Programming in Lua – The Lua Implementation

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Navigating the source

- The source code for Lua 5.2 is online at http://www.lua.org/source/5.2/
- *Includes* lists the three include files that external libraries use, plus `luaconf.h`, for compile-time configuratio of Lua
- *Core* lists the files that implement the Lua compiler and virtual machine
- *Libraries* is the code for the built-in functions and modules of the standard library, all implemented in terms of the C API
- *Interpreter* is actually just the REPL, the hard work is done by the core; the REPL just uses API functions!
- *Compiler* is also just a shell around the actual compiler that is in the core

A quick tour of the core

- `lapi.c` implements the C API (functions with `lua_` prefix); the `luaL_` API functions are actually in `lauxlib.c`!
- `lobject.h` has the representation of Lua values
- `lstate.h` has the (internal) representation of Lua states, private to the core
- `lopcodes.h` has the instruction format and the list of instructions for the virtual machine
- `lvm.c` is the core of the virtual machine, with its execution loop (in `luaV_execute`) and some support functions

A quick tour of the core (2)

- `ldo.c` implements function calls and the management of the call stack and the value stack, as well as error handling
- `lstring.c` manages the “string table”, where Lua keeps a canonical copy of each string; the actual string values are just pointers to entries in this table
- `ltable.c` is the implementation of tables, and has the logic for handling the table’s array and hash parts, and resizing
- `ltm.c` has a few functions to fetch metamethods (they were called *tag methods* prior to Lua 5.0)
- `lfunc.c` has a few functions to handle prototypes (the code for a function) and closures

A quick tour of the core (3)

- `ldebug.c` has the functions of the debug API, and their support functions
- `lgc.c` is the *garbage collector*, managing the memory used by Lua and freeing memory when it is not used anymore
- `ldump.c` and `lundump.c` handle VM instruction serialization and deserialization
- `lparser.c` and `lcode.c` are the recursive descent parser and the code generator for the Lua compiler
- `llex.c` is the scanner for the compiler; the scanner and deserializer both use the stream interface in `lzio.c` to get the bytes they need

The Lua scanner

- Lua has a simple lexical structure, and uses a hand-written scanner
- The scanner itself has some complexity due to it having to interface with the stream interface, the memory manager, and the string table
- We do not actually need to change the source code for the scanner to do some simple changes
- We have some simple hooks into the scanner in the form of `lis*` macros that it uses to classify a byte as a digit, alphabetic, alphanumeric, or space character

UTF-8 identifiers

- We can use the hooks in to the scanner to add support for UTF-8 identifiers

- We just change the definitions of some of the macros in `lctype.h`:

```
/*all utf-8 chars are always alphabetic character (everthing higher then
  2^7 is always a valid char), end of stream (-1) is not valid */
#define lislalpha(c) (((0x80&c)||isalpha(c))&&c!=-1)
/*all utf-8 chars are always alphabetic character or numbers, end of
  stream (-1) is not valid*/
#define lislalnum(c) (((0x80&c)||isalnum(c))&&c!=-1)
```

```
function 提出反()
  local n = 0
  return function ()
           n = n + 1
           return n
         end
end

计数器 = 提出反()
print(计数器())   -- 1
print(计数器())   -- 2
print(计数器())   -- 3
```

The Lua parser

- Lua uses a hand-written recursive parser; basically, each grammar rule corresponds to a function in the parser, beginning with `statlist` for a list of statements

- But the parser is greatly complicated by the fact that the parser is generating code as it goes, instead of first building an intermediate representation

- The exception is the *expression parser*, a precedence climbing parser that generates an abstract syntax tree for expressions

- The code generator for expressions traverses this tree

Values

- Lua values are *tagged unions*: a structure containing a *tag* for the value (the type plus some bookkeeping information for the VM) and an union with fields for each kind of value:

```
union Value {
    GCObject *gc;     /* collectable objects */
    void *p;          /* light userdata */
    int b;            /* booleans */
    lua_CFunction f; /* light C functions */
    numfield          /* numbers */
};
```

- GCObjects are strings, tables, functions, threads, and userdata; all types that have memory managed by the Lua garbage collector

- Plus some internal values that the VM uses: upvalues and prototypes

GCObjects

- The common header is duplicated in all of the different GCObject parts, and is bookkeeping information for the garbage collector:

```
union GCObject {
    GCheader gch;  /* common header */
    union TString ts;
    union Udata u;
    union Closure cl;
    struct Table h;
    struct Proto p;
    struct UpVal uv;
    struct lua_State th;  /* thread */
};
```

- Notice that threads are just Lua states; the difference is that they have a link to, and share global variables with, their parent Lua state

Tables

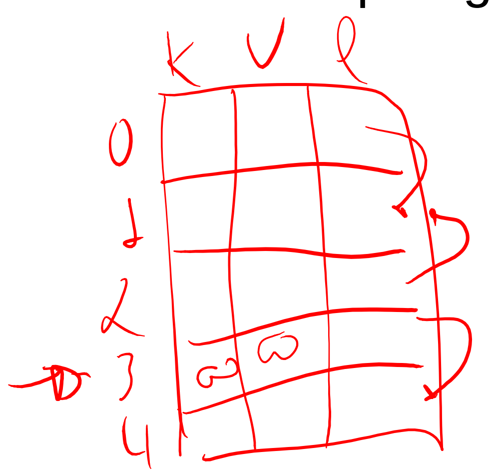
- Tables have an *array* part and a *hash* part (the array of nodes in node, below):

```
typedef struct Table {
    CommonHeader;
    lu_byte flags;  /* 1<<p means tagmethod(p) is not present */
    lu_byte lsizenode;  /* log2 of size of `node' array */
    struct Table *metatable;
    TValue *array;  /* array part */
    Node *node;
    Node *lastfree;  /* any free position is before this position */
    GCObject *gclist;
    int sizearray;  /* size of `array' array */
} Table;
```

- Notice that the fact that a metatable *must* be another table is fixed in the implementation

Tables – hash part

- Each node in the hash part has a *key*, a *value*, and a link that is used for collision resolution in the hash table
- Lua uses a has algorithm that can handle a close to full table quite well, so the hash table only grows when it runs out of space
- Each time the hash part grows it doubles in size



"foo" ⇒ 53 % 5 = 3

Tables – array part

- Lua tries to keep as many values with integer keys as it can in the *array* part of the table, without wasting much space
- Each time the table rehashes, Lua sets the array part to size n, where n:
  - Is a power of 2
  - Containts at least $n/2$ values in the interval $[1,n]$, that is, is at least half full
  - Has at least one value in $[n/2 + 1, n]$, that is, it is not wasting the upper half
- Rehashing is an expensive operation, but the doubling in size of each part makes it infrequent

Virtual Machine

- Lua has a *register-based* virtual machine

- Each Lua function gets a number of *virtual registers*; it will have one for each argument, usually one for each local variable, and how many it may need to keep temporary values

- Makes for very compact code, and a large number of virtual registers simplifies code generation, there is no need for “register allocation” in the Lua compiler

- Instructions can take up to three registers, although some of them operate on *ranges* of registers

- The second and third operands can also be *constants,* which are indexes on an array of literals that each function has

Examples

- In the instructions below, registers are given by R*n*, where *n* is the register number, and numbers are indexes in the array of constants:

```
ADD R0 R0 3
DIV R0 3 R0
GETTABLE R0 R1 4
SETTABLE R0 R1 4
```

< 256

→ order is backwards

- If we assume that `R0` is the local variable `a`, `R1` is the local variable `t`, constant `3` is the number `1`, and constant `4` is the string “`x`”, then the above corresponds to the Lua code:

```
a = a + 1
a = 1 / a
a = t.x
t.x = a
```

- Sometimes the second and third operands are neither registers nor constants; the “register” is just an integer: `NEWTABLE R1 R0 R0 ; t = {}`

“Large” operands and tests

- A second instruction format takes just two operands, where the second can be a large number (usually for a jump offset, but it can also be an index in the array of literals):

```
LOADK R0 1000   ; assigns literal with index 1000 to the first register
JMP R0 -500     ; jumps backwards (ignores the first operand)
```

- Tests have a dummy first argument that is either R0 or R1 and gives the “polarity” of the test; R0 makes it skip the jump if the test succeeds, and R1 makes it skip the jump if the test fails:

```
LT  R0 R0 3         ; if a < 1 then a = a - 1 else a = a + 1 end
JMP R0 2            ; jumps 3 instructions ahead
SUB R0 R0 3
JMP R0 1            ; jumps 2 instructions ahead
ADD R0 R0 3
```

Protypes and closures

- The Lua compiler produces a *prototype* for each function
- The prototype has the instructions for the function, and metadata used by the virtual machine:
  - How many registers the function uses
  - In which source file and at which line the function comes from
  - Which local variables from outside its scope the function uses
- A function declaration becomes a `CLOSURE` instruction, which creates a *closure* from the prototype

Creating a closure

- When the virtual machine creates a closure, it uses the list of external variables to fill the closure's *display*

- The display is an array of *upvalues*, one for each external variable the function uses

- Upvalues may be *open* or *closed*; an open upvalue means that the variable is still in scope, and points the the location of the variable in the *stack*

- A closed upvalue means the variable has gone out of scope, and now holds the value the variable had

Closures and sharing

- Two or more closures may share a local variable, so each variable must have at most just one open upvalue pointing to it
- Lua keeps the implementation simple by maitaining a linked list of open upvalues, and searching this list each time it needs to create a closure
- If no open upvalue for a variable is found, Lua creates one and adds it to the list
- When an upvalue is closed it is removed from the list
- Each time a block goes out of scope the Lua compiler generates code to close any open upvalues in it, using the first argument of the `JMP` instruction

Lua assembler/disassembler

- `luaa.lua` and `luad.lua` are two Lua scripts that let us experiment with programming directly to the Lua VM
- One is an *assembler*, to turn textual instructions into executable code, and the other is a *disassembler*, to turn Lua code into textual instructions:

```
$ lua luad.lua -o test.asm test.lua
$ cat test.asm
function main(0):
        .upvalue _ENV, 1, 0
        1       [1]     LOADK           R0, 5
        2       [2]     LT              0, R0, 1
        3       [2]     JMP             R0, 6
        4       [3]     SUB             R0, R0, 1
        5       [3]     JMP             R0, 7
        6       [5]     ADD             R0, R0, 1
        7       [6]     RETURN          R0, 1
```

```lua
-- test.lua
local a = 5
if a < 1 then
  a = a - 1
else
  a = a + 1
end
```

Assembler syntax

- Each function declaration in the assembler listing actually declares a *prototype*; the `main` function is the main chunk of the script, and in parentheses we have the number of explicit arguments that the function takes (not counting `...`)

- The disassembler embeds literals directly in instructions that can have them as operands, and fills out the necessary literal array

- In the same way, the assembler figures out how many registers the function uses

- Finally, jumps are *absolute* instead of relative, and can be done to symbolic *labels*, the assembler turns both into offsets

Upvalues

- We have to list the upvalues that the closure will have with `.upvalue` clauses; we give the name of the upvalue, 0 if it comes from an upvalue of the enclosing function, or 1 if it comes from a register, and either the upvalue index in the enclosing function's closure or the register

```
function counter(0):
  loadk r0, 0
  closure r1, anon
  return r1, 2

function anon(0):
  .upvalue n, 1, 0
  getupval r0, 0
  add r0, r0, 1
  setupval 0, r0      ; yes, this is backwards!
  getupval 0, r0
  return r0, 2
```

```lua
local function counter()
  local n = 0
  return function ()
           n = n + 1
           return n
         end
end
```

Globals

- Global variables are actually fields in a table usually stored in upvalue 0:

```
function main(0):
  .upvalue _ENV, 1, 0
  closure r0, hello
  settabup 0, "n", 5
  move r1, r0
  call r1, 1, 1
  return r0, 1

function hello(0):
  .upvalue _ENV, 0, 0
  gettabup r0, 0, "n"
  add r0, r0, 1
  settabup 0, "n", r0
  gettabup r0, 0, "print"
  loadk r1, "hello world"
  gettabup r2, 0, "n"
  call r0, 3, 1
  return r0, 1
```

```lua
local function hello()
  n = n + 1
  print("hello world", n)
end

n = 5
hello()
```

Quiz

- What Lua code corresponds to the instructions below, assuming that `R0` is the local variable t, `R1` the local variable l and `R2` the local variable `x`?

```
NEWTABLE R0 R0 R0
SETTABLE R0 R1 R2
GETTABLE R1 R0 R1
```

t = {}

l[x] = t

l = t[l]