to [8]
[7] jmp 1 ; to [9]
[8] forloop 0 -4 ; to [5] if loop
[9] return 0 1
; end of function

```

In the second loop example above, except for a negative loop step size, the structure of the loop is identical. The body of the loop is from line [5] to line [8]. Since no additional stacks or states are used, a **break** translates simply to a JMP instruction (line [7]). There is nothing to clean up after a FORLOOP ends or after a JMP to exit a loop.

Apart from a numeric **for** loop (implemented by FORPREP and FORLOOP), Lua has a generic **for** loop, implemented by TFORLOOP:

```

TFORLOOP  A C      R(A+3), ... ,R(A+2+C) := R(A)(R(A+1), R(A+2));
                if R(A+3) ~= nil then {
                    R(A+2) = R(A+3);
                } else {
                    PC++;
                }

```

Performs an iteration of a generic **for** loop. A Lua 5-style generic **for** loop keeps 3 items in consecutive register locations to keep track of things. R(A) is the *iterator function*, which is called once per loop. R(A+1) is the *state*, and R(A+2) is the enumeration index. At the start, R(A+2) has an initial value. R(A), R(A+1) and R(A+2) are internal to the loop and cannot be accessed by the programmer; at first, they are set with an initial state.

In addition to these internal loop variables, the programmer specifies one or more loop variables that are external and visible to the programmer. These loop variables reside at locations R(A+3) onwards, and their count is specified in operand C. Operand C must be at least 1. They are also local to the loop body, like the external loop index in a numerical **for** loop.

Each time TFORLOOP executes, the iterator function referenced by R(A) is called with two arguments: the state and the enumeration index (R(A+1) and R(A+2).) The results are returned in the local loop variables, from R(A+3) onwards, up to R(A+2+C).

Next, the first return value, R(A+3), is tested. If it is **nil**, the iterator loop is at an end, and TFORLOOP skips the next instruction and the **for** loop block ends. Note that the state of the generic **for** loop does not depend on any of the external iterator variables that are visible to the programmer.

If R(A+3) is not **nil**, there is another iteration, and R(A+3) is assigned as the new value of the enumeration index, R(A+2). Then next instruction, which *must* be a JMP, is immediately executed, sending execution back to the beginning of the loop. This is an optimization case; TFORLOOP will not work correctly without the JMP instruction.

Like the numerical **for** loop, the generic **for** loop behave a little differently in Lua 5.1 compared to Lua 5.0.2. In the following example:

```
local a = {[1]=2,[2]=4,[3]=8}
local b = {}
for i,v in pairs(a) do
  b[i] = function() return v end
end
print(b[1>(), b[2>(), b[3]())
```

Lua 5.0.2 will print out 3 **nils**, while Lua 5.1 will print out 2, 4 and 8. In Lua 5.0.2, the scope of the external iterator variables encloses the **for** loop, resulting in the creation of a single upvalue. In Lua 5.1, the iterator variables are truly local to the loop, resulting in the creation of separate upvalues.

This example has a loop with one additional result (**v**) in addition the loop enumerator (**i**):

```
>for i,v in pairs(t) do print(i,v) end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 8 stacks
.function 0 0 2 8
.local "(for generator)" ; 0
.local "(for state)" ; 1
.local "(for control)" ; 2
.local "i" ; 3
.local "v" ; 4
.const "pairs" ; 0
.const "t" ; 1
.const "print" ; 2
[01] getglobal 0 0 ; pairs
[02] getglobal 1 1 ; t
[03] call 0 2 4
[04] jmp 4 ; to [9]
[05] getglobal 5 2 ; print
[06] move 6 3
[07] move 7 4
[08] call 5 3 1
[09] tforloop 0 2 ; to [11] if exit
[10] jmp -6 ; to [5]
[11] return 0 1
; end of function
```

The iterator function is located in register 0, and is named (**for generator**) for debugging purposes. The state is in register 1, and has the name (**for state**). The enumeration index, (**for control**), is contained in register 2. These correspond to locals R(A), R(A+1) and R(A+2) in the TFORLOOP description. Results from the iterator function call is placed into register 3

and 4, which are locals **i** and **v**, respectively. On line [9], the operand C of TFORLOOP is 2, corresponding to two iterator variables (**i** and **v**).

Line [1]–[3] prepares the iterator state. Note that the call to the **pairs** standard library function has 1 parameter and 3 results. After the call in line [3], register 0 is the iterator function, register 1 is the loop state, register 2 is the initial value of the enumeration index. The iterator variables **i** and **v** are both invalid at the moment, because we have not entered the loop yet.

Line [4] is a JMP to TFORLOOP on line [9]. With the initial (or *zeroth*) iterator state, TFORLOOP calls the iterator function, generating the first set of enumeration results in locals **i**, **v**. If **i** is not **nil**, the internal enumeration index (register 2) is set and the JMP on the next line is immediately executed, starting the first iteration of the loop body (lines [5]–[8]).

The body of the generic **for** loop executes (`print(i,v)`) and then TFORLOOP is encountered again, calling the iterator function to get the next iteration state. Finally, when the first result is a **nil**, the loop ends, and execution continues on line [11].

repeat and **while** loops use a standard test-and-jump structure. Here is a **repeat** loop:

```
>local a = 0; repeat a = a + 1 until a == 10
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const 0 ; 0
.const 1 ; 1
.const 10 ; 2
[1] loadk      0 0 ; 0
[2] add        0 0 257 ; 1
[3] eq         0 0 258 ; 10, to [5] if true
[4] jmp        -3 ; to [2]
[5] return     0 1
; end of function
```

The body of the **repeat** loop is line [2], while the test-and-jump scheme is implemented in lines [3] and [4]. Although two instructions are needed to loop the loop, Lua 5.1 executes EQ and JMP together, saving some time.

```
>local a = 1; while a < 10 do a = a + 1 end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const 1 ; 0
.const 10 ; 1
[1] loadk      0 0 ; 1
[2] lt         0 0 257 ; 10, to [4] if true
[3] jmp        2 ; to [6]
[4] add        0 0 256 ; 1
[5] jmp        -4 ; to [2]
[6] return     0 1
; end of function
```

For a **while** loop, the test (line[2]) is made first. If the test is **true**, execution continues with the loop body (line [4]). A JMP on line [5] returns execution to the loop test instruction. This is a little different from Lua 5.0.2 **while** loops, which have the loop test at the end of the loop block and has a loop condition size limitation.

A **while** loop in the Lua 5.0.2 style will look like this:

```
>local a = 1; while a < 10 do a = a + 1 end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "a" ; 0
.const 1 ; 0
.const 10 ; 1
[1] loadk      0 0          ; 1
[2] jmp       1          ; to [4]
[3] add       0 0 256     ; 1
[4] lt        1 0 257    ; 10, to [6] if false
[5] jmp      -3          ; to [3]
[6] return    0 1
; end of function
```

The sense of the condition test is reversed, while the loop body is at line [3]. The condition test is made at the end of the loop on line [4].

13 Table Creation

There are two instructions for table creation and initialization. One instruction creates a table while the other instruction sets the array elements of a table.

NEWTABLE **A B C** $R(A) := \{\}$ (size = B,C)

Creates a new empty table at register $R(A)$. B and C are the encoded size information for the array part and the hash part of the table, respectively. Appropriate values for B and C are set in order to avoid rehashing when initially populating the table with array values or hash key-value pairs.

Operand B and C are both encoded as a “floating point byte” (so named in `lobject.c`) which is `eeeeexxx` in binary, where x is the mantissa and e is the exponent. The actual value is calculated as $1xxx \cdot 2^{(eeee-1)}$ if $eeee$ is greater than 0 (a range of 8 to $15 \cdot 2^{30}$.) If $eeee$ is 0, the actual value is xxx (a range of 0 to 7.)

If an empty table is created, both sizes are zero. If a table is created with a number of objects, the code generator counts the number of array elements and the number of hash elements. Then, each size value is rounded up and encoded in B and C using the floating point byte format.

Creating an empty table forces both array and hash sizes to be zero:

```
>local q = {}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "q" ; 0
[1] newtable 0 0 0 ; array=0, hash=0
[2] return 0 1
; end of function
```

In later examples, we will see how the size values are encoded. But first, we need to learn about the `SETLIST` instruction, which is used to initialize array elements in a table.

SETLIST **A B C** $R(A)[(C-1) \cdot \text{FPF} + i] := R(A+i)$, $1 \leq i \leq B$

Sets the values for a range of *array elements* in a table referenced by $R(A)$. Field B is the number of elements to set. Field C encodes the block number of the table to be initialized. The values used to initialize the table are located in registers $R(A+1)$, $R(A+2)$, and so on.

The block size is denoted by `FPF`. `FPF` is “fields per flush”, defined as `LFIELDS_PER_FLUSH` in the source file `lopcodes.h`, with a value of 50. For example, for array locations 1 to 20, C will be 1 and B will be 20.

If B is 0, the table is set with a variable number of array elements, from register $R(A+1)$ up to the top of the stack. This happens when the last element in the table constructor is a function call or a `vararg` operator.

If C is 0, the *next instruction* is cast as an integer, and used as the C value. This happens only when operand C is unable to encode the block number, i.e. when $C > 511$, equivalent to an array index greater than 25550.

We'll start with a simple example:

```
>local q = {1,2,3,4,5,}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 6 stacks
.function 0 0 2 6
.local "q" ; 0
.const 1 ; 0
.const 2 ; 1
.const 3 ; 2
.const 4 ; 3
.const 5 ; 4
[1] newtable 0 5 0 ; array=5, hash=0
[2] loadk 1 0 ; 1
[3] loadk 2 1 ; 2
[4] loadk 3 2 ; 3
[5] loadk 4 3 ; 4
[6] loadk 5 4 ; 5
[7] setlist 0 5 1 ; index 1 to 5
[8] return 0 1
; end of function
```

A table with the reference in register 0 is created in line [1] by NEWTABLE. Since we are creating a table with no hash elements, the array part of the table has a size of 5, while the hash part has a size of 0.

Constants are then loaded into temporary registers 1 to 5 (lines [2] to [6]) before the SETLIST instruction in line [7] assigns each value to consecutive table elements. The start of the block is encoded as 1 in operand C. The starting index is calculated as $(1-1)*50+1$ or 1. Since B is 5, the range of the array elements to be set becomes 1 to 5, while the objects used to set the array elements will be R(1) through R(5).

Next is a larger table with 55 array elements. This will require two blocks to initialize. Some lines have been removed and ellipsis (...) added to save space.

```
>local q = {1,2,3,4,5,6,7,8,9,0,1,2,3,4,5,6,7,8,9,0, \
>>1,2,3,4,5,6,7,8,9,0,1,2,3,4,5,6,7,8,9,0, \
>>1,2,3,4,5,6,7,8,9,0,1,2,3,4,5,}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 51 stacks
.function 0 0 2 51
.local "q" ; 0
.const 1 ; 0
.const 2 ; 1
...
.const 0 ; 9
[01] newtable 0 30 0 ; array=56, hash=0
[02] loadk 1 0 ; 1
[03] loadk 2 1 ; 2
...
[51] loadk 50 9 ; 0
[52] setlist 0 50 1 ; index 1 to 50
[53] loadk 1 0 ; 1
[54] loadk 2 1 ; 2
...
[57] loadk 5 4 ; 5
[58] setlist 0 5 2 ; index 51 to 55
[59] return 0 1
; end of function
```

Since FPF is 50, the array will be initialized in two blocks. The first block is for index 1 to 50, while the second block is for index 51 to 55. Each array block to be initialized requires one SETLIST instruction. On line [1], NEWTABLE has a field B value of 30, or 00011110 in binary. From the description of NEWTABLE, xxx is 110_2 , while eeeee is 11_2 . Thus, the size of the array portion of the table is $(1110)*2^{(11-1)}$ or $(14*2^2)$ or 56.

Lines [2] to [51] sets the values used to initialize the first block. On line [52], SETLIST has a B value of 50 and a C value of 1. So the block is from 1 to 50. Source registers are from R(1) to R(50). Lines [53] to [57] sets the values used to initialize the second block. On line [58], SETLIST has a B value of 5 and a C value of 2. So the block is from 51 to 55. The start of the block is calculated as $(2-1)*50+1$ or 51. Source registers are from R(1) to R(5).

Here is a table with hashed elements:

```
>local q = {a=1,b=2,c=3,d=4,e=5,f=6,g=7,h=8,}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "q" ; 0
.const "a" ; 0
.const 1 ; 1
.const "b" ; 2
.const 2 ; 3
.const "c" ; 4
.const 3 ; 5
.const "d" ; 6
.const 4 ; 7
.const "e" ; 8
.const 5 ; 9
.const "f" ; 10
.const 6 ; 11
.const "g" ; 12
.const 7 ; 13
.const "h" ; 14
.const 8 ; 15
[01] newtable 0 0 8 ; array=0, hash=8
[02] settable 0 256 257 ; "a" 1
[03] settable 0 258 259 ; "b" 2
[04] settable 0 260 261 ; "c" 3
[05] settable 0 262 263 ; "d" 4
[06] settable 0 264 265 ; "e" 5
[07] settable 0 266 267 ; "f" 6
[08] settable 0 268 269 ; "g" 7
[09] settable 0 270 271 ; "h" 8
[10] return 0 1
; end of function
```

In line [1], NEWTABLE is executed with an array part size of 0 and a hash part size of 8. On lines [2] to line [9], key-value pairs are set using SETTABLE. The SETLIST instruction is only for initializing array elements. Using SETTABLE to initialize the key-value pairs of a table in the above example is quite efficient as it can reference the constant pool directly.

If there are both array elements and hash elements in a table constructor, both SETTABLE and SETLIST will be used to initialize the table after the initial NEWTABLE. In addition, if the last element of the table constructor is a function call or a vararg operator, then the B operand of SETLIST will be 0, to allow objects from R(A+1) up to the top of the stack to be initialized as array elements of the table.

```

>return {1,2,3,a=1,b=2,c=3,foo()}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.const 1 ; 0
.const 2 ; 1
.const 3 ; 2
.const "a" ; 3
.const "b" ; 4
.const "c" ; 5
.const "foo" ; 6
[01] newtable 0 3 3 ; array=3, hash=3
[02] loadk 1 0 ; 1
[03] loadk 2 1 ; 2
[04] loadk 3 2 ; 3
[05] settable 0 259 256 ; "a" 1
[06] settable 0 260 257 ; "b" 2
[07] settable 0 261 258 ; "c" 3
[08] getglobal 4 6 ; foo
[09] call 4 1 0
[10] setlist 0 0 1 ; index 1 to top
[11] return 0 2
[12] return 0 1
; end of function

```

In the above example, the table is first created in line [1] with its reference in register 0, and it has both array and hash elements to be set. The size of the array part is 3 while the size of the hash part is also 3.

Lines [2]–[4] loads the values for the first 3 array elements. Lines [5]–[7] sets the 3 key-value pairs for the hash part of the table. In lines [8] and [9], the call to function **foo** is made, and then in line [10], the SETLIST instruction sets the first 3 array elements (in registers 1 to 3) plus whatever additional results returned by the **foo** function call (from register 4 onwards.) This is accomplished by setting operand B in SETLIST to 0. For the first block, operand C is 1 as usual. If no results are returned by the function, the top of stack is at register 3 and only the 3 constant array elements in the table are set.

```

>local a; return {a(), a(), a()}
; function [0] definition (level 1)
; 0 upvalues, 0 params, 5 stacks
.function 0 0 2 5
.local "a" ; 0
[01] newtable 1 2 0 ; array=2, hash=0
[02] move 2 0
[03] call 2 1 2
[04] move 3 0
[05] call 3 1 2
[06] move 4 0
[07] call 4 1 0
[08] setlist 1 0 1 ; index 1 to top
[09] return 1 2
[10] return 0 1
; end of function

```

Note that only the last function call in a table constructor retains all results. Other function calls in the table constructor keep only one result. This is shown in the above example. For vararg operators in table constructors, please see the discussion for the VARARG instruction for an example.

14 Closures and Closing

The final two instructions of the Lua virtual machine are a little involved because of the handling of upvalues. The first is CLOSURE, for instantiating function prototypes:

```
CLOSURE    A Bx    R(A) := closure(KPROTO[Bx], R(A), ... ,R(A+n))
```

Creates an instance (or closure) of a function. Bx is the function number of the function to be instantiated in the table of function prototypes. This table is located after the constant table for each function in a binary chunk. The first function prototype is numbered 0. Register R(A) is assigned the reference to the instantiated function object.

For each upvalue used by the instance of the function KPROTO[Bx], there is a pseudo-instruction that follows CLOSURE. Each upvalue corresponds to either a MOVE or a GETUPVAL pseudo-instruction. Only the B field on either of these pseudo-instructions are significant.

A MOVE corresponds to local variable R(B) in the current lexical block, which will be used as an upvalue in the instantiated function. A GETUPVAL corresponds upvalue number B in the current lexical block. The VM uses these pseudo-instructions to manage upvalues.

If the function prototype has no upvalues, then CLOSURE is pretty straightforward: Bx has the function number and R(A) is assigned the reference to the instantiated function object. However, when an upvalue comes into the picture, we have to look a little more carefully:

```
>local u; \  
>>function p() return u end  
; function [0] definition (level 1)  
; 0 upvalues, 0 params, 2 stacks  
.function 0 0 2 2  
.local "u" ; 0  
.const "p" ; 0  
  
; function [0] definition (level 2)  
; 1 upvalues, 0 params, 2 stacks  
.function 1 0 0 2  
.upvalue "u" ; 0  
[1] getupval 0 0 ; u  
[2] return 0 2  
[3] return 0 1  
; end of function  
  
[1] closure 1 0 ; 1 upvalues  
[2] move 0 0  
[3] setglobal 1 0 ; p  
[4] return 0 1  
; end of function
```

In the example, the upvalue in the level 2 function is **u**, and within the main chunk there is a single function prototype (indented in the listing above for clarity.) In the top-level function, line [1], the closure is made. In line [3] the function reference is saved into global **p**. Line [2] is a part of the CLOSURE instruction (it not really an actual MOVE,) and its B field specifies that upvalue number 0 in the closed function is really local **u** in the enclosing function.

Here is another example, with 3 levels of function prototypes:

```

>local m \
>>function p() \
>> local n \
>> function q() return m,n end \
>>end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "m" ; 0
.const "p" ; 0

; function [0] definition (level 2)
; 1 upvalues, 0 params, 2 stacks
.function 1 0 0 2
.local "n" ; 0
.upvalue "m" ; 0
.const "q" ; 0

; function [0] definition (level 3)
; 2 upvalues, 0 params, 2 stacks
.function 2 0 0 2
.upvalue "m" ; 0
.upvalue "n" ; 1
[1] getupval 0 0 ; m
[2] getupval 1 1 ; n
[3] return 0 3
[4] return 0 1
; end of function

[1] closure 1 0 ; 2 upvalues
[2] getupval 0 0 ; m
[3] move 0 0
[4] setglobal 1 0 ; q
[5] return 0 1
; end of function

[1] closure 1 0 ; 1 upvalues
[2] move 0 0
[3] setglobal 1 0 ; p
[4] return 0 1
; end of function

```

First, look at the top-level function and the level 2 function – there is one upvalue, **m**. In the top-level function, the closure in line [1] has one more instruction following it (the MOVE), for the upvalue **m**. This is similar to the previous example.

Next, compare the level 2 function and the level 3 function – now there are two upvalues, **m** and **n**. The **m** upvalue is found 2 levels up. In the level 2 function, the closure in line [1] has two instructions following it. The first is for upvalue number 0 (**m**) – it uses GETUPVAL to indicate that the upvalue is one or more level lower down. The second is for upvalue number 1 (**n**) – it uses MOVE which indicate that the upvalue is in the same level as the CLOSURE instruction. For both of these pseudo-instructions, the B field is used to point either to the upvalue or local in question. The Lua virtual machine uses this information (CLOSURE information and upvalue lists) to manage upvalues; for the programmer, upvalues just works.

The last instruction to be covered in this guide, CLOSE, also deals with upvalues:

CLOSE **A** close all variables in the stack up to (\geq) R(A)

Closes all local variables in the stack from register R(A) onwards. This instruction is only generated if there is an upvalue present within those local variables. It has no effect if a local isn't used as an upvalue.

If a local is used as an upvalue, then the local variable need to be placed somewhere, otherwise it will go out of scope and disappear when a lexical block enclosing the local variable ends. CLOSE performs this operation for all affected local variables for **do end** blocks or loop blocks. RETURN also does an implicit CLOSE when a function returns.

It is easier to understand CLOSE with an example:

```
>do \  
>> local p,q \  
>> r = function() return p,q end \  
>>end  
; function [0] definition (level 1)  
; 0 upvalues, 0 params, 3 stacks  
.function 0 0 2 3  
.local "p" ; 0  
.local "q" ; 1  
.const "r" ; 0  
  
; function [0] definition (level 2)  
; 2 upvalues, 0 params, 2 stacks  
.function 2 0 0 2  
.upvalue "p" ; 0  
.upvalue "q" ; 1  
[1] getupval 0 0 ; p  
[2] getupval 1 1 ; q  
[3] return 0 3  
[4] return 0 1  
; end of function  
  
[1] closure 2 0 ; 2 upvalues  
[2] move 0 0  
[3] move 0 1  
[4] setglobal 2 0 ; r  
[5] close 0  
[6] return 0 1  
; end of function
```

p and **q** are local to the **do end** block, and they are upvalues as well. The global **r** is assigned an anonymous function that has **p** and **q** as upvalues. When **p** and **q** go out of scope at the end of the **do end** block, both variables have to be put somewhere because they are part of the environment of the function instantiated in **r**. This is where the CLOSE instruction comes in.

In the top-level function, the CLOSE in line [5] makes the virtual machine find all affected locals (they have to be open upvalues,) take them out of the stack, and place them in a safe place so that they do not disappear when the block or function goes out of scope. A RETURN instruction does an implicit CLOSE so the latter won't appear very often in listings.

Here is another example which illustrates a rather subtle point with CLOSE (thanks to Rici Lake for this nugget):

```

>do \
>> local p \
>> while true do \
>>   q = function() return p end \
>>   break \
>> end \
>>end
; function [0] definition (level 1)
; 0 upvalues, 0 params, 2 stacks
.function 0 0 2 2
.local "p" ; 0
.const "q" ; 0

; function [0] definition (level 2)
; 1 upvalues, 0 params, 2 stacks
.function 1 0 0 2
.upvalue "p" ; 0
[1] getupval 0 0 ; p
[2] return 0 2
[3] return 0 1
; end of function

[1] closure 1 0 ; 1 upvalues
[2] move 0 0
[3] setglobal 1 0 ; q
[4] jmp 1 ; to [6]
[5] jmp -5 ; to [1]
[6] close 0
[7] return 0 1
; end of function

```

In the above example, a function is instantiated within a loop. In real-world code, a loop may instantiate a number of such functions. Each of these functions will have its own **p** upvalue. The subtle point is that the **break** (the JMP on line [4]) does not jump to the RETURN instruction in line [7]; instead it reaches the CLOSE instruction on line [6]. Whether or not execution exits a loop normally or through a **break**, the code within the loop may have caused the instantiation of one or more functions and their associated upvalues. Thus the enclosing **do end** block must execute its CLOSE instruction; if we always remember to associate the CLOSE with the **do end** block, there will be no confusion.

CLOSE also appears when **for** loops are used in the same manner. When using loop indices or loop iterators as upvalues to instantiate functions, each instantiation will have its own unique upvalue. This is the expected behaviour in Lua 5.1 if loop indices or iterators are to be considered as locals to the loop body. Previously, Lua 5.0.2 considers loop indices or iterators to be local to a block enclosing the entire loop, and instantiation of multiple functions only results in a single upvalue shared between the functions. Please see the section on loop instructions for sample code that illustrates this behaviour.

15 Comparing Lua 5.0.2 and Lua 5.1

The following is list of changes to the Lua virtual machine instructions from version 5.0.2 to version 5.1. This list is *non-exhaustive*, only changes noted during the writing of this guide are listed. For the details, please read the relevant sections. If you are not familiar with Lua 5.0.2 virtual machine instructions, please read the older Lua 5.0.2 version of this guide.

- Number of opcodes increased from 35 to 38.
- Operand fields rearranged, from A|B|C|Opcode to B|C|A|Opcode. Bx and sBx fields rearranged in the same way as well.
- Maximum number of parameters per function is no longer limited to 100. It is now limited by the maximum number of locals per function, which is 200.
- Maximum number of upvalues per function increased to 60. Some of these limits have their names changed.
- Opcodes renamed: TEST has been renamed to TESTSET
- Opcodes deleted: TFORPREP, SETLISTO
- Opcodes added: MOD, LEN, TEST, VARARG, FORPREP
- Also, some opcodes' functionality have been changed. The numerical values of some opcodes have changed as well.
- Major changes to the binary chunk header. It now has a fixed size and the loader no longer accepts chunks with a different endianness.
- A format version byte has been added.
- Operand width bytes have been deleted.
- lua_Number encoding in the header has been simplified.
- For a function prototype header, a last line defined has been added. The is_vararg flag has changed considerably; it now has 3 fields.
- For a function prototype, debug data has been pushed to the end, while the code list has been brought to the front. The list of constants can have LUA_TBOOLEAN.
- For RK(B) or RK(C) operands, an MSB flag is used instead of a biasing number to differentiate registers and constants.
- LOADNILs at the start of a function are now optimized away.
- Limited constant folding is performed for arithmetic instructions, namely: ADD, SUB, MUL, DIV, POW, MOD and UNM.
- The MOD instruction is new.
- The LEN instruction is new.
- The VARARG instruction is new.
- What used to be TEST in 5.0.2 is now TESTSET in 5.1.
- The TEST instruction is new.
- The FORPREP instruction is new.
- FORLOOP behaviour has changed.
- The semantics of the loop index for FORLOOP has changed.
- TFORLOOP behaviour has changed.
- TFORPREP has been deleted. Lua 5.1 no longer supports old-style generic loops.
- The semantics of loop iterators for TFORLOOP has changed.
- The limit to the complexity of **while** conditions has been removed.
- The encoding of sizes for NEWTABLE has changed.
- SETLIST behaviour has changed.
- SETLISTO has been deleted. Its functionality has been merged into SETLIST.

16 Digging Deeper

For studying larger snippets of Lua code and its disassembly, you can try ChunkSpy's various disassembly functions. Both `vmmerge5` and `ChunkSpy` can merge source code lines into a disassembly listing. `ChunkSpy` can provide more detail, because it processes every bit of a binary chunk.

A good way of studying how any instruction functions is to find where its opcode appears in the Lua sources. For example, to see what `MOVE` does, look for `OP_MOVE` in `lparser.c` (the parser), `lcode.c` (the code generator) and `lvm.c` (the virtual machine.) From the code implementing `OP_MOVE`, you can then move deeper into the code by following function calls. I found this approach (bottoms up, following the execution path from generated opcodes to the functions that performs code generation) is a little easier than following the recursive descent parser's call graph. Once you have lots of little pictures, the big picture will form on its own.

I hope you have enjoyed, as I did, poking your way through the internal organs of this Lua thingy. Now that the Lua internals seem less magical and more practical, I look forward to some Dr Frankenstein experiments with my newfound knowledge...

17 Acknowledgements

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18 ChangeLog & ToDos

Older changes can be found in the Lua 5.0.2 version of this document.

Changes:

20060313 Initial public release, adapted from the Lua 5.0.2 version of the document.
Thanks to Rici Lake for info about the semantics of **for** loops in Lua 5.1.