The Implementation of Lua 5.0

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MAIN GOALS

- Portability
  - ANSI C and C++
  - avoid dark corners
- Simplicity
  - small size
- Efficiency

Values and Objects

- Values represent all Lua values
- Objects represent values that involve memory allocation
  - strings, tables, functions, heavy userdata, threads
- Representation of Values: tagged unions

```
typedef union {
  GCObject *gc;
  void *p;
  lua_Number n;
  int b;
} Value;
```

```
typedef struct lua_TValue {
  Value value;
  int tt
} TValue;
```

OBJECTS

- Pointed by field `GCObject *gc` in values
- Union with common head:

```
GCObject *next; lu_byte tt; lu_byte marked
```

- Redundant tag used by GC
- Strings are hibrid
  - Objects from an implementation point of view
  - Values from a semantics point of view

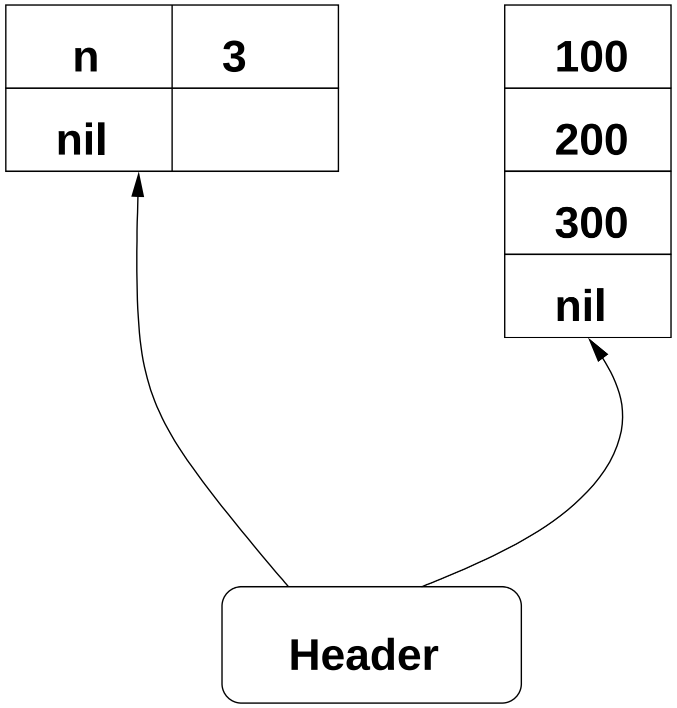
STRINGS

- Represented with explicit length

- *Internalized*
  - save space
  - save time for comparison/hashing
  - more expensive when creating strings

Implementation of Tables

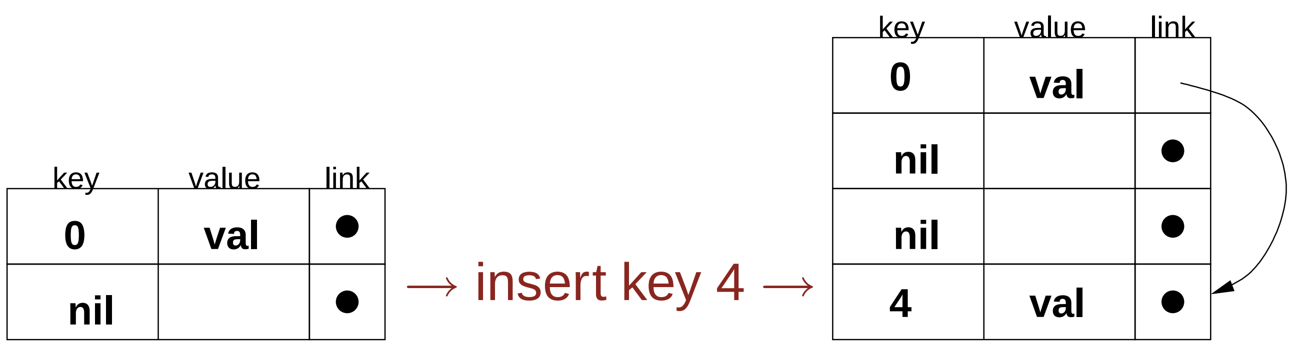
- Each table may have two parts, a “hash” part and an “array” part
- Example: `{n = 3; 100, 200, 300}`



TABLES: HASH PART

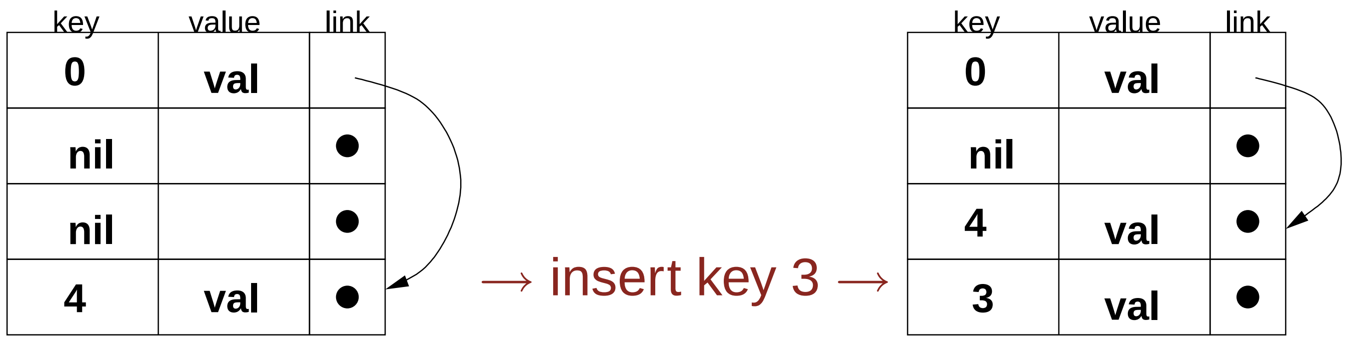
- Hashing with internal lists for collision resolution

- Run a *rehash* when table is full:



TABLES: HASH PART (2)

- Avoid secondary collisions, moving old elements when inserting new ones



TABLES: ARRAY PART

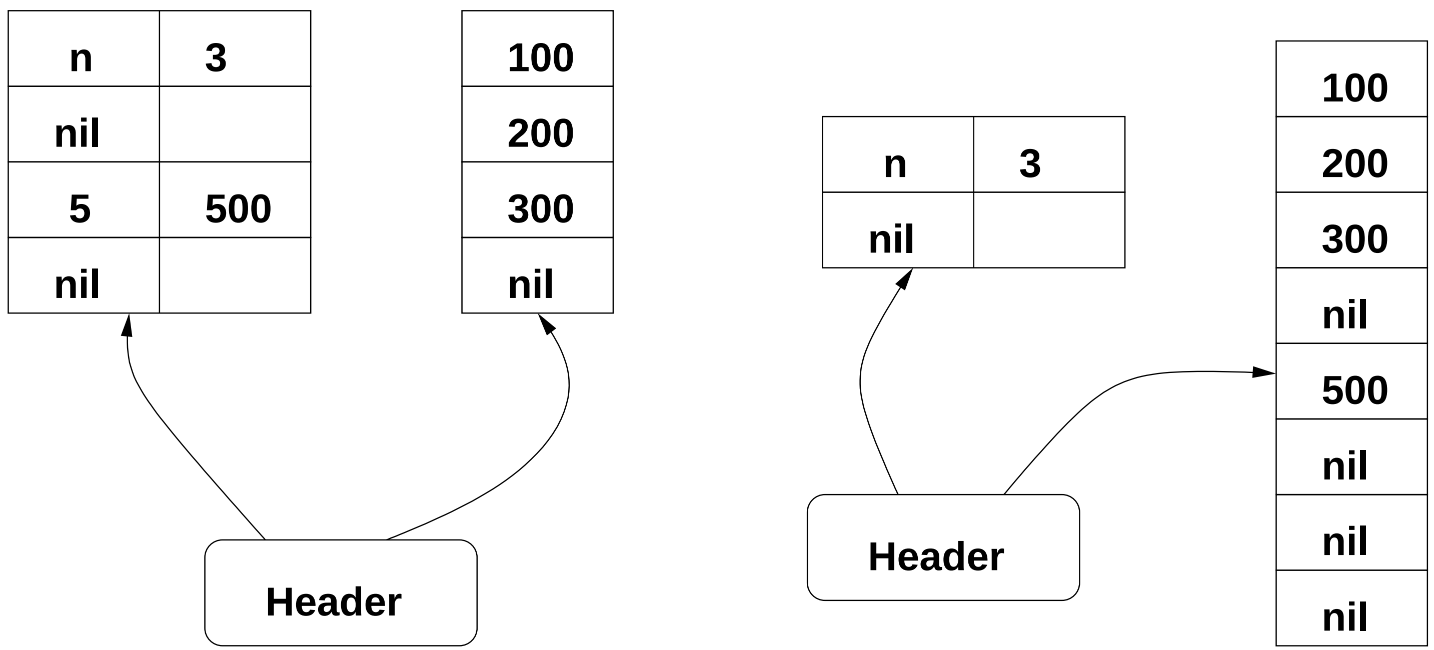
- Problem: how to distribute elements among the two parts of a table?
  - or: what is the best size for the array?

- Sparse arrays may waste lots of space
  - A table with a single element at index 10,000 should not have 10,000 elements

TABLES: ARRAY PART (2)

- How should next table behave when we try to insert index 5?

```
a = {n = 3; 100, 200, 300}; a[5] = 500
```



Computing the Size of a Table

- When a table rehashes, it recomputes the size of both its parts
- The array part has size N, where N satisfies the following rules:
  - N is a power of 2
  - the table contains at least $N/2$ integer keys in the interval $[1, N]$
  - the table has at least one integer key in the interval $[N/2 + 1, N]$
- Algorithm is $O(n)$, where n is the total number of elements in the table

Computing the Size of a Table (2)

- Basic algorithm: to build an array where a_i is the number of integer keys in the interval $(2^{i-1}, 2^i]$
  - array needs only 32 entries

- Easy task, given a fast algorithm to compute $\lfloor \log_2 x \rfloor$
  - the index of the highest one bit in x

COMPUTING THE SIZE OF A TABLE (3)

- Now, all we have to do is to traverse the array:

```
total = 0
bestsize = 0
for i=0,32 do
  if a[i] > 0 then
    total += a[i]
    if total >= 2^(i-1) then
      bestsize = i
    end
  end
end
```

VIRTUAL MACHINE

- Most virtual machines use a stack model
  - heritage from Pascal *p-code*, followed by Java, etc.
- Example in Lua 4.0:

```
 while a<lim do a=a+1 end

3   GETLOCAL    0       ; a
4   GETLOCAL    1       ; lim
5   JMPGE       4       ; to 10
6   GETLOCAL    0       ; a
7   ADDI        1
8   SETLOCAL    0       ; a
9   JMP        -7       ; to 3
```

Another Model for Virtual Machines

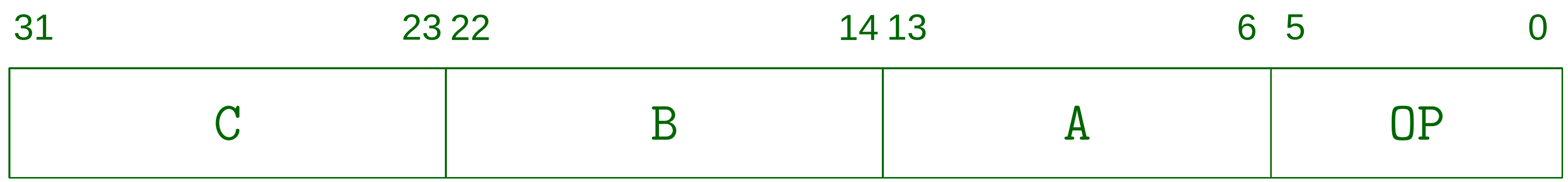
- Stack-machine instructions are too low level
- Interpreters add high overhead per instruction
- Register machines allow more powerful instructions

```
ADD  0  0  [1]    ; a=a+1
```

- Overhead to decode more complex instruction is compensated by fewer instructions
- "registers" for each function are allocated on the execution stack at activation time
  - large number of registers (up to 256) simplifies code generation

INSTRUCTION FORMATS

- Three-argument format, used for most operators



- All instructions have a 6-bit opcode
- Operand `A` refers to a register
- Operands `B` and `C` can refer to a register or a constant
  - a constant can be any Lua value, stored in an array of constants private to each function

INSTRUCTION EXAMPLES

```
ADD       0  0   259     ; a = a+1

DIV       0  259 0       ; a = 1/a

GETTABLE  0  1   260     ; a = t.x

SETTABLE  0  1   260     ; t.x = a
```

- assuming that the variable `a` is in register 0, `t` is in register 1, the number `1` is at index 3 in the array of constants, and the string `"x"` is at index 4.

INSTRUCTION FORMATS

- There is an alternative format for instructions that do not need three arguments or with arguments that do not fit in 9 bits
  - used for jumps, access to global variables, access to constants with indices greater than 256, etc.

31 … 14	13 … 6	5 … 0
Bx	A	OP

INSTRUCTION EXAMPLES

```
GETGLOBAL 0   260          ; a = x
SETGLOBAL 1   260          ; x = t
LT        0   259          ; a < 1 ?
JMP       *   13
```

- assuming that the variable `a` is in register 0, `t` is in register 1, the number `1` is at index 3 in the array of constants, and the string `"x"` is at index 4.
- conceptually, `LT` skips the next instruction (always a jump) if the test fails. In the current implementation, it does the jump if the test succeeds.
- jumps interpret the `Bx` field as a signed offset (in excess-2^{17})

Code Example

(all variables are local)

```
while i<lim do a[i] = 0 end
```

```
 -- Lua 4.0

2 GETLOCAL 2     ; i
3 GETLOCAL 1     ; lim
4 JMPGE    5     ; to 10
5 GETLOCAL 0     ; a
6 GETLOCAL 2     ; i
7 PUSHINT  0
8 SETTABLE
9 JMP      -8    ; to 2
```

```
 -- Lua 5.0

2 JMP      * 1      ; to 4
3 SETTABLE 0 2 256  ; a[i] = 0
4 LT       * 2 1    ; i < lim?
5 JMP      * -3     ; to 3
```

CLOSURES

- Lua has first-class functions with lexical scoping
- Variables in each function may have different scopes

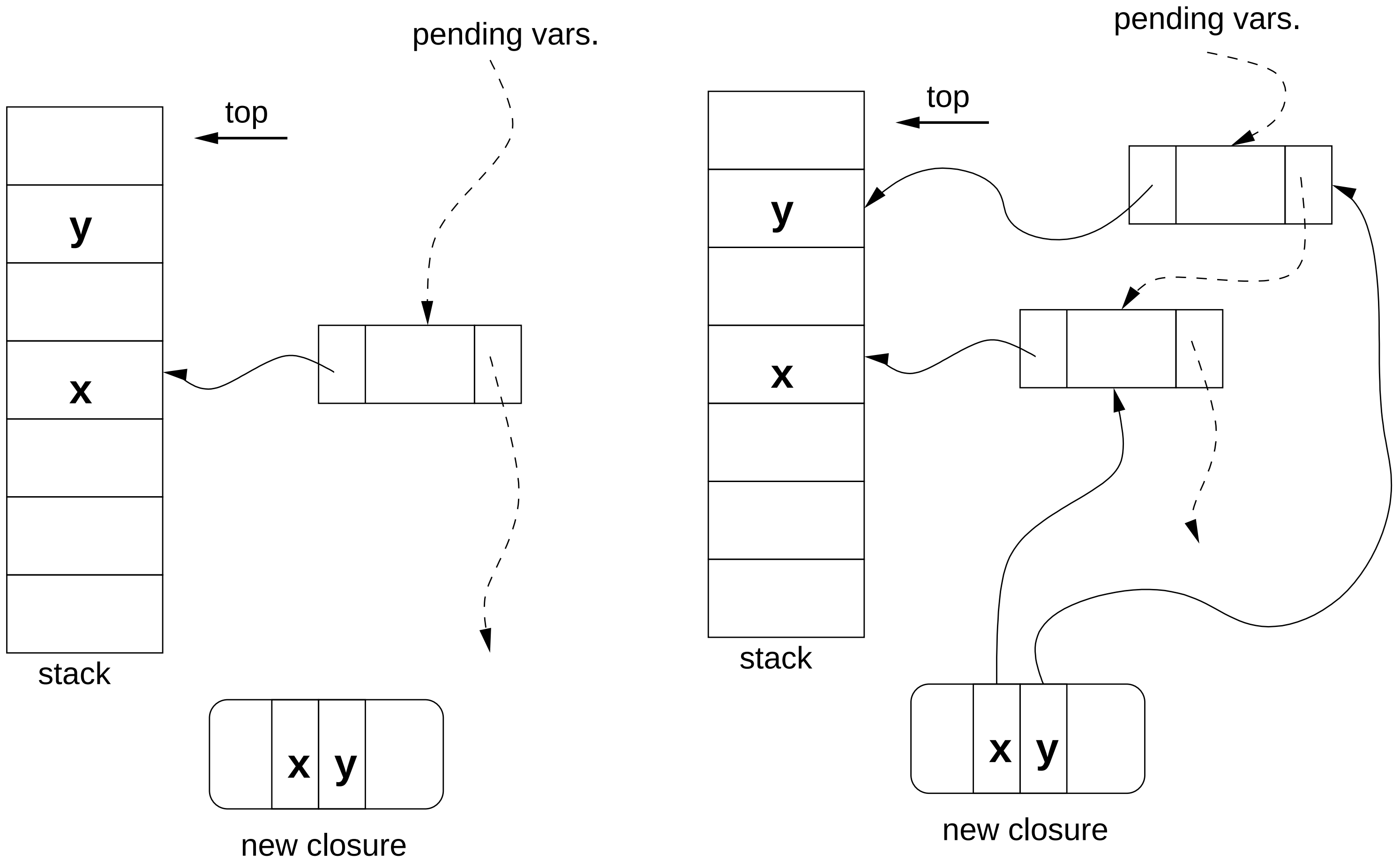
```
local a = 
local x = 0
for i = 1, N do
  local y = i
  a[i] = function (z) y=z; return x+y end
end
```

- Small implementation rules out complex algorithms
- One-pass compiler cannot know in advance whether a variable is used by a inner function
  - How to assign variables to the stack?

IMPLEMENTATION OF CLOSURES (1/4)

- All variables go to the stack
- Use of *upvalues* to represent external variables
- When a Closure is created, it searchs for an upvalue for each of its external variables
  - if upvalue not found, create a new one
  - search is fast, because lists are typically very short

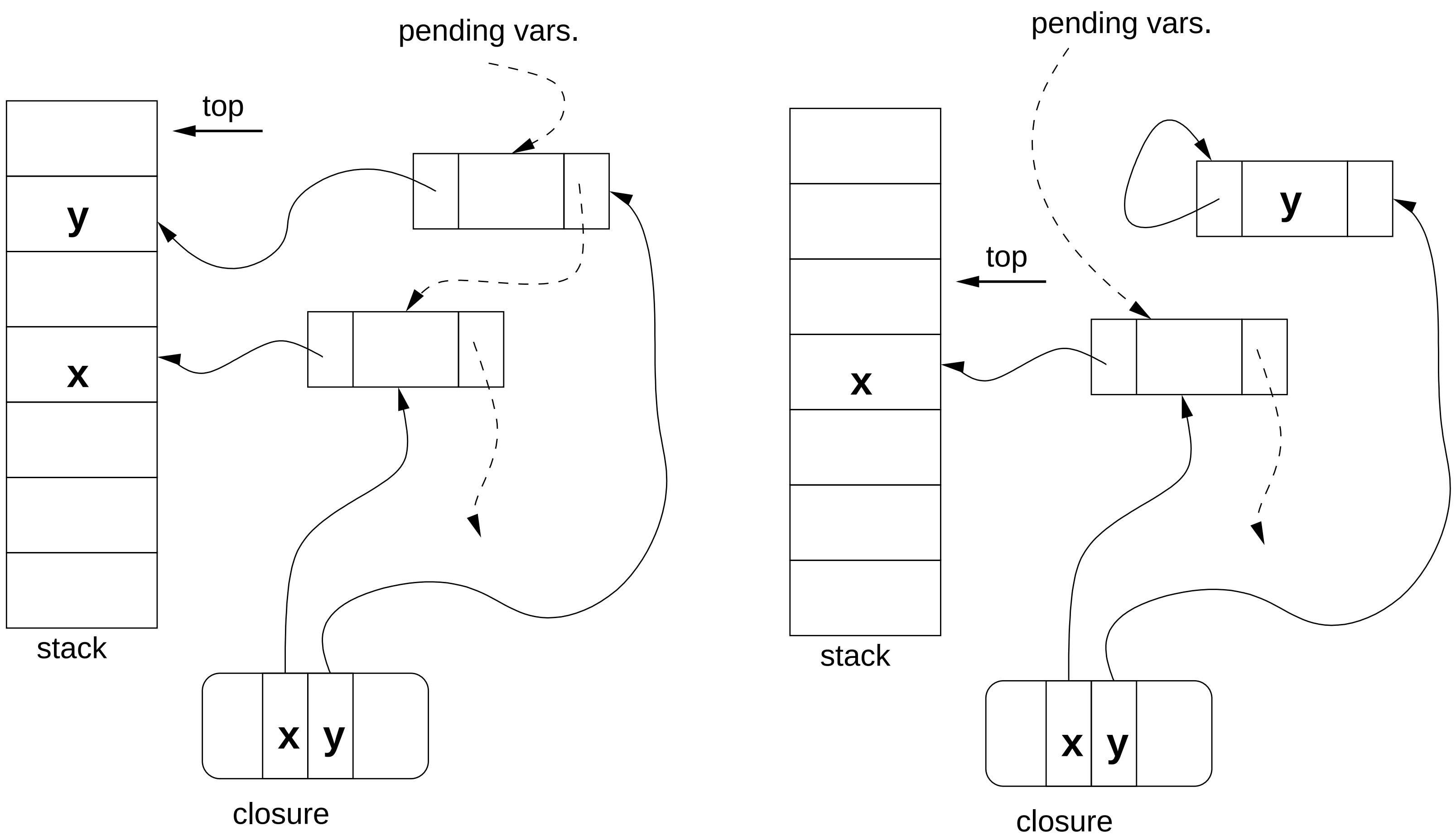
IMPLEMENTATION OF CLOSURES (2/4)



IMPLEMENTATION OF CLOSURES (3/4)

- All accesses to external variables are through a pointer in the upvalue
- When an upvalue in the stack goes out of scope, the upvalue is *closed*
  - upvalue is removed from list
  - the value is copied to an area in the upvalue itself
  - the upvalue points to itself

Implementation of Closures (4/4)



INCREMENTAL GARBAGE COLLECTOR

- Uses a three-color algorithm
  - white objects are not marked
  - grey objects are marked but not traversed
  - black objects are marked and traversed
- Main invariant: black objects never point to white objects
- Well known, but with several undocumented details

Three-Color Algorithm: Mark

- Mark root objects as grey
- At each step, traverses a grey object (turning it black) and mark new accessible objects as grey
- Stops when there are no more grey objects; white objects are garbage
- Write barrier detects when storing a white object into a black one
- Optimization: stacks are always grey
  - avoids barrier when writing to stacks

Three-Color Algorithm: Atomic Step

- Traverses stacks
- Separates dead userdata with finalizers
- Traverses them
- Clears weak tables
- Changes white objects to dead
  - trick: toggles between two whites

Three-Color Algorithm: Sweep

- Sweep all objects
- Collect dead objects
- Change black objects to white

Garbage-Collector Details

- Upvalues x dead threads
  - dead threads are not traversed in the atomic step but when alive they may have changed value pointed by an upvalue
  - because threads have no barrier, upvalue may point to dead object
- solution: traverse all open upvalues in the atomic step

GARBAGE-COLLECTOR DETAILS (2)

- Granularity
  - several tasks are atomic
  - seems to be no problem in real use
- Step size
  - how much to do at each step?
  - how to compare ?step size? across different phases?
- Collector speed
  - stops between steps and between collections

FINAL REMARKS

- Lexical scoping: no overhead for non users
- Virtual machine: good performance gains
  - plus potential gains with CSE optimizations
  - compiler for register-based machine is more complex
- Representation for tables
  - arrays save more than 50% memory
  - efficient representation both for dense and sparse arrays
- Incremental Garbage Collector