Function Calls in Real and Virtual Machines

- Function calls in real and virtual machines tend to be more complicated than interpreting function calls in high-level languages due to the fact that there is typically no notion of scope.
- We begin by studying function calls in our bytecode machine and then look at function calls on the Intel chip.

Exp2Bytecode

- In order to facilitate function calls on our bytecode machine we add the following:
    - A runtime stack and a ‘top of stack’ register
    - A ‘return value’ register
    - A set of instructions that manipulate the runtime stack
        - pushv -- push a value on the stack
        - popv -- pop a value off the stack
        - pushf -- push a stack frame
        - popf -- pop a stack frame
    - Instructions for calling and returning from functions
        - call -- jumps to function
        - return -- continues execution at the instruction after the call instruction

Exp2Bytecode

- We also introduce the idea of *indirect addressing* in order to access stack locations
- We let %tsx be the top of stack register, in order access the second to top element we write: %tsx[-1]
  - We can read the value, e.g.
    - store a %tsx[-1]
  - We can write a value to that location, e.g.
    - store %tsx[-1] 3

Exp2Bytecode

```
prog : instr_list

instr_list : labeled_instr instr_list
           | empty

labeled_instr : label_def instr

label_def : NAME ':'
          | empty

instr : PRINT opt_string exp ';'
      | INPUT opt_string storable ';'
      | STORE storable exp ';'
      | JUMPT exp label ';'
      | JUMPF exp label ';'
      | JUMP label ';'
      | CALL label ';'
      | RETURN ';'
      | PUSHV exp ';'
      | POPV opt_storable ';'
      | PUSHF size ';'
      | POPF size ';'
      | STOP ';'
      | NOOP ';'

opt_string : STRING
           | empty

opt_storable : storable
             | empty

size : exp

label : NAME
```

```
exp : '+' exp exp
    | '-' exp exp
    | '-' exp
    | '*' exp exp
    | '/' exp exp
    | EQ exp exp
    | LE exp exp
    | '!' exp
    | '(' exp ')'
    | storable
    | NUMBER

storable : var
         | RVX
         | TSX opt_offset

opt_offset : '[' offset ']'
           | empty

offset : exp

var : NAME
```

exp2bytecode_gram.py

Exp2Bytecode

exp2bytecode_lex.py

```python
# Lexer for Exp2bytecode

from ply import lex

reserved = {
    'print' : 'PRINT',
    'input' : 'INPUT',
    'store' : 'STORE',
    'jumpT' : 'JUMPT',
    'jumpF' : 'JUMPF',
    'jump'  : 'JUMP',
    'call'  : 'CALL',
    'return': 'RETURN',
    'pushv' : 'PUSHV',
    'popv'  : 'POPV',
    'pushf' : 'PUSHF',
    'popf'  : 'POPF',
    'stop'  : 'STOP',
    'noop'  : 'NOOP'
}

literals = ['!',':',';','+','-','*','/','(',')','[',']']

tokens = ['NAME','NUMBER','EQ','LE','RVX','TSX','STRING'] +\
    list(reserved.values())

t_EQ = '=='
t_LE = '<='
t_RVX = '%rvx'
t_TSX = '%tsx'
t_ignore = ' \t'
```

```python
def t_NAME(t):
    r'[a-zA-Z_][a-zA-Z_0-9]*'
    t.type = reserved.get(t.value,'NAME')    # Check for reserved words
    return t

def t_NUMBER(t):
    r'[0-9]+'
    t.value = int(t.value)
    return t

def t_STRING(t):
    r'\".*\"'
    t.value = t.value[1:-1] # strip the quotes
    return t

def t_NEWLINE(t):
    r'\n'
    pass

def t_COMMENT(t):
    r'\#.*'
    pass

def t_error(t):
    print("Illegal character %s" % t.value[0])
    t.lexer.skip(1)

# build the lexer
lexer = lex.lex(debug=0)
```

Calling Convention

- In order to execute function calls the calling function and the called function have to agree upon how parameters are passed and return values are returned -- this is called the *calling convention*.
- Our calling convention is fairly straight forward:
  - Parameters are passed by pushing them on the stack in reverse order
  - Return values are returned in the %rvx register
  - Each function is responsible for maintaining the integrity of the runtime stack, that is, if it pushed something on the stack then it has to also remove it (this is not true for all calling conventions)

Example Program

- The first program we consider is written in Cuppa3 as follows:

```
declare add(a,b) {
  return a+b
}

declare x = 3;
declare y = 2;
put add(x,y);
```

Example Program

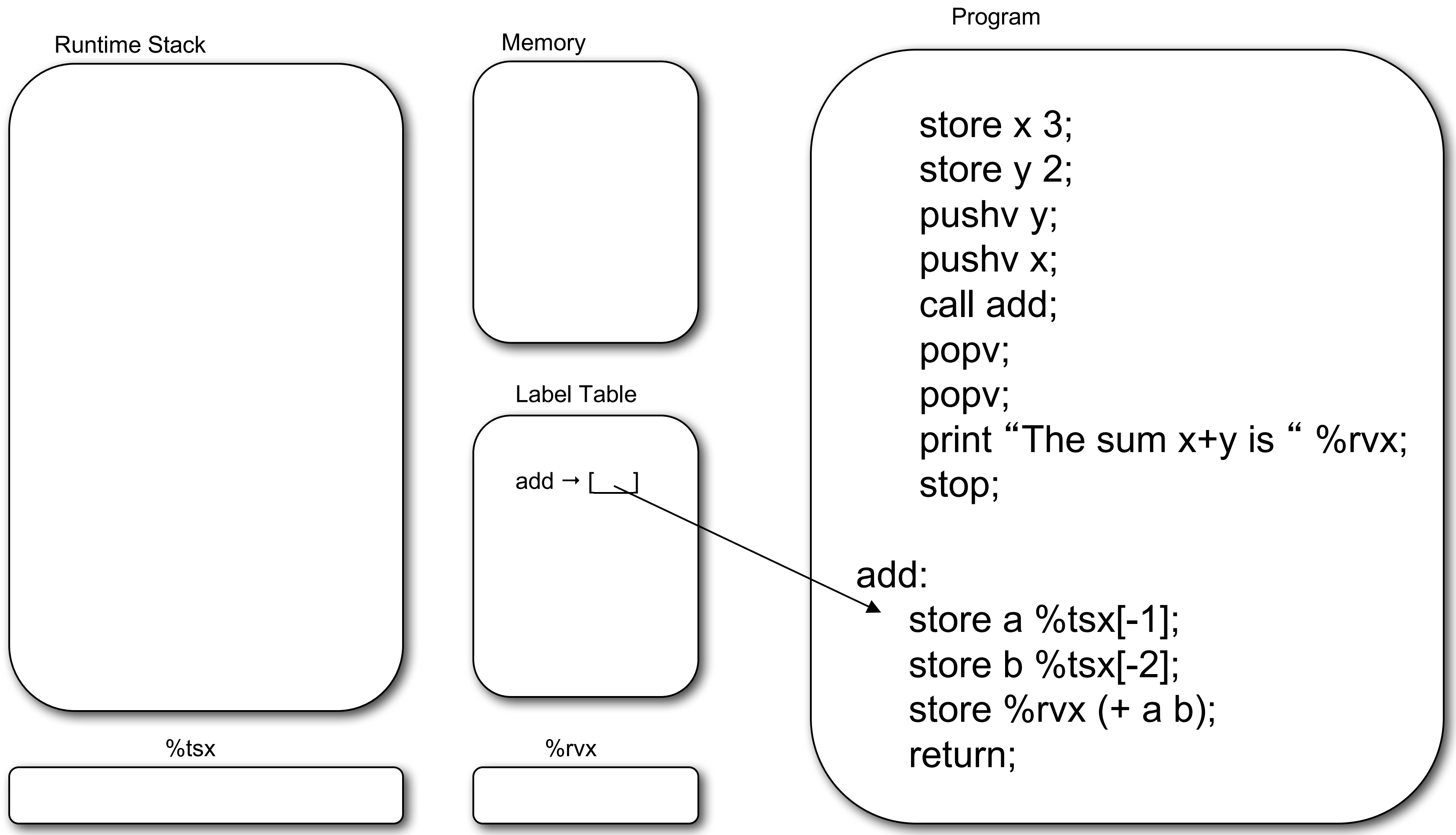
```
declare add(a,b) {
  return a+b
}

declare x = 3;
declare y = 2;
put add(x,y);
```

```
     store x 3;
     store y 2;
     pushv y;                  # push second parameter onto stack
     pushv x;                  # push first parameter onto stack
     call add;                 # push current address onto stack and jump to function
     popv;                     # pop first parameter
     popv;                     # pop second parameter
     print "The sum x+y is " %rvx;
     stop;

add:
    store a %tsx[-1];          # get value of first parameter
    store b %tsx[-2];          # get value of second parameter
    store %rvx (+ a b);        # store the sum in the 'return value register'
    return;                    # pop return address off stack and return to that address
```

Virtual Machine Design



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    pushv y;
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    call add;
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add:
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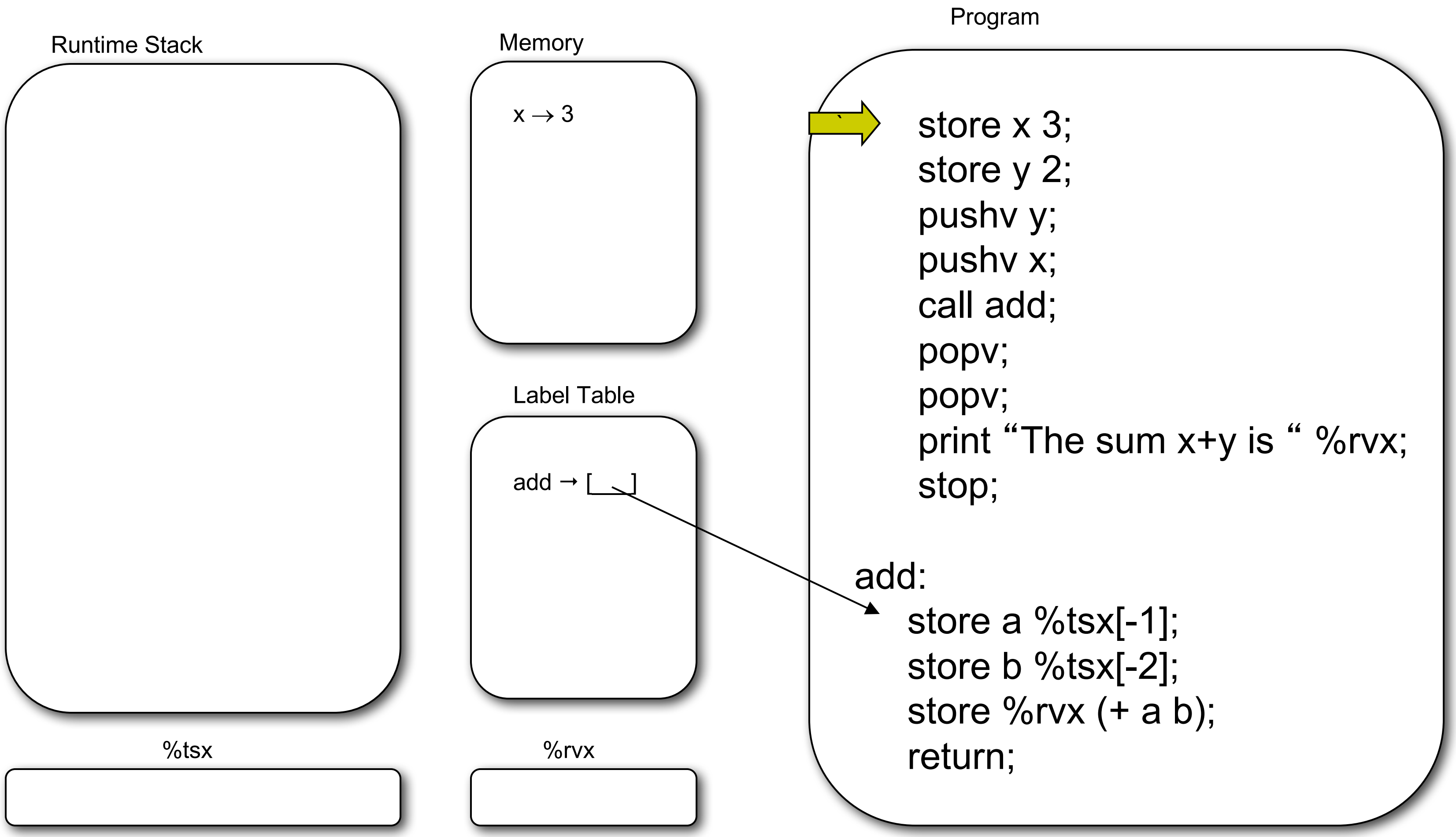
Virtual Machine Design



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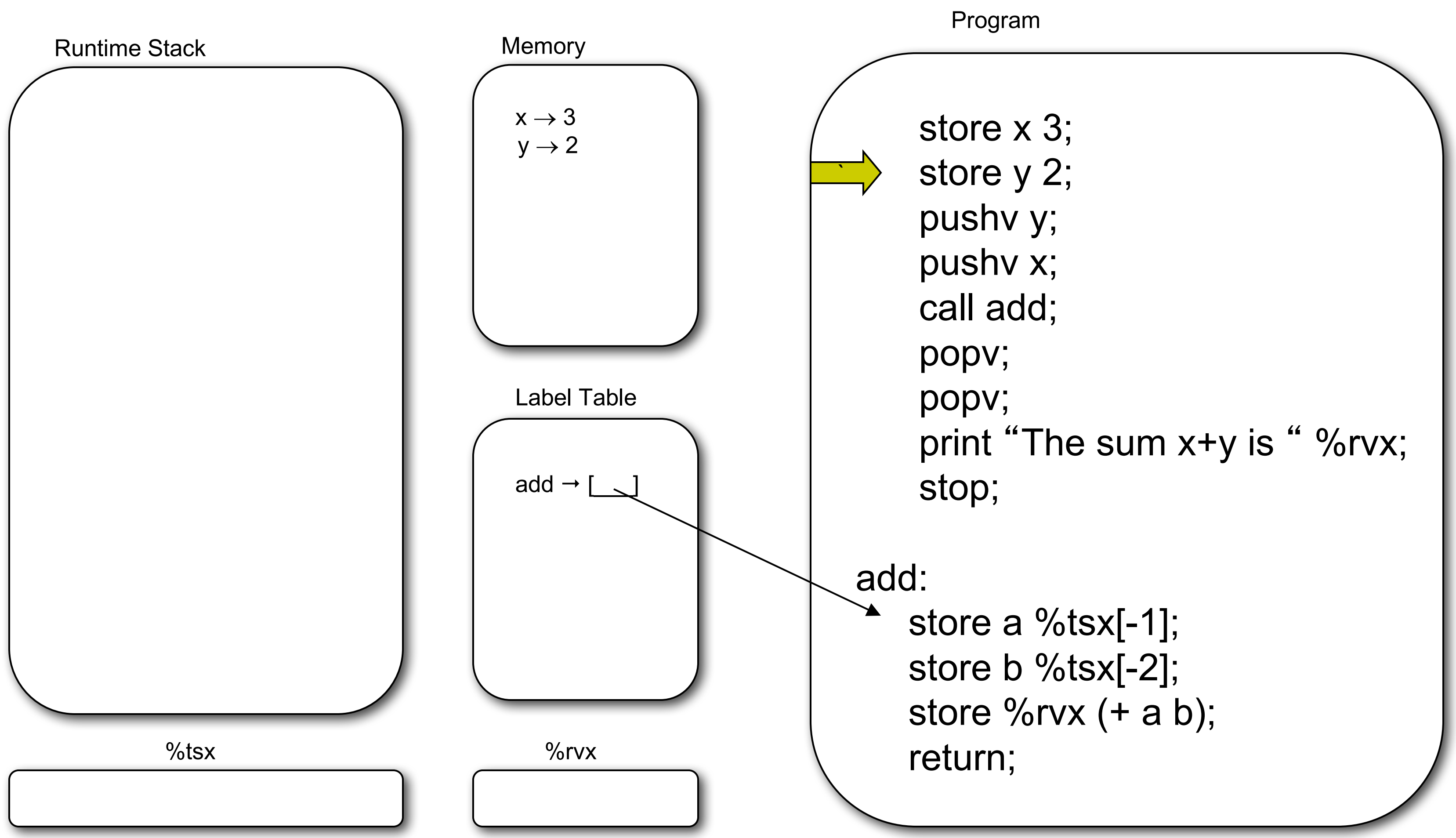

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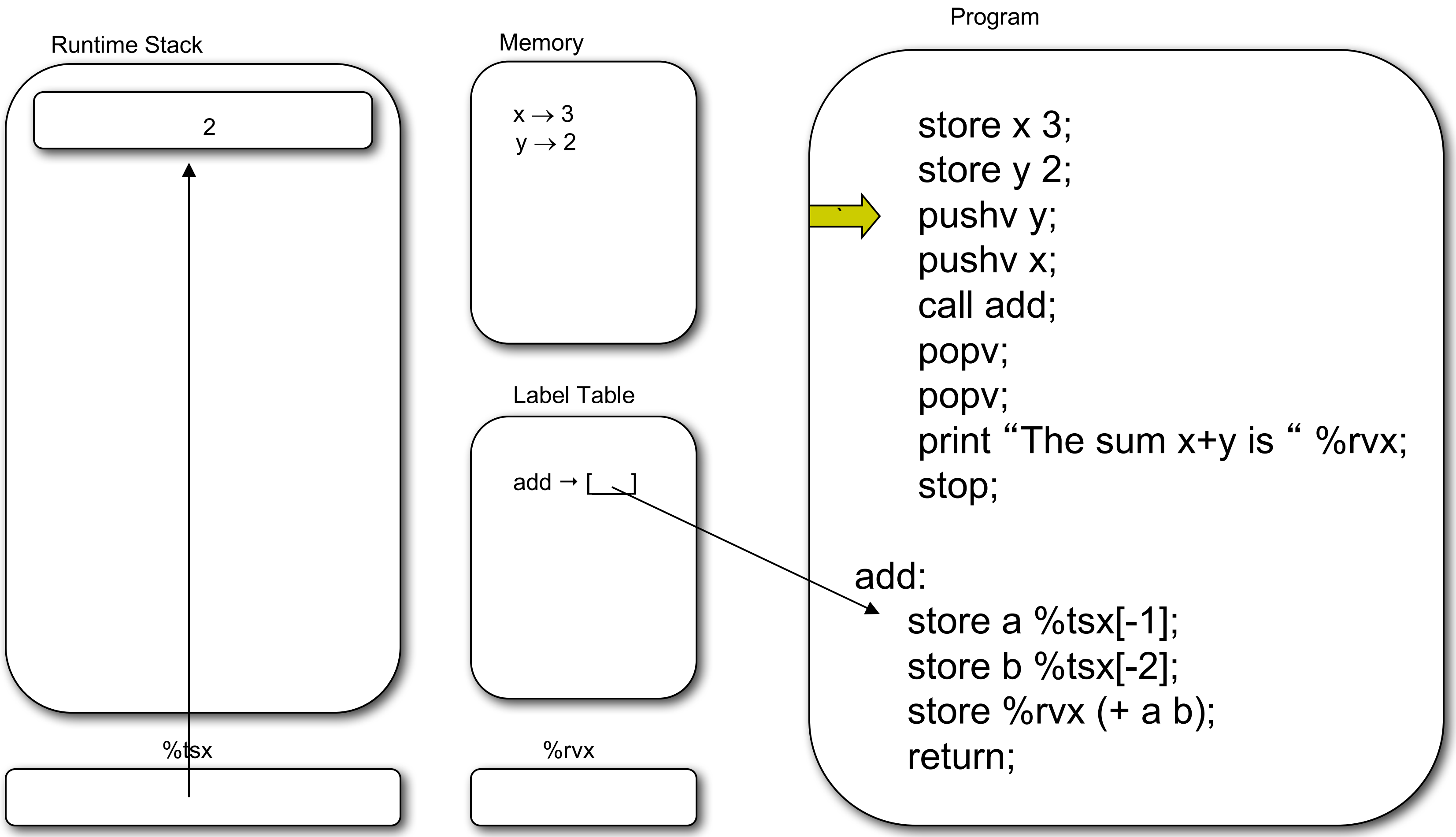

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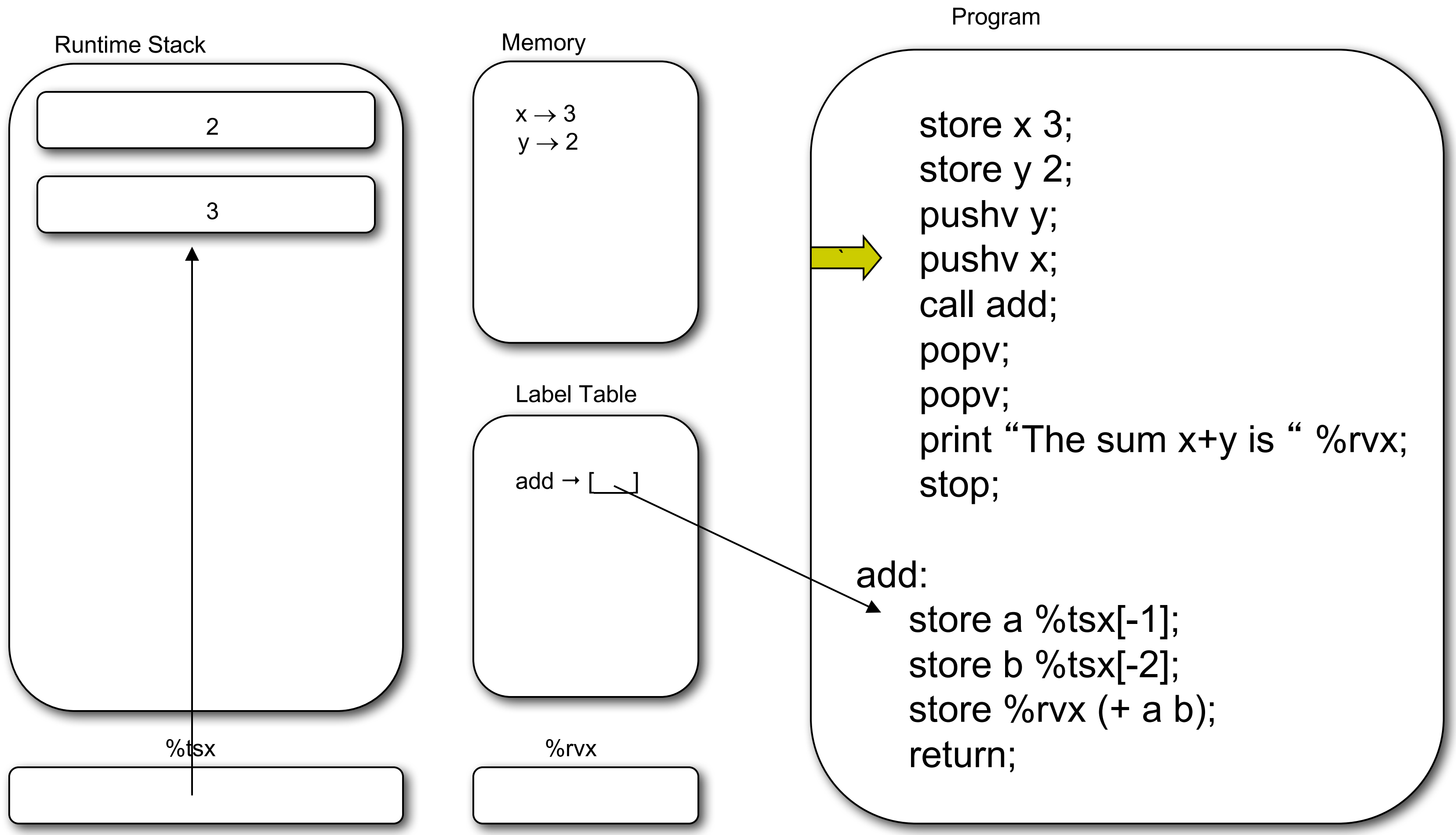

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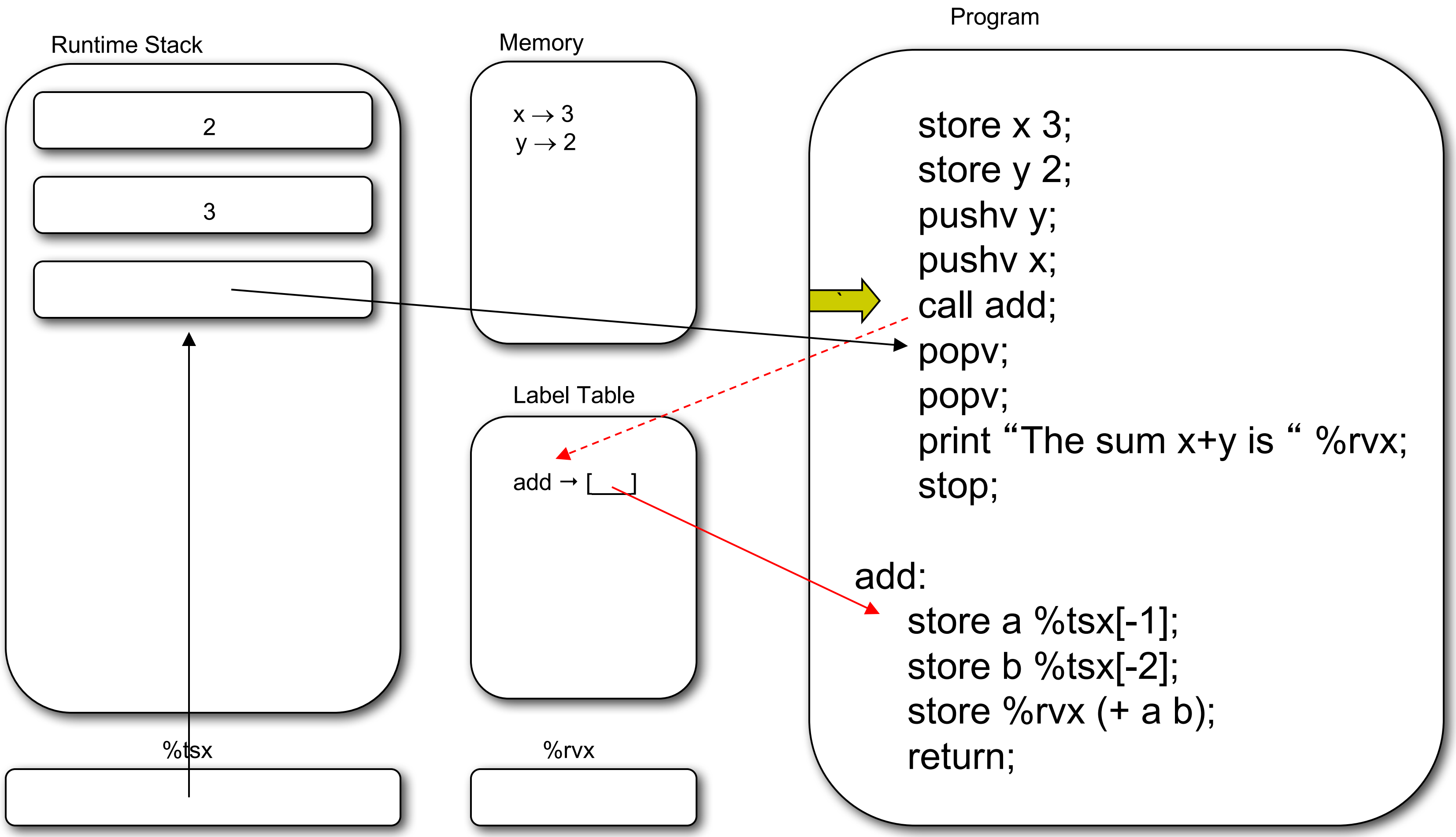

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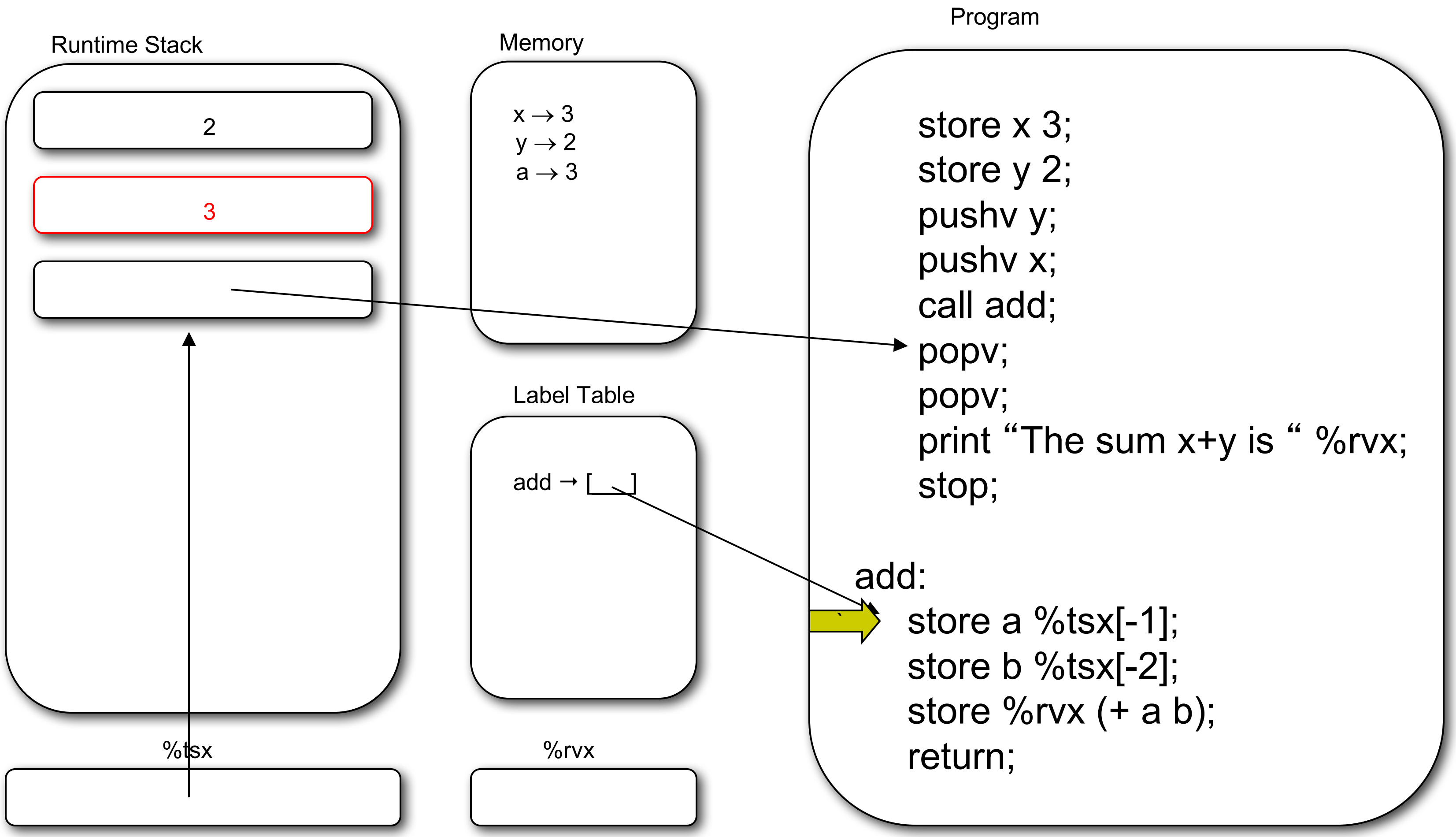
Virtual Machine Design



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pushv y;
pushv x;
call add;
popv;
popv;
print “The sum x+y is “ %rvx;
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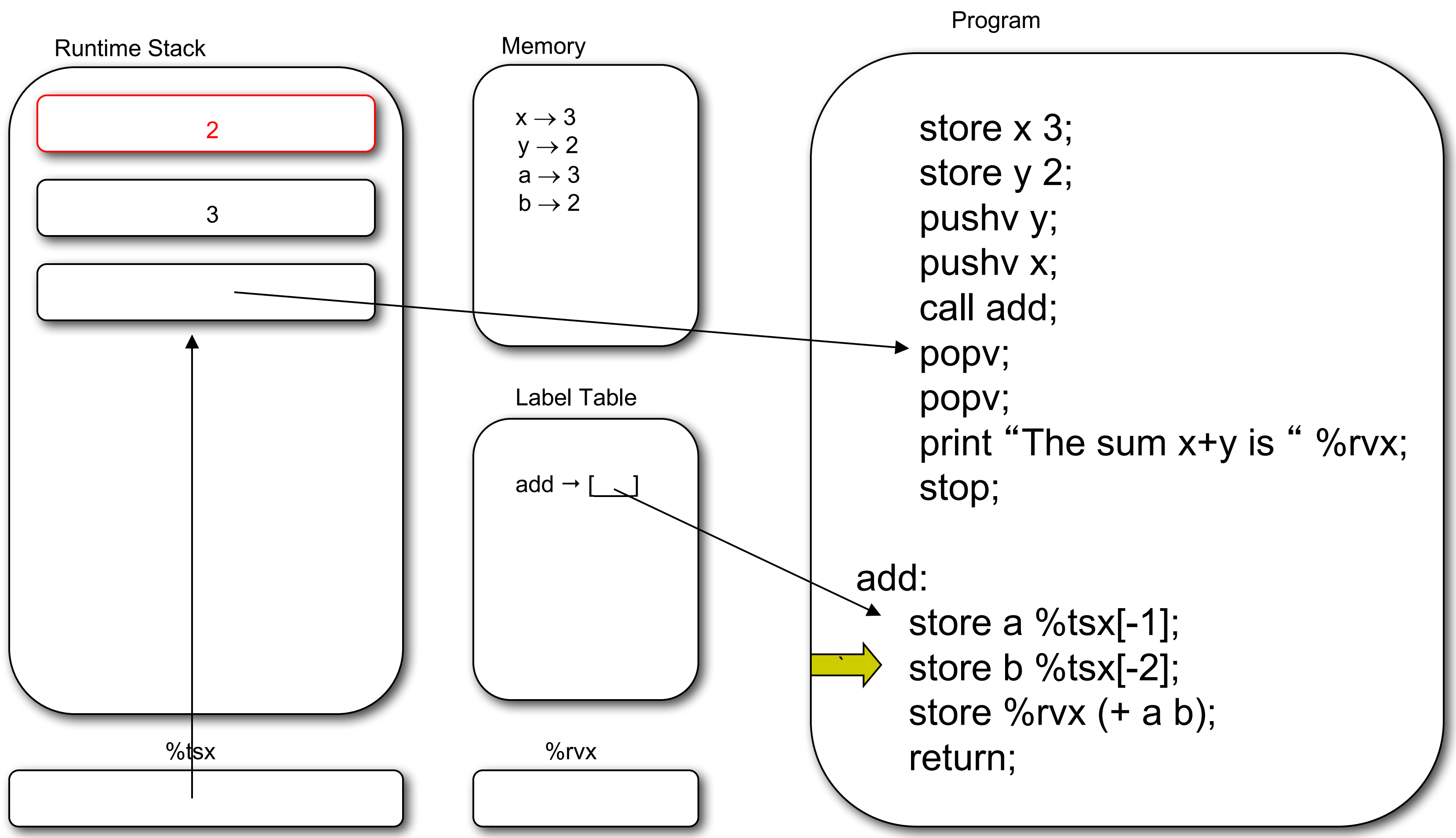
Virtual Machine Design



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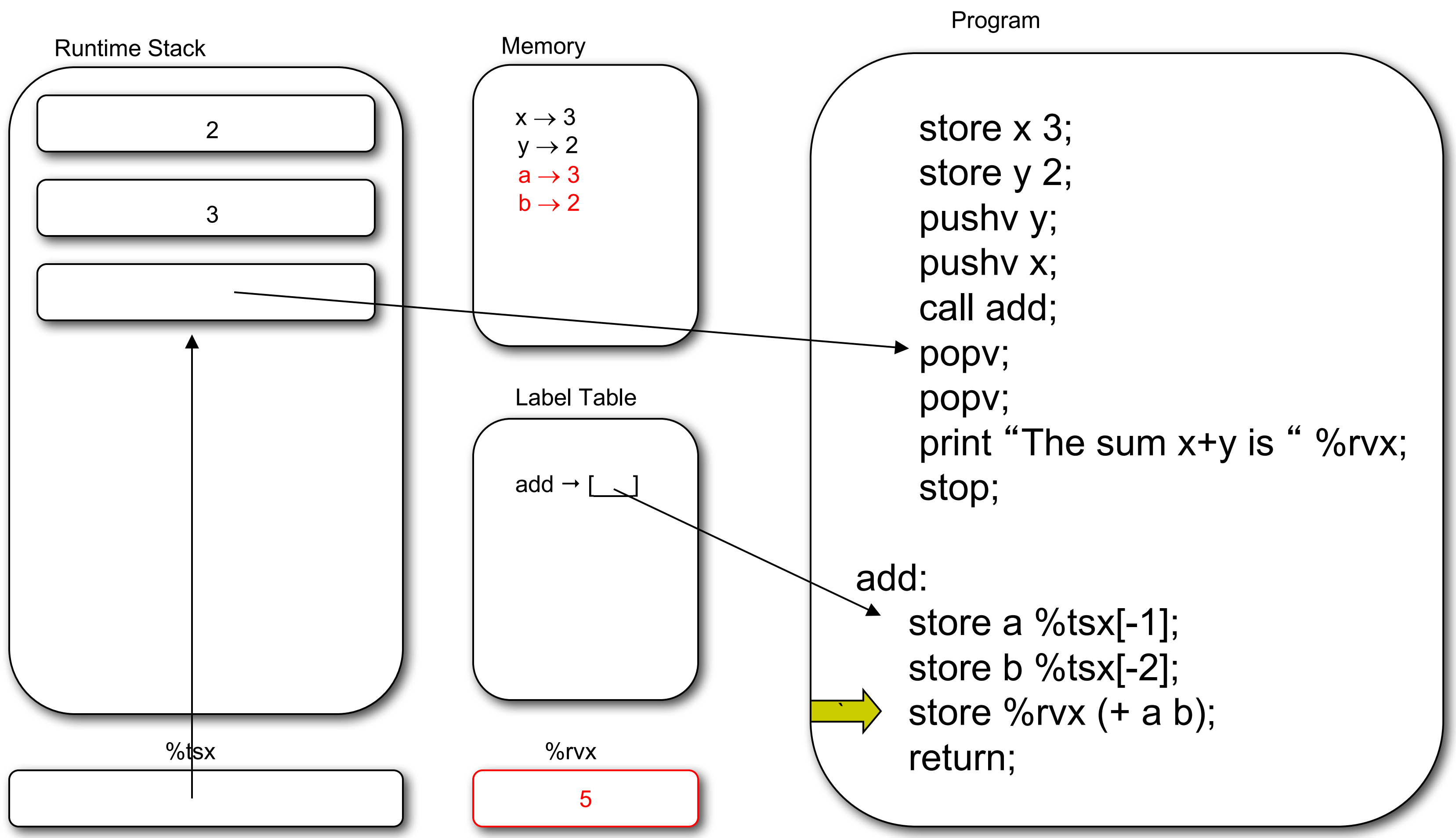

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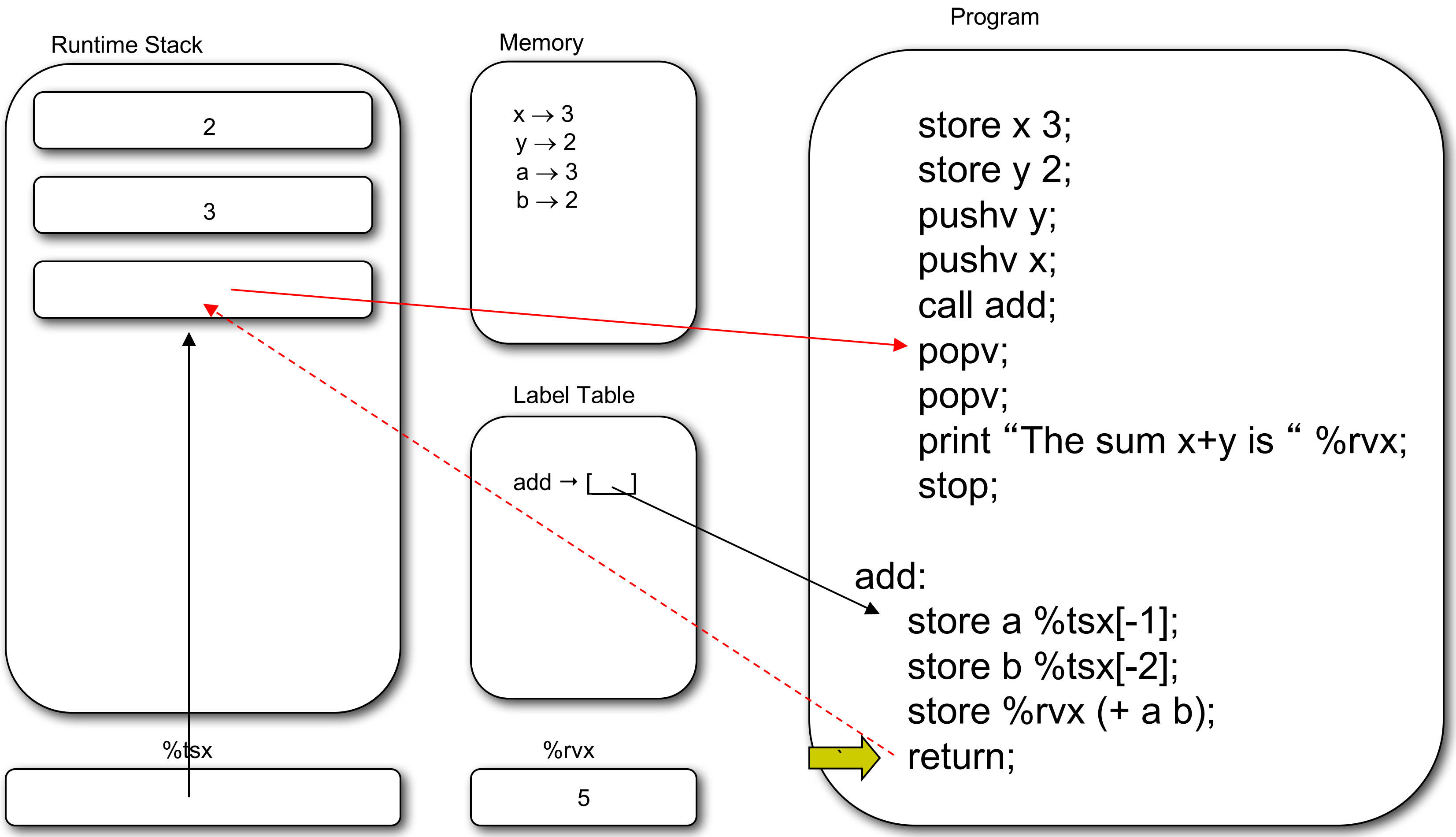

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   call add;
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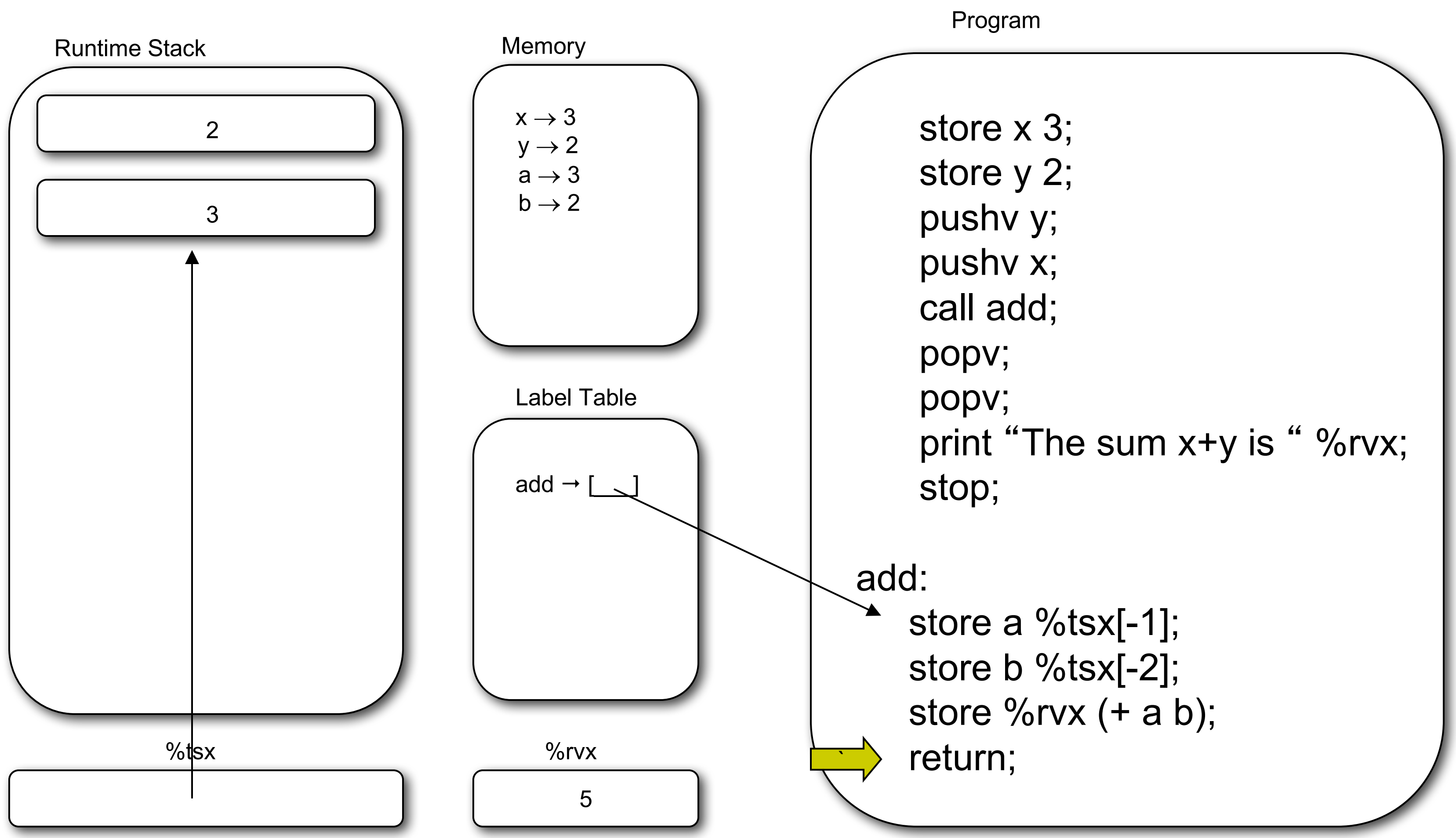
Virtual Machine Design



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   popv;
   popv;
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  store %rvx (+ a b);
  return;
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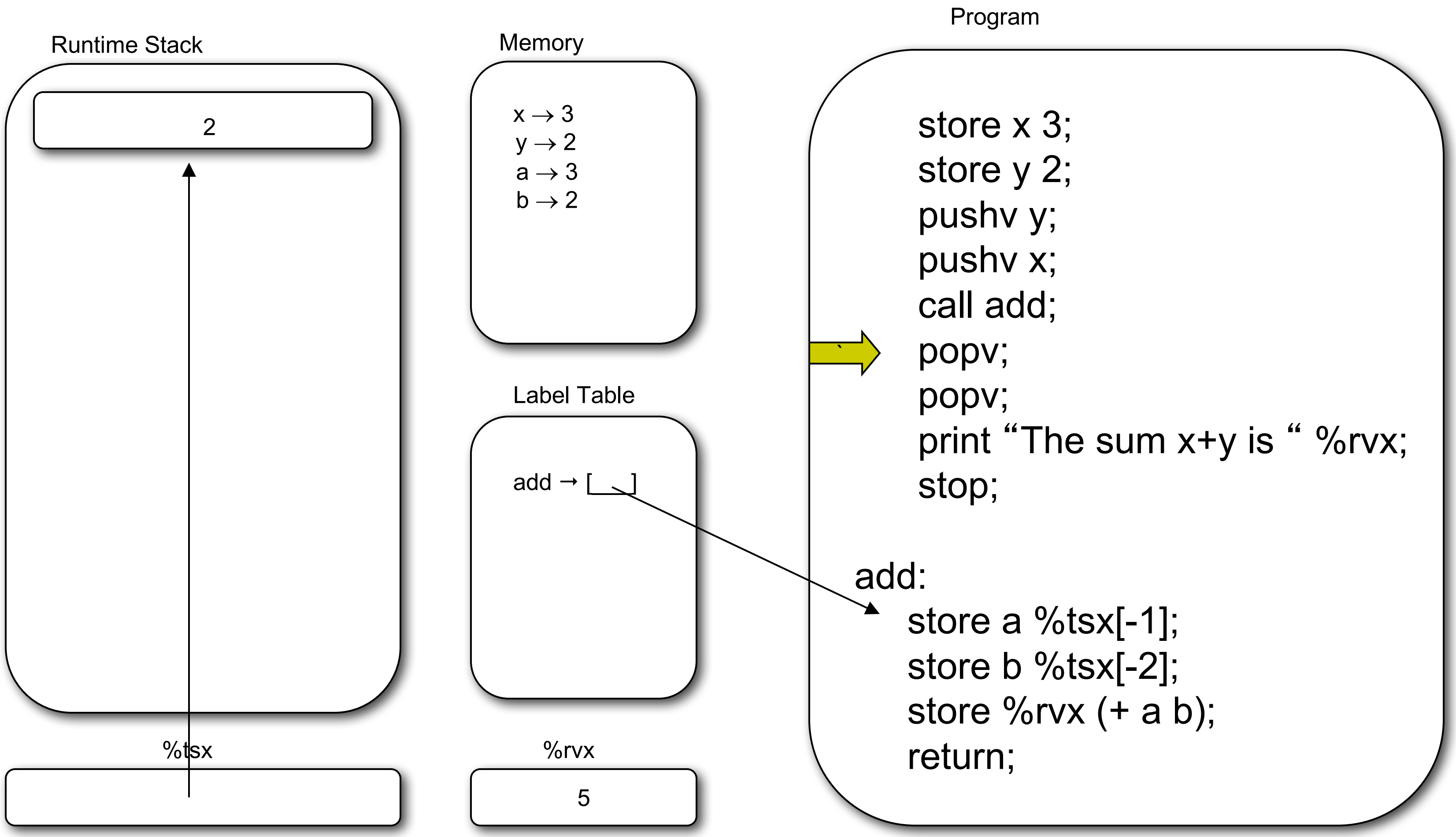
Virtual Machine Design



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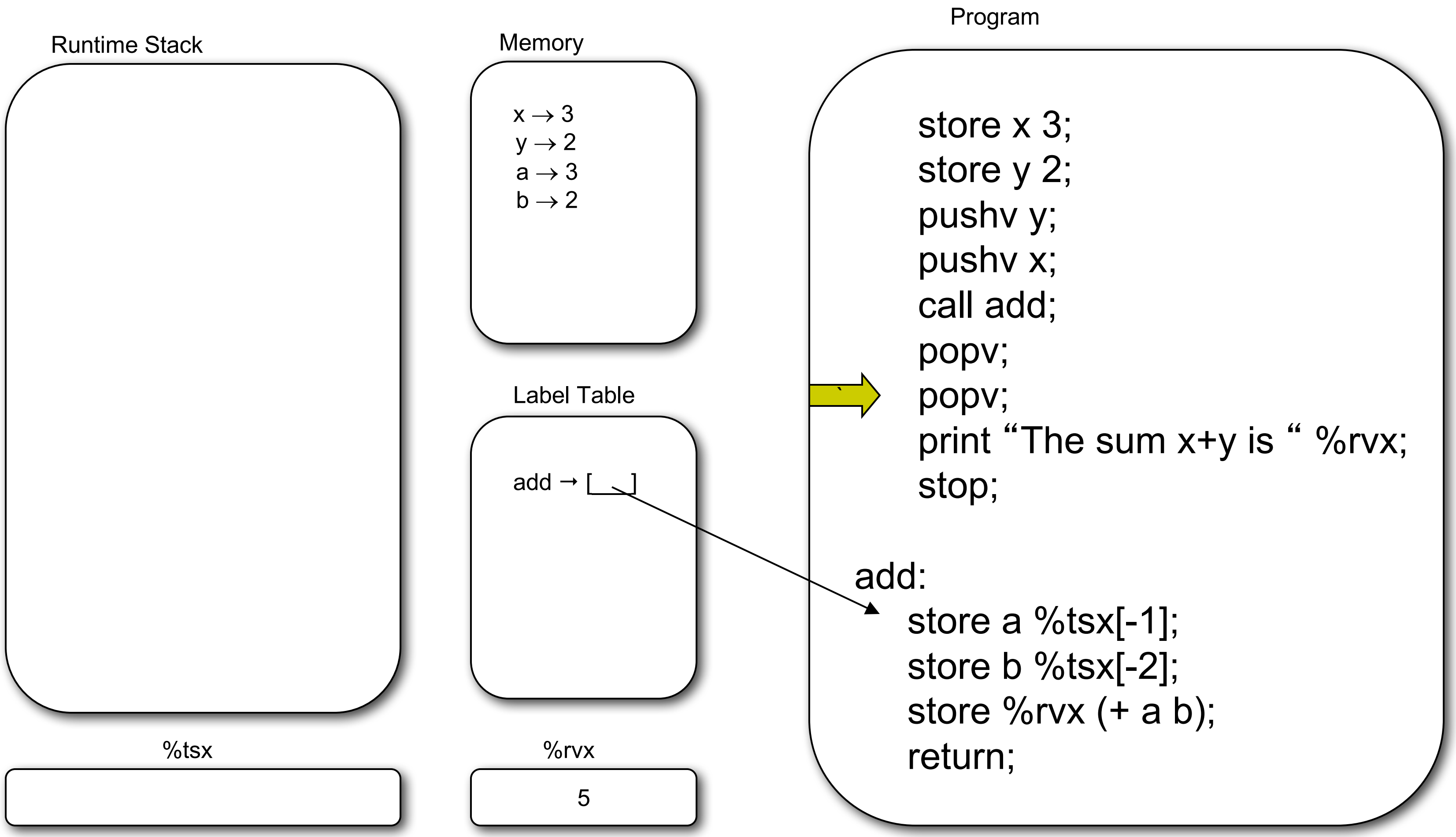
Virtual Machine Design



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    pushv y;
    pushv x;
    call add;
    popv;
    popv;
    print "The sum x+y is " %rvx;
    stop;

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   store a %tsx[-1];
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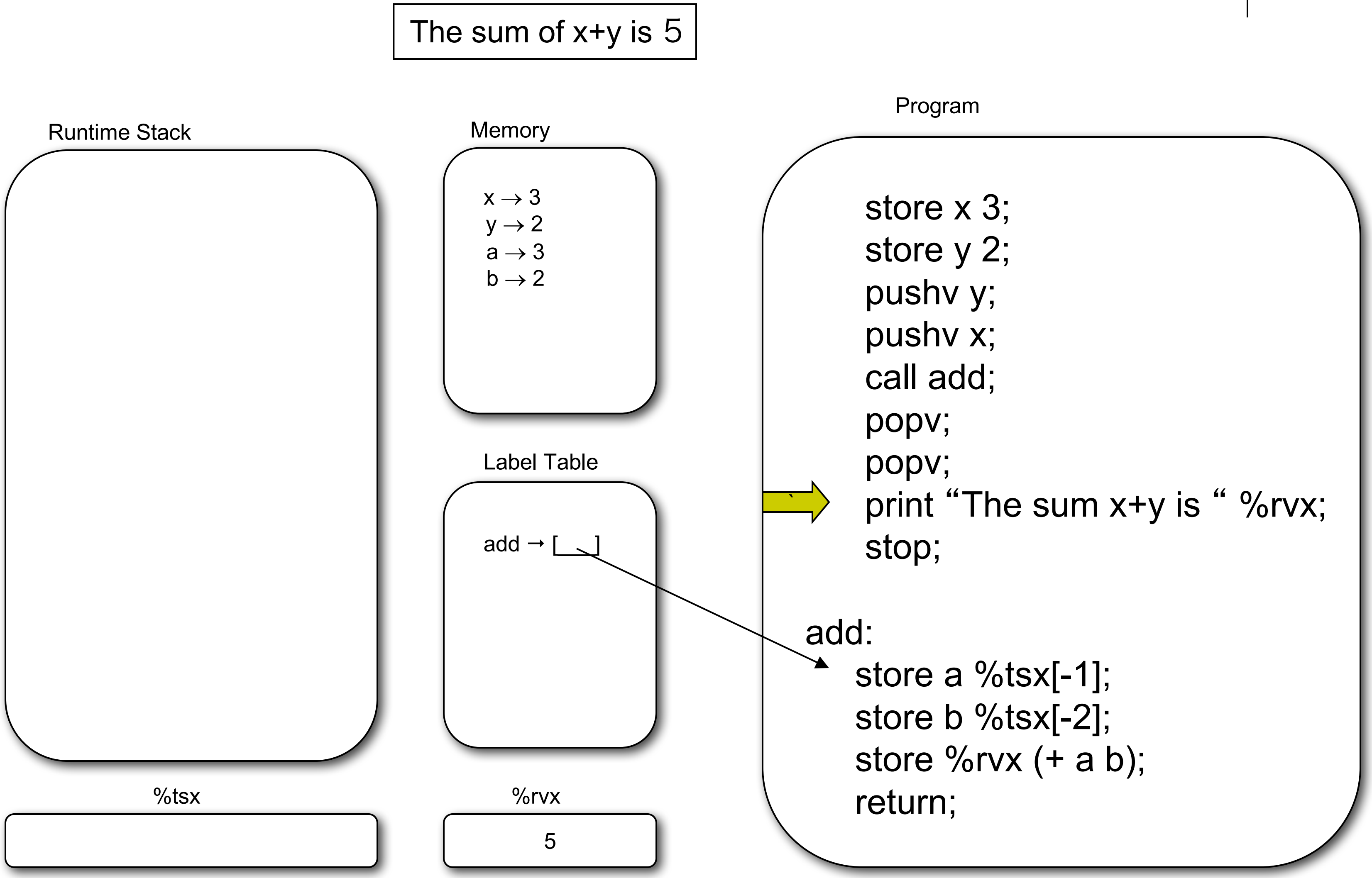
   return;
```

Virtual Machine Design



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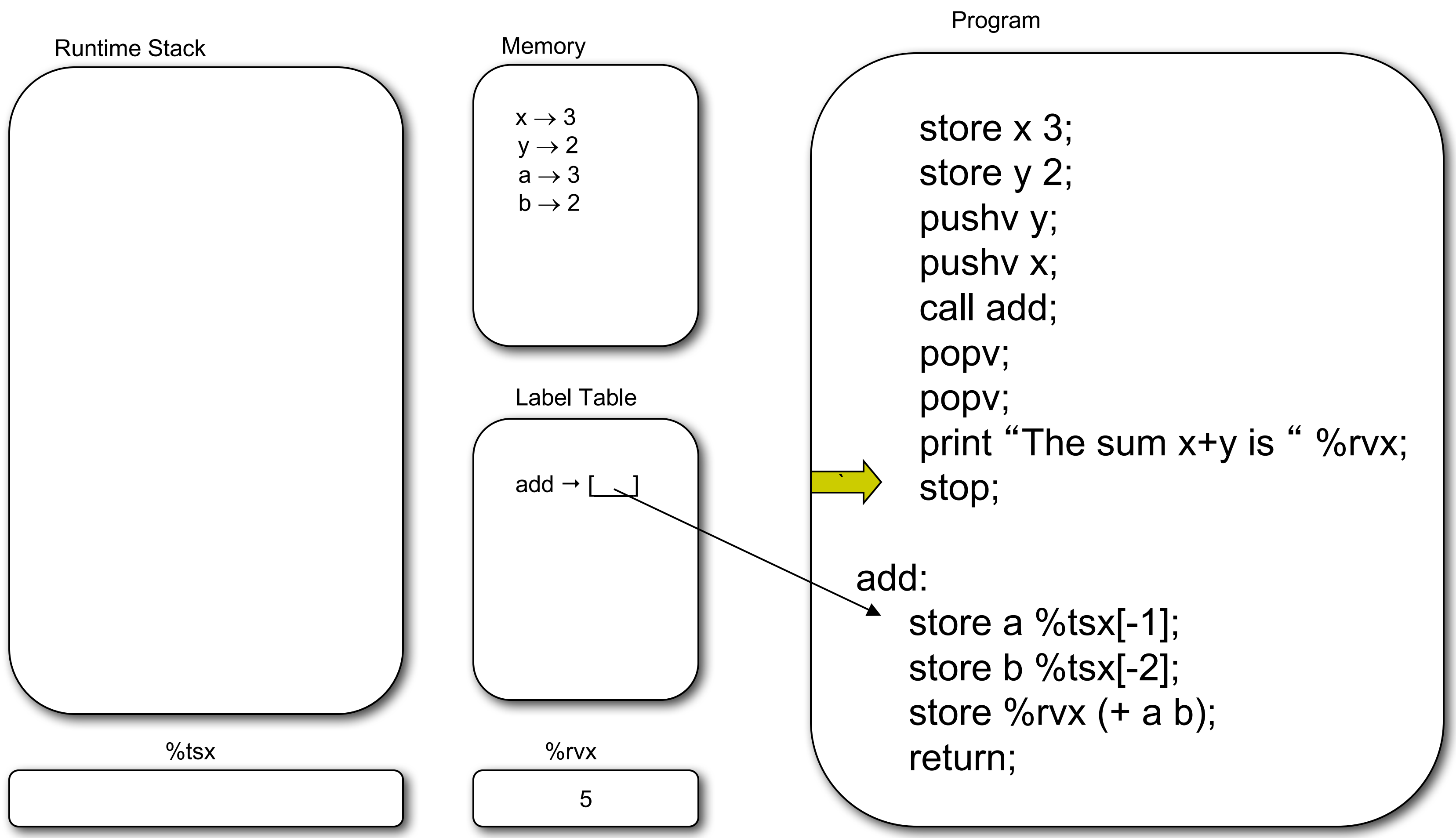
Virtual Machine Design



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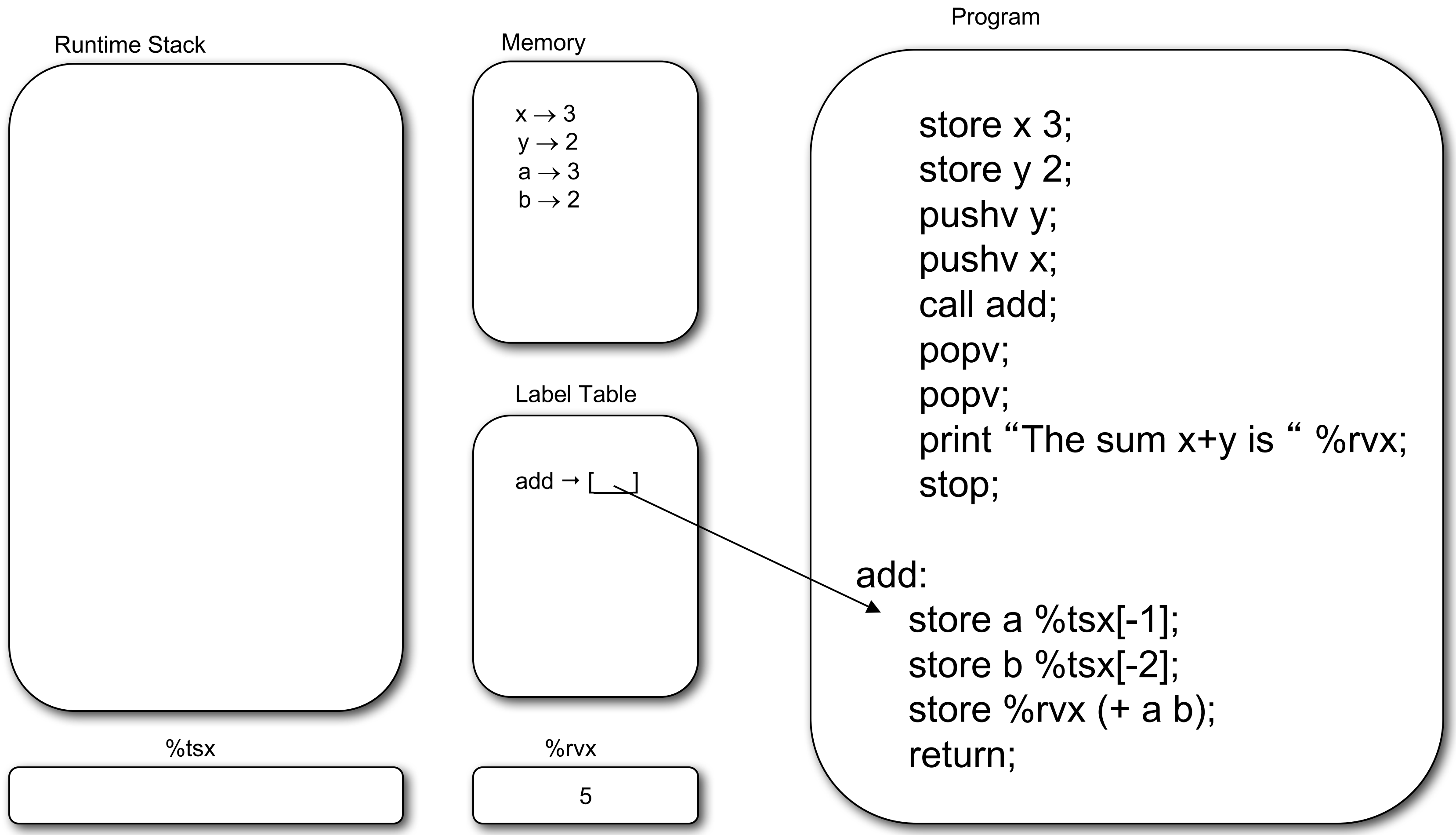
Virtual Machine Design



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    pushv y;
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    call add;
    popv;
    popv;
    print “The sum x+y is “ %rvx;
    stop;

add:
    store a %tsx[-1];
    store b %tsx[-2];
    store %rvx (+ a b);
    return;
```

Example Program

- Here is another way to write the same program taking advantage of indirect addressing.

```
        store x 3;
        store y 2;
        pushv y;
        pushv x;
        call add;
        popv;
        popv;
        print “The sum x+y is “ %rvx;
        stop;

add:
       store %rvx (+ %tsx[-1] %tsx[-2]);
       return;
```

Recursive Program

- Recursive programs are tricky because function local variables, if one is not careful, are overwritten by recursive calls to the same function.
- Solution: store function local variables in a *stack frame* with one stack frame for each function invocation.

Recursive Programs

- As an example we will study the bytecode that implements the following Cuppa3 program:

```
// print the sequence 0 1 2
declare seq(x) {
    if (1<=x)
        seq(x-1)
    put(x)
}

seq(2)
```

Recursive Programs

- Our first attempt:

```
    // print the sequence 0 1 2
    pushv 2;
    call seq;
    popv;
    stop;

seq:
    store x %tsx[-1];
    jumpF x L1;
    pushv (- x 1);
    call seq;
    popv;
L1:
    print x;
    return;
```

Note: this program does **NOT** work because x is a global variable which will get overwritten by each invocation of seq.

Recursive Programs

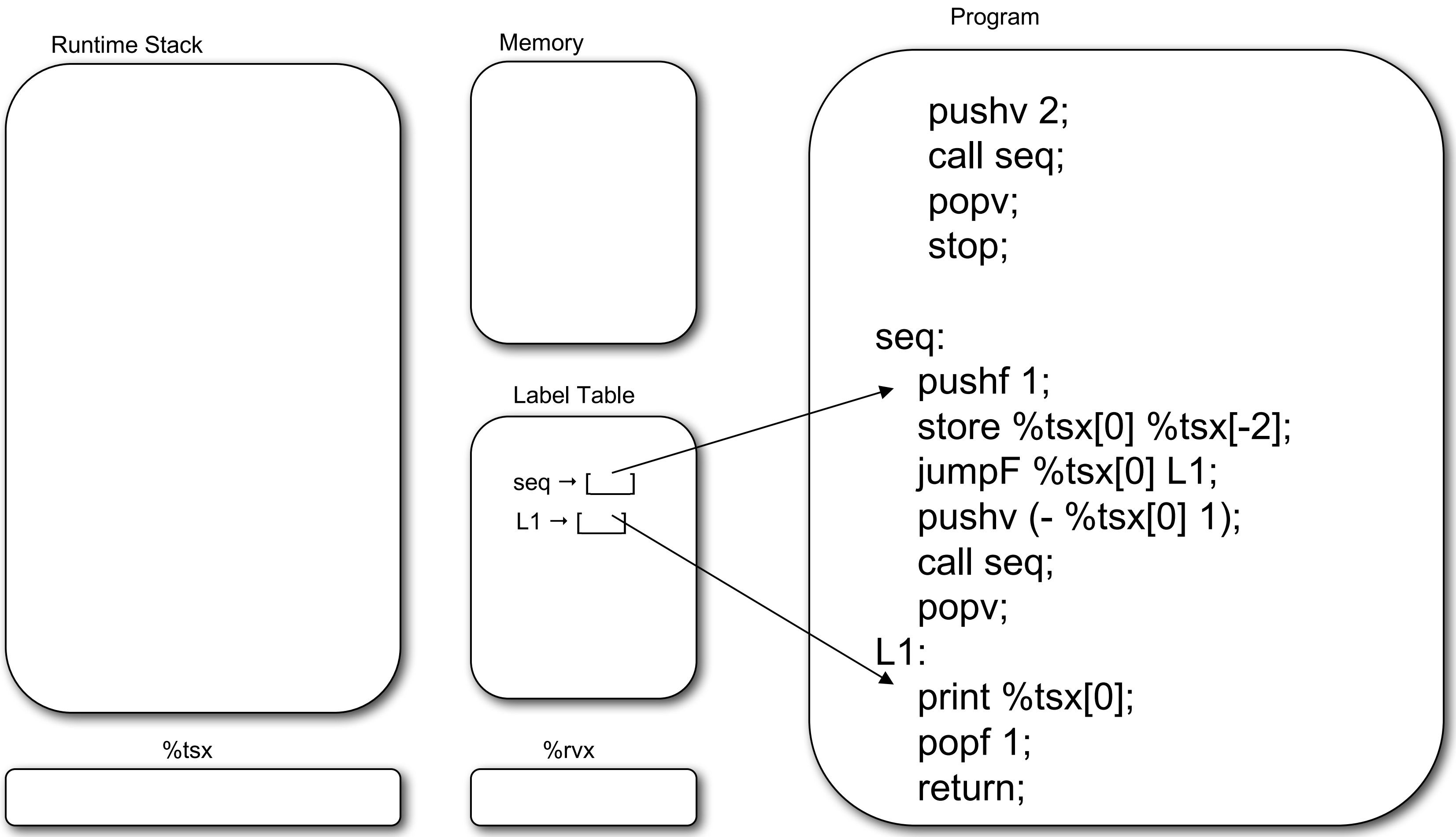
- We rewrite the program using *stack frames* to store function local variables.

```
    # print the sequence 0 1 2
    pushv 2;
    call seq;
    popv;
    stop;

seq:
    pushf 1;                        # push a frame of size 1 - variable x
    store %tsx[0] %tsx[-2];  # initialize x with the actual parameter
    jumpF %tsx[0] L1;         # test x
    pushv (- %tsx[0] 1);
    call seq;
    popv;
L1:
    print %tsx[0];
    popf 1;                         # remove the frame from the stack
    return;
```

Note: This program now works, local variables have their own location on the stack per function invocation.

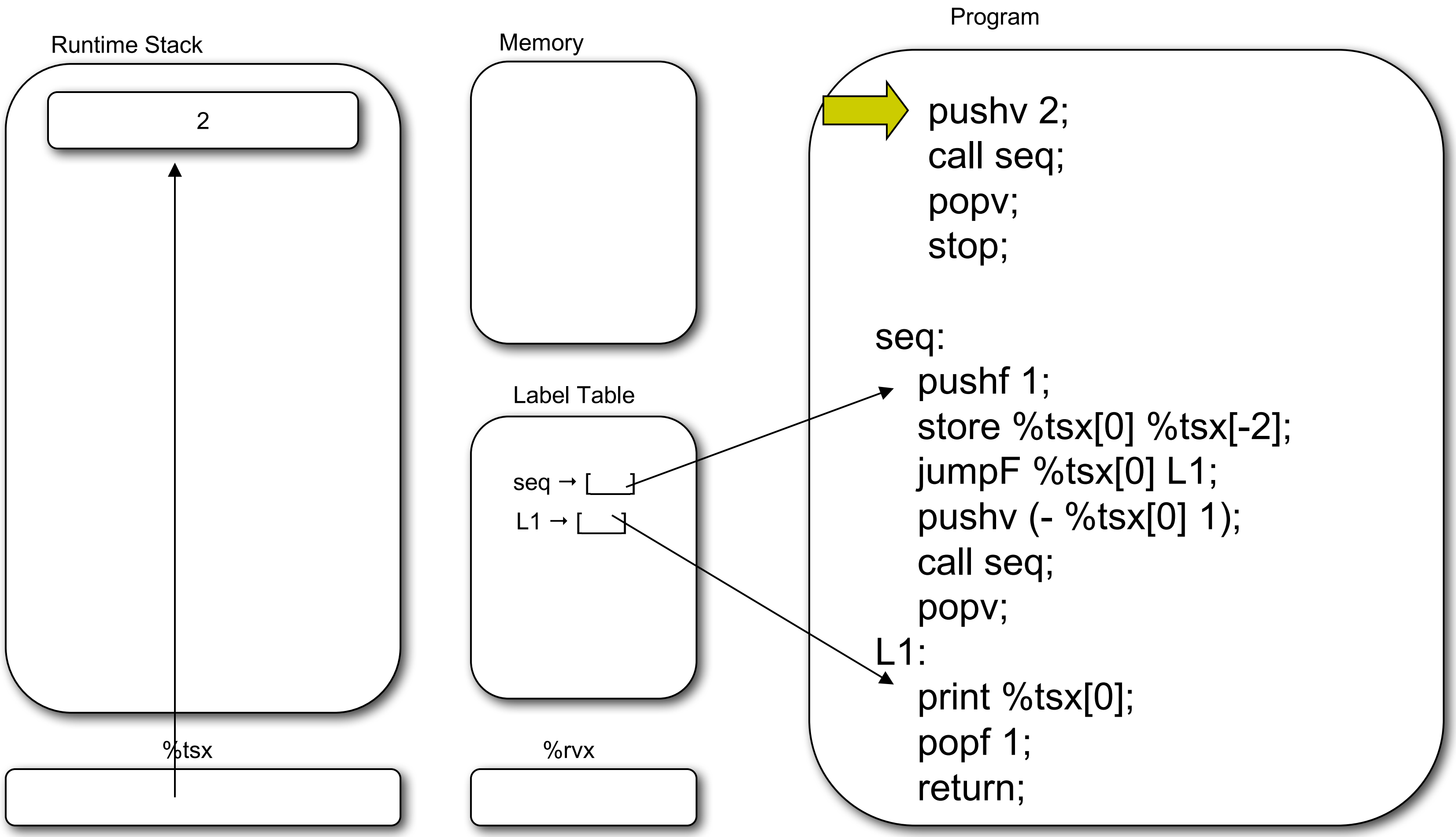
Virtual Machine Design



```
     pushv 2;
     call seq;
     popv;
     stop;

seq:
    pushf 1;
    store %tsx[0] %tsx[-2];
    jumpF %tsx[0] L1;
    pushv (- %tsx[0] 1);
    call seq;
    popv;
L1:
    print %tsx[0];
    popf 1;
    return;
```

Virtual Machine Design



```
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   popf 1;
   return;
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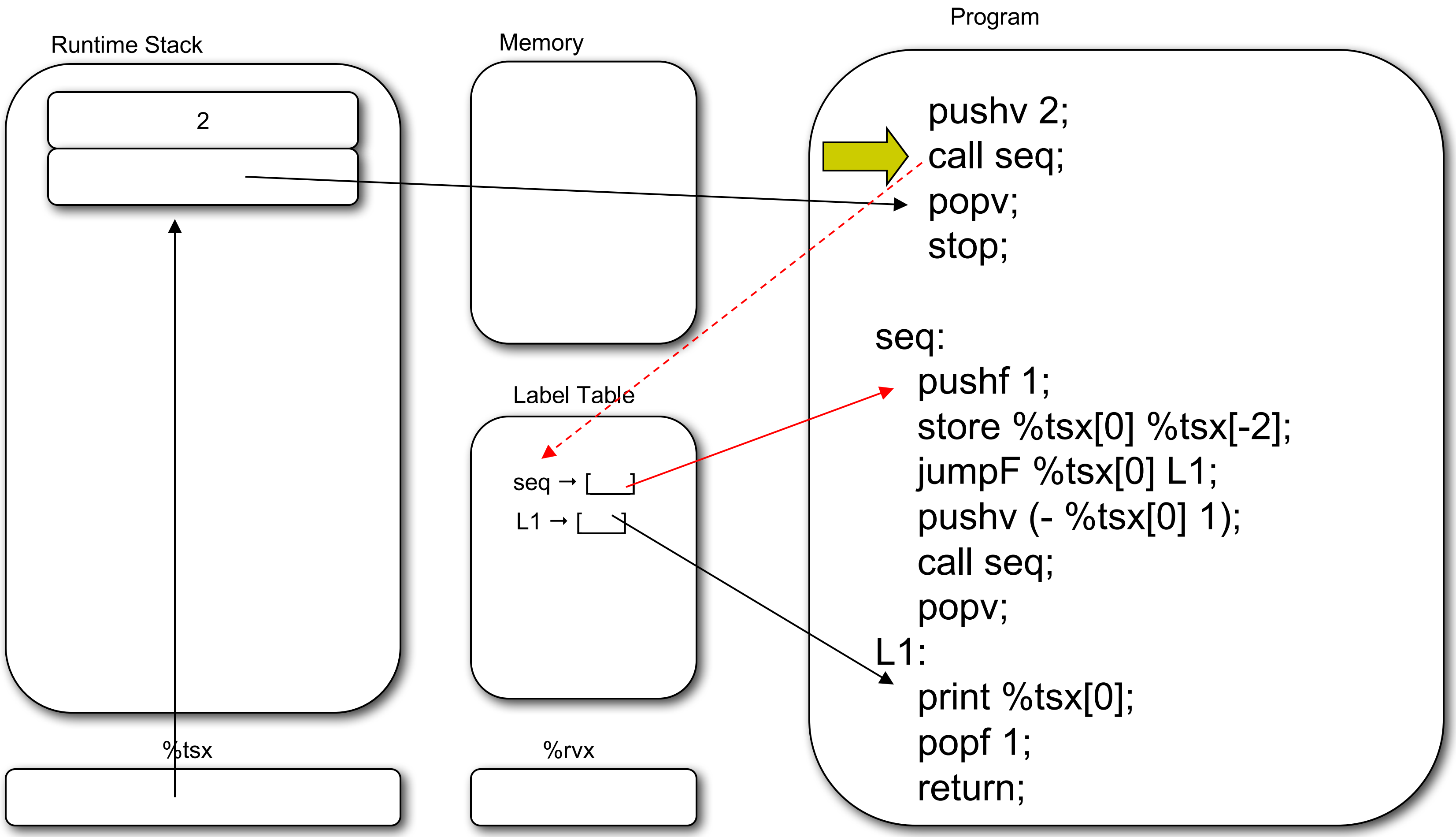
Virtual Machine Design



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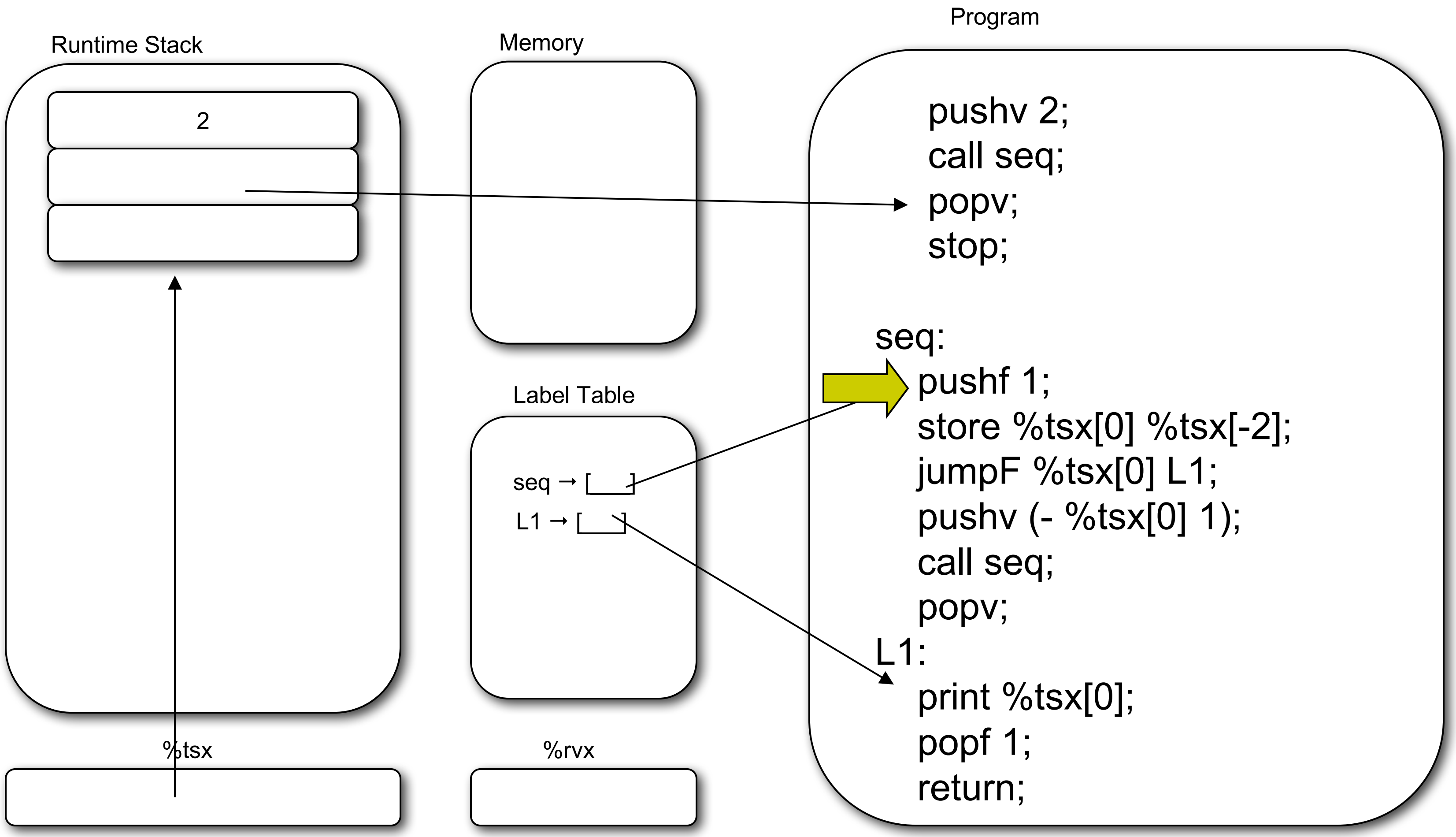
Virtual Machine Design



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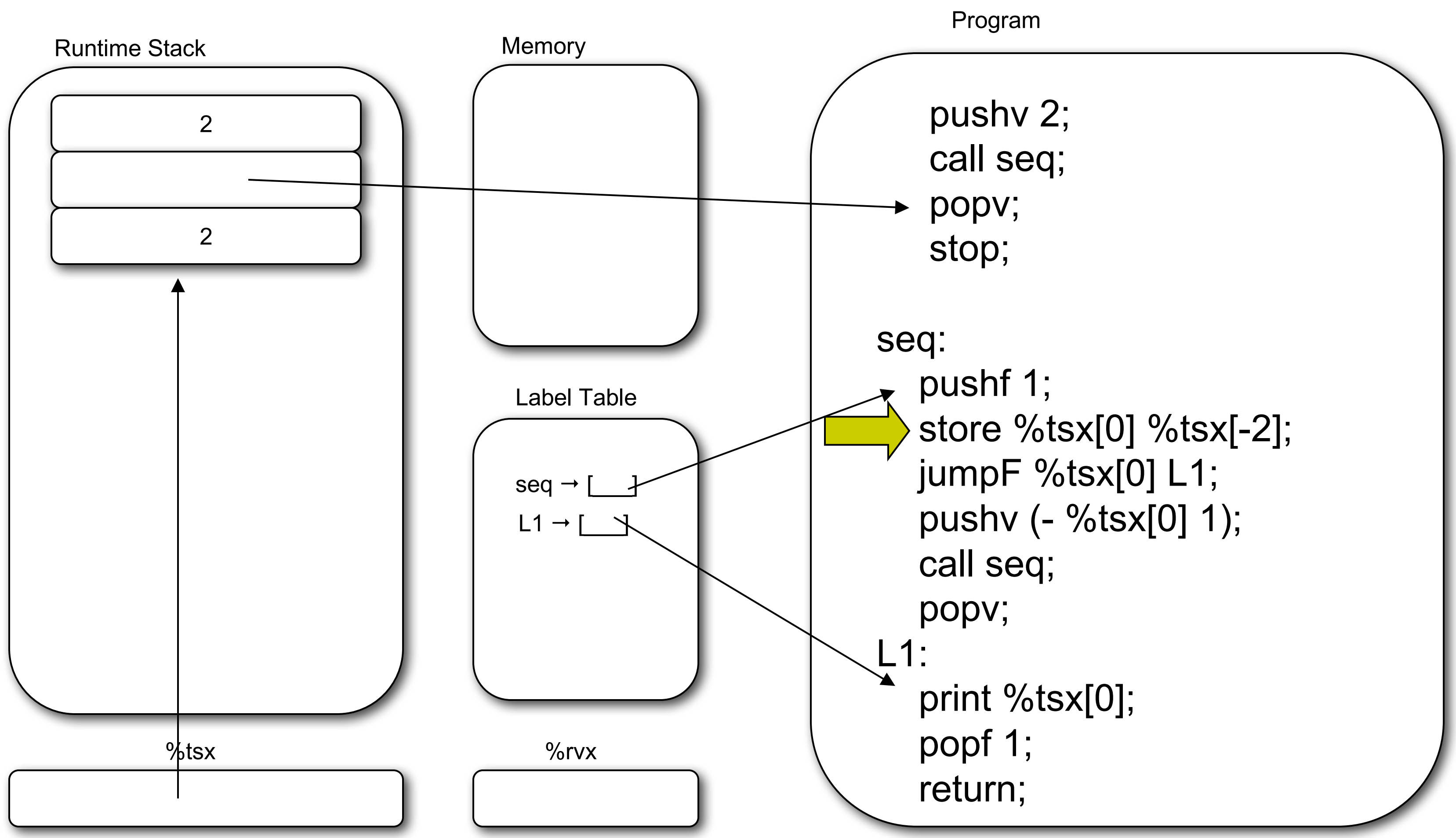

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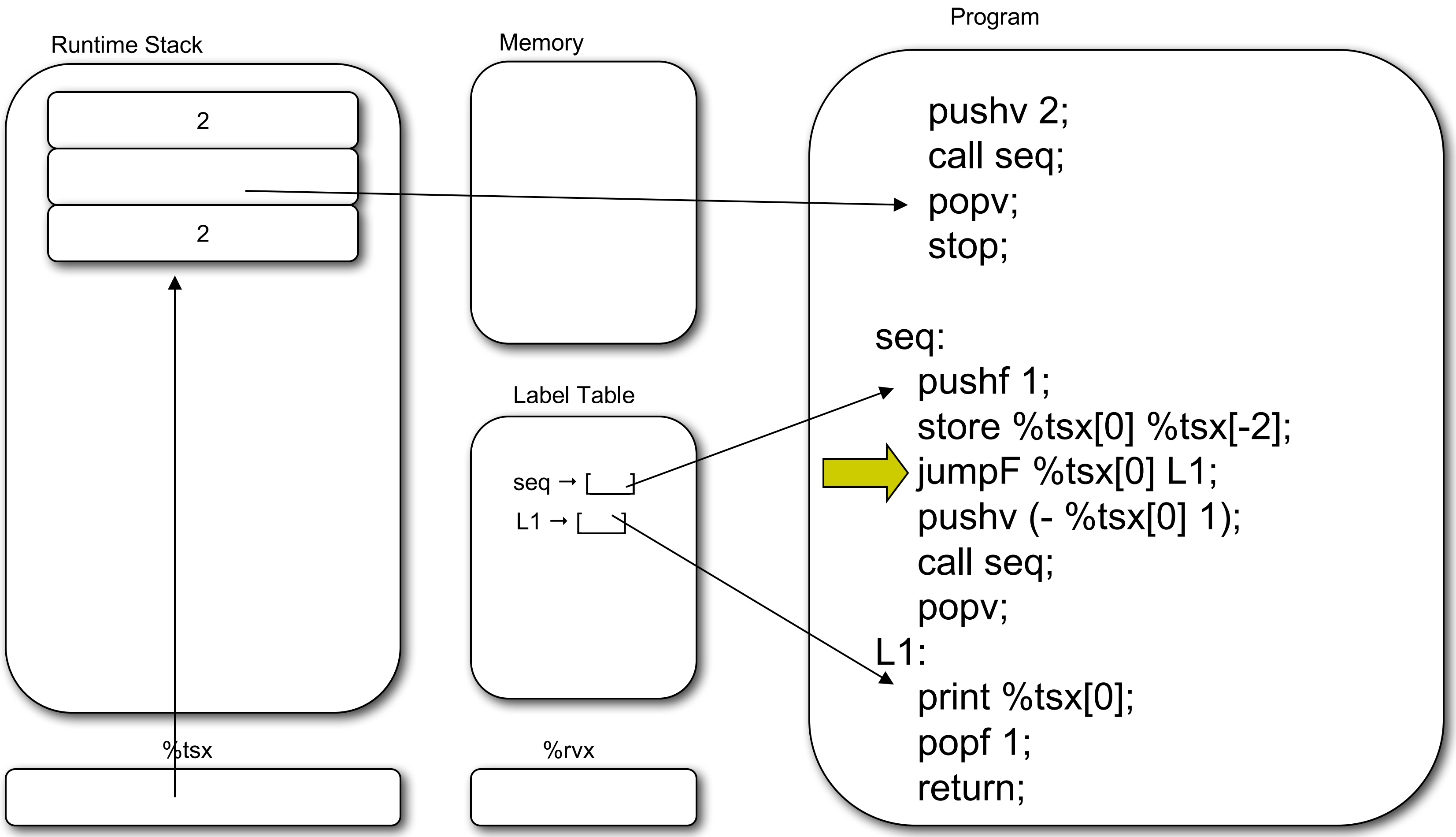

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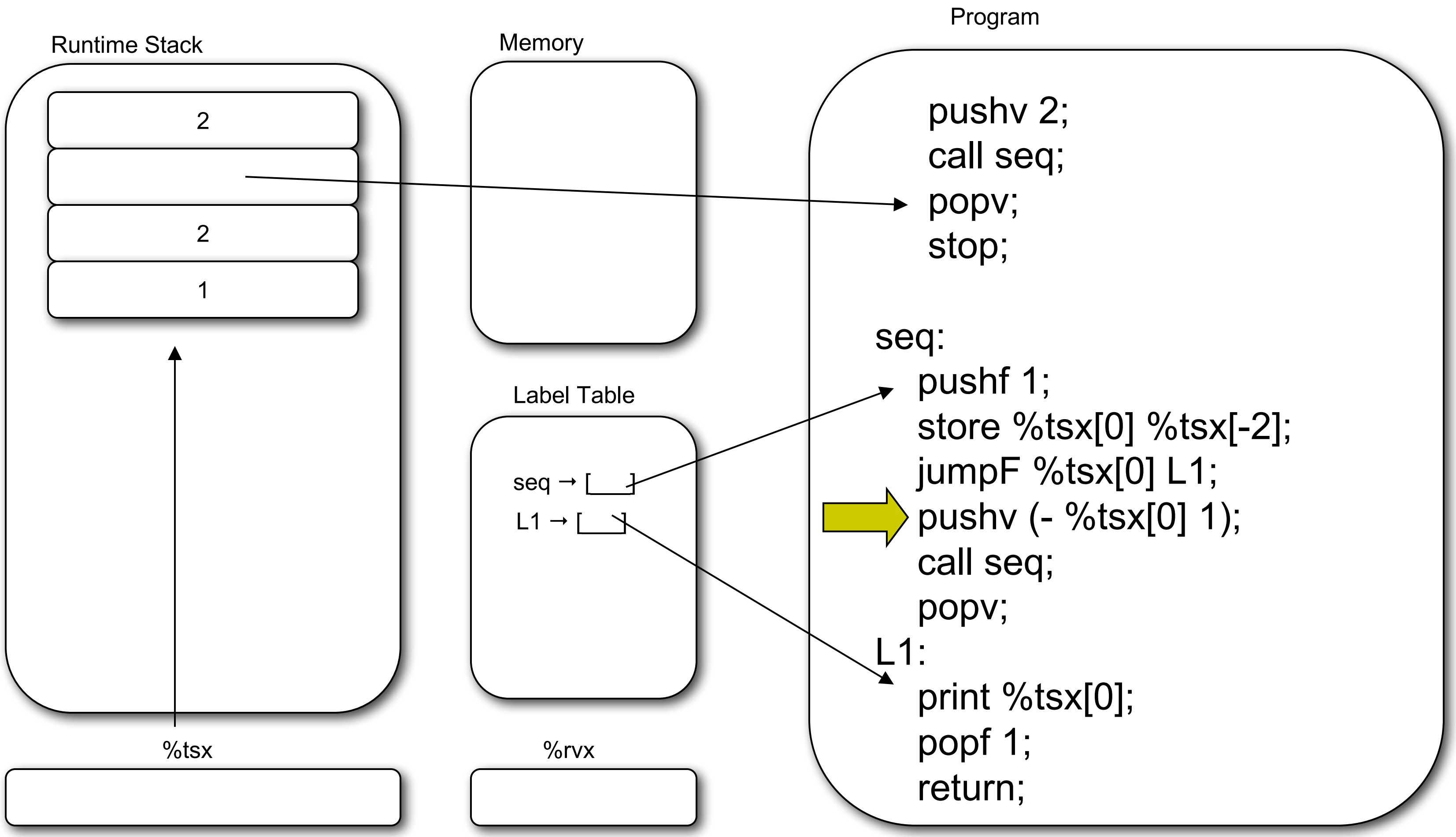

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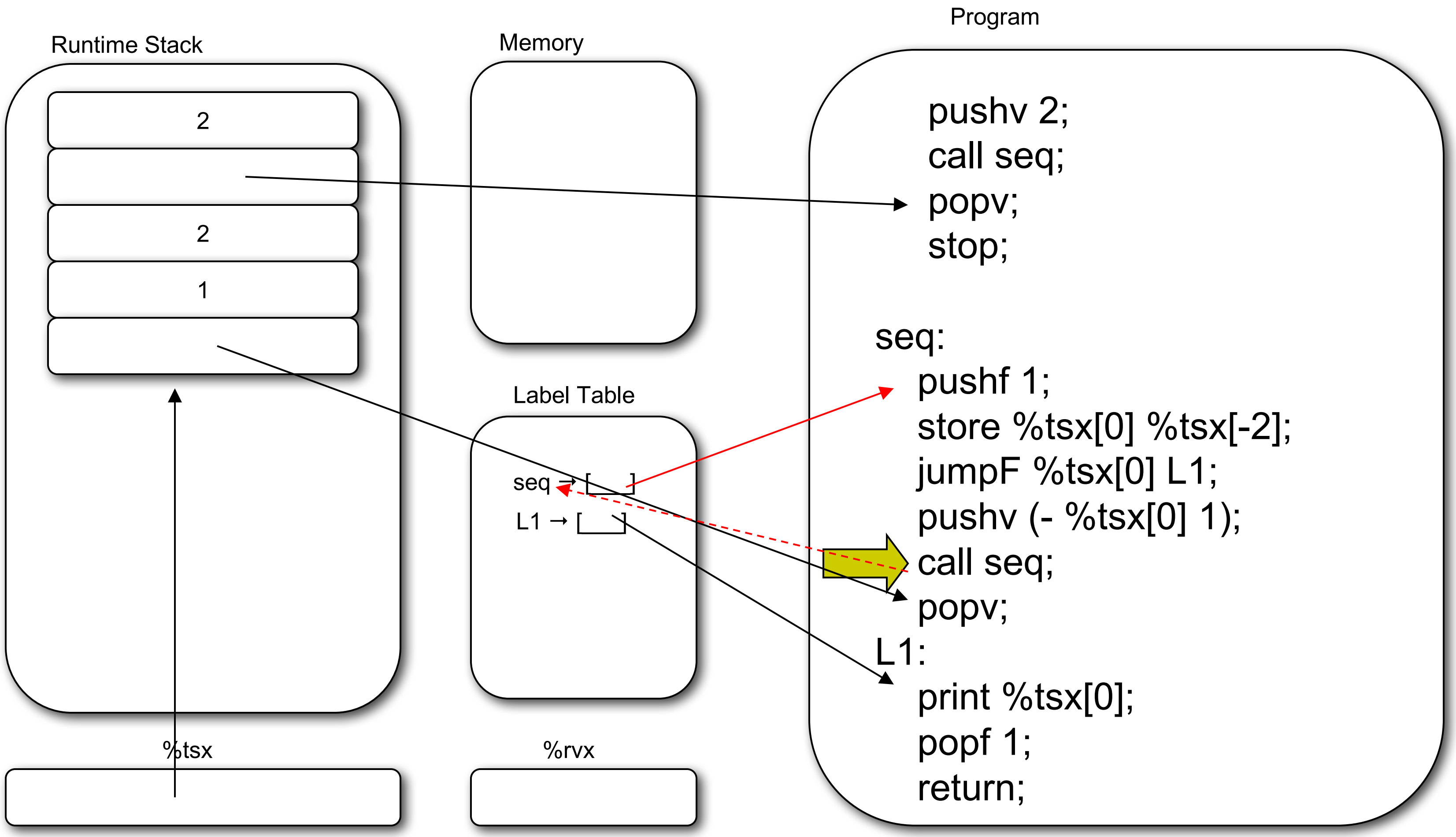

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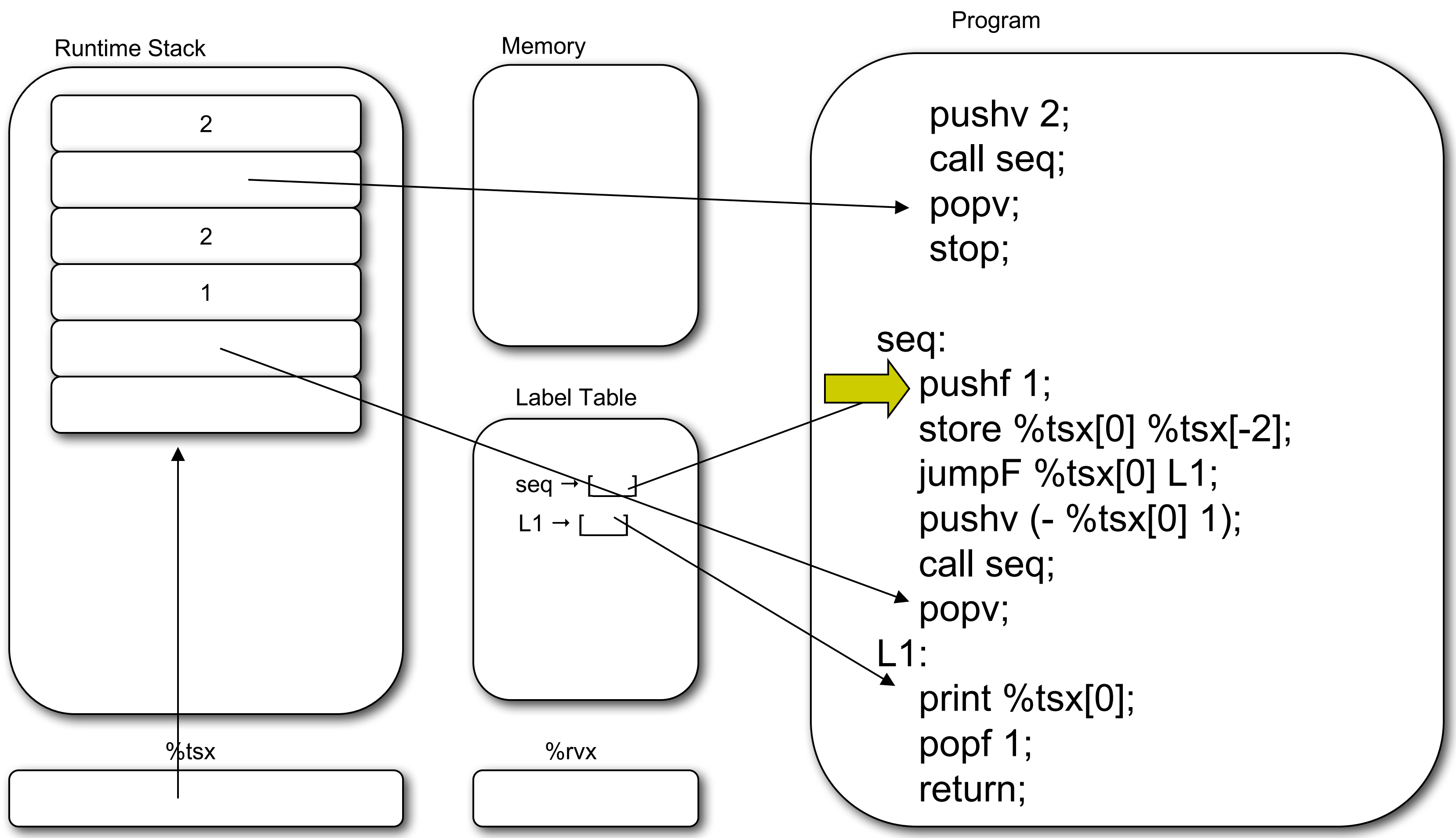

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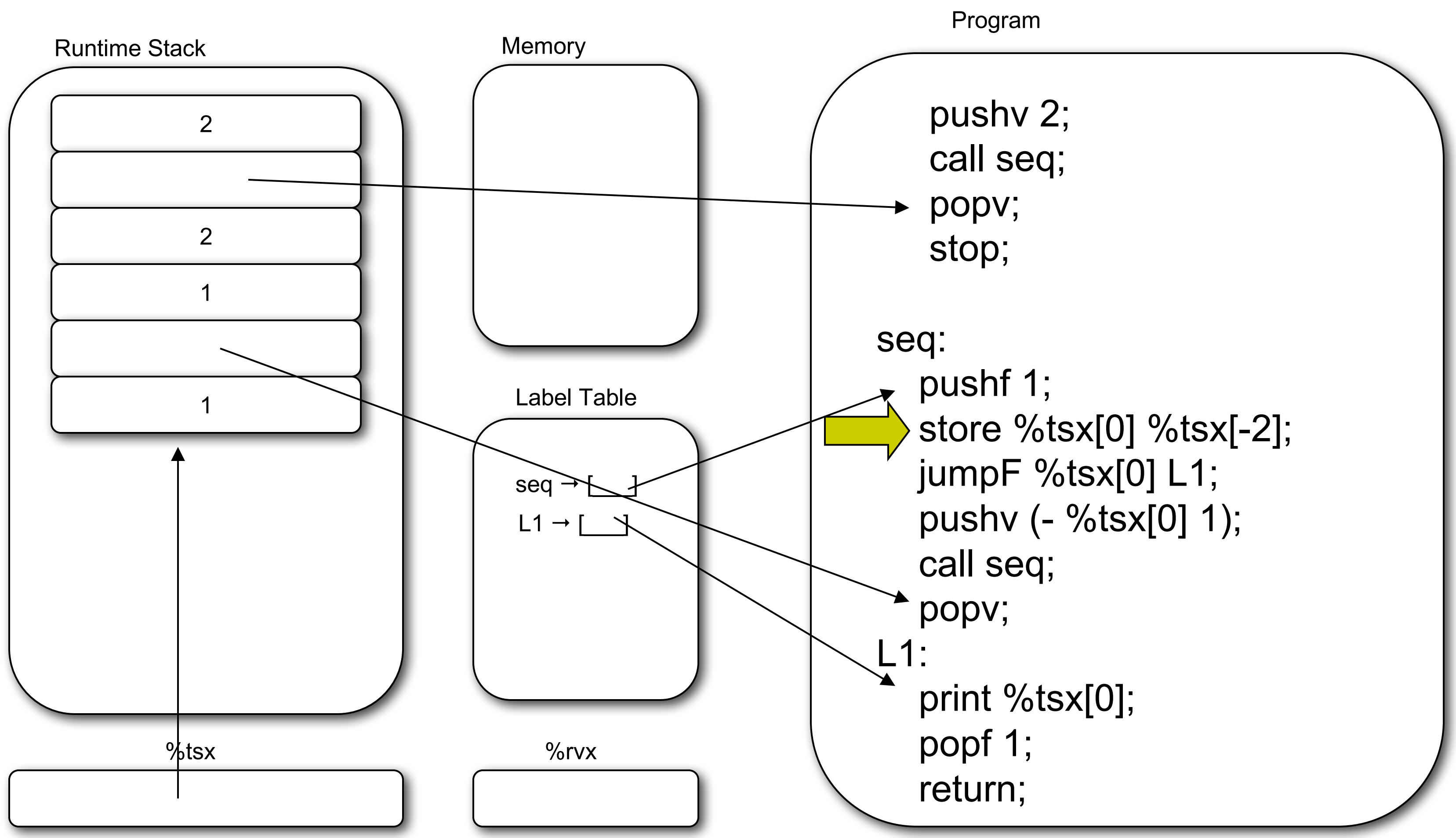

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```
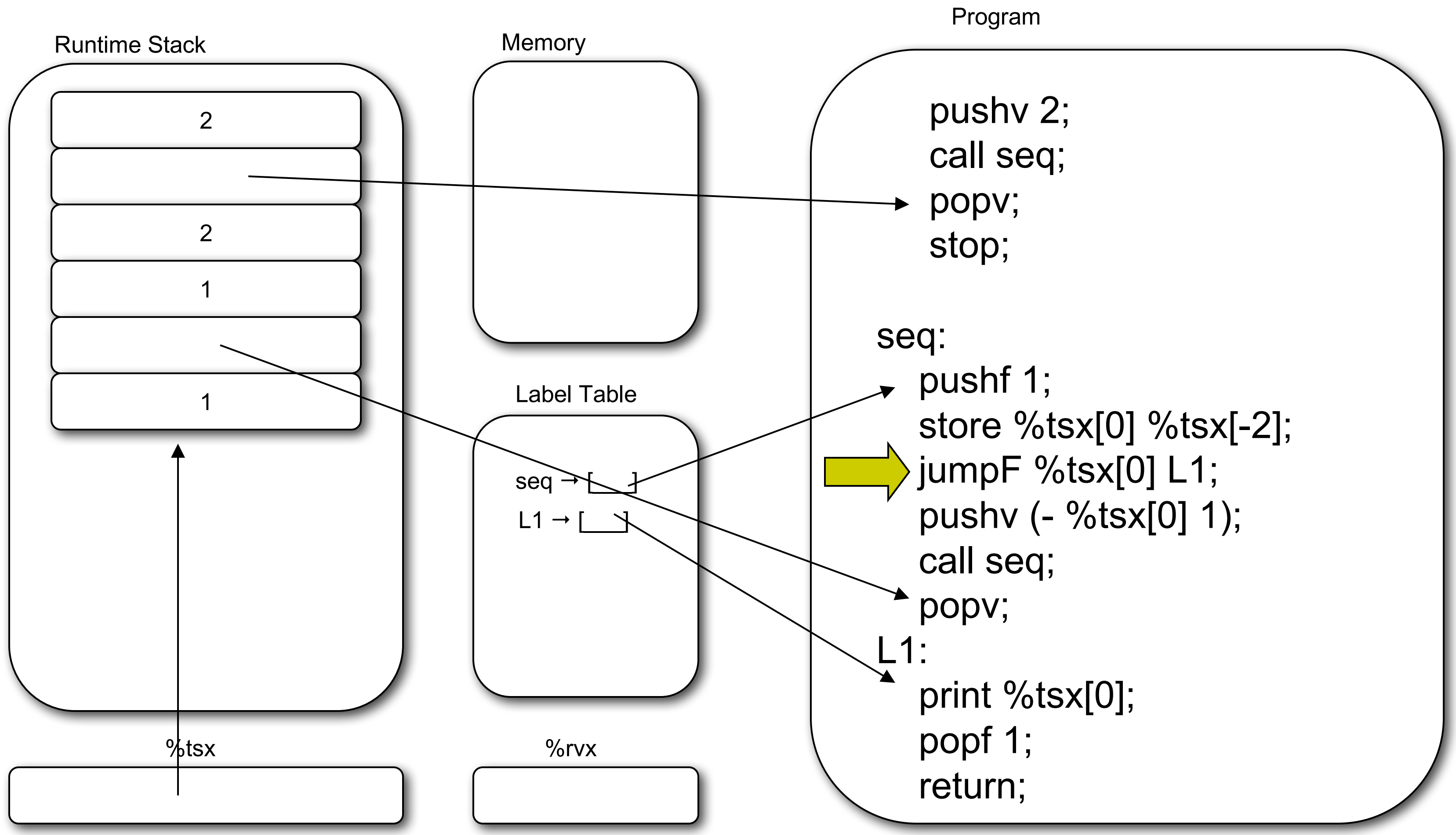

Virtual Machine Design



```
  pushv 2;
  call seq;
  popv;
  stop;

seq:
  pushf 1;
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  jumpF %tsx[0] L1;
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L1:
  print %tsx[0];
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```
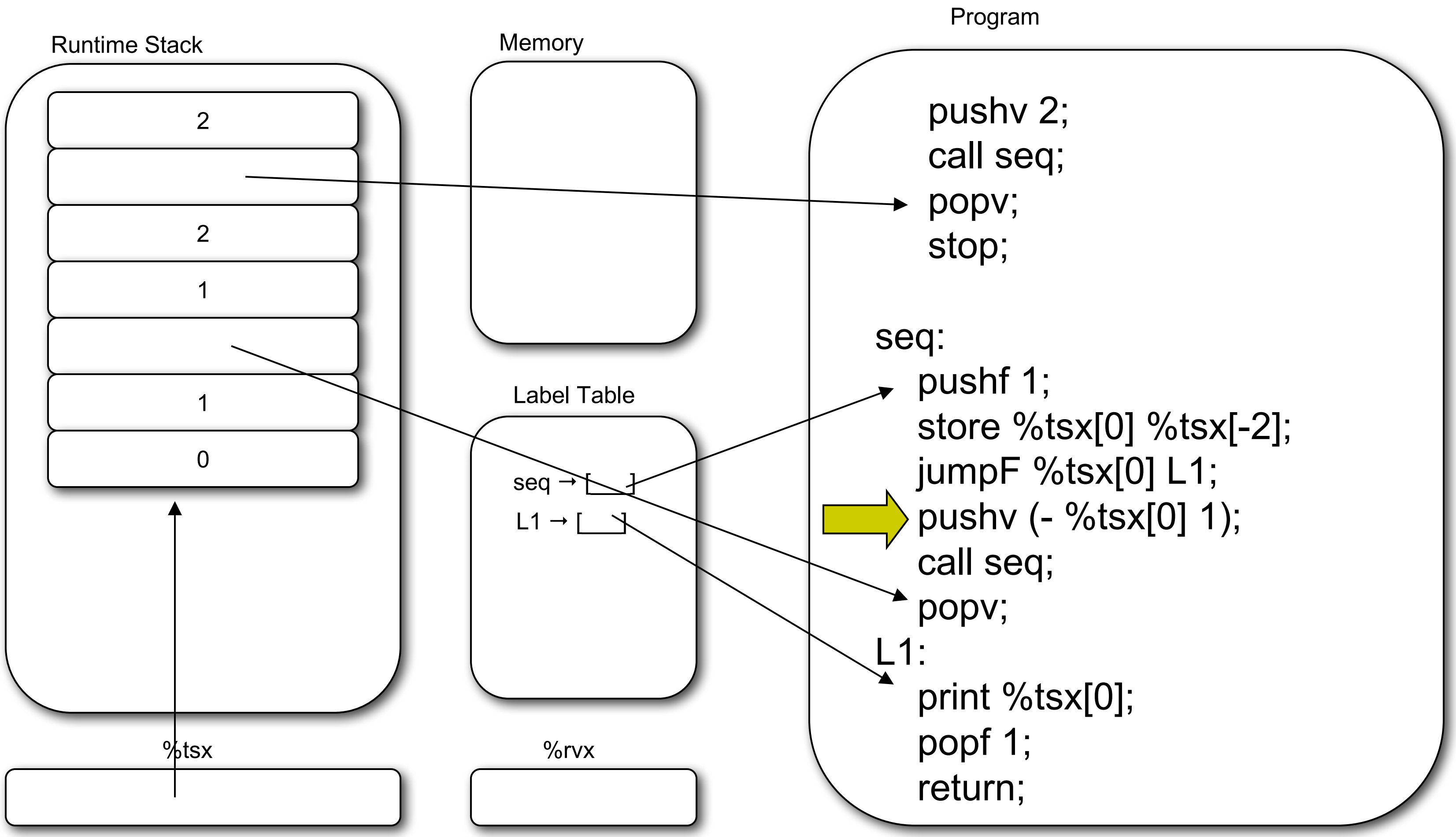

Virtual Machine Design



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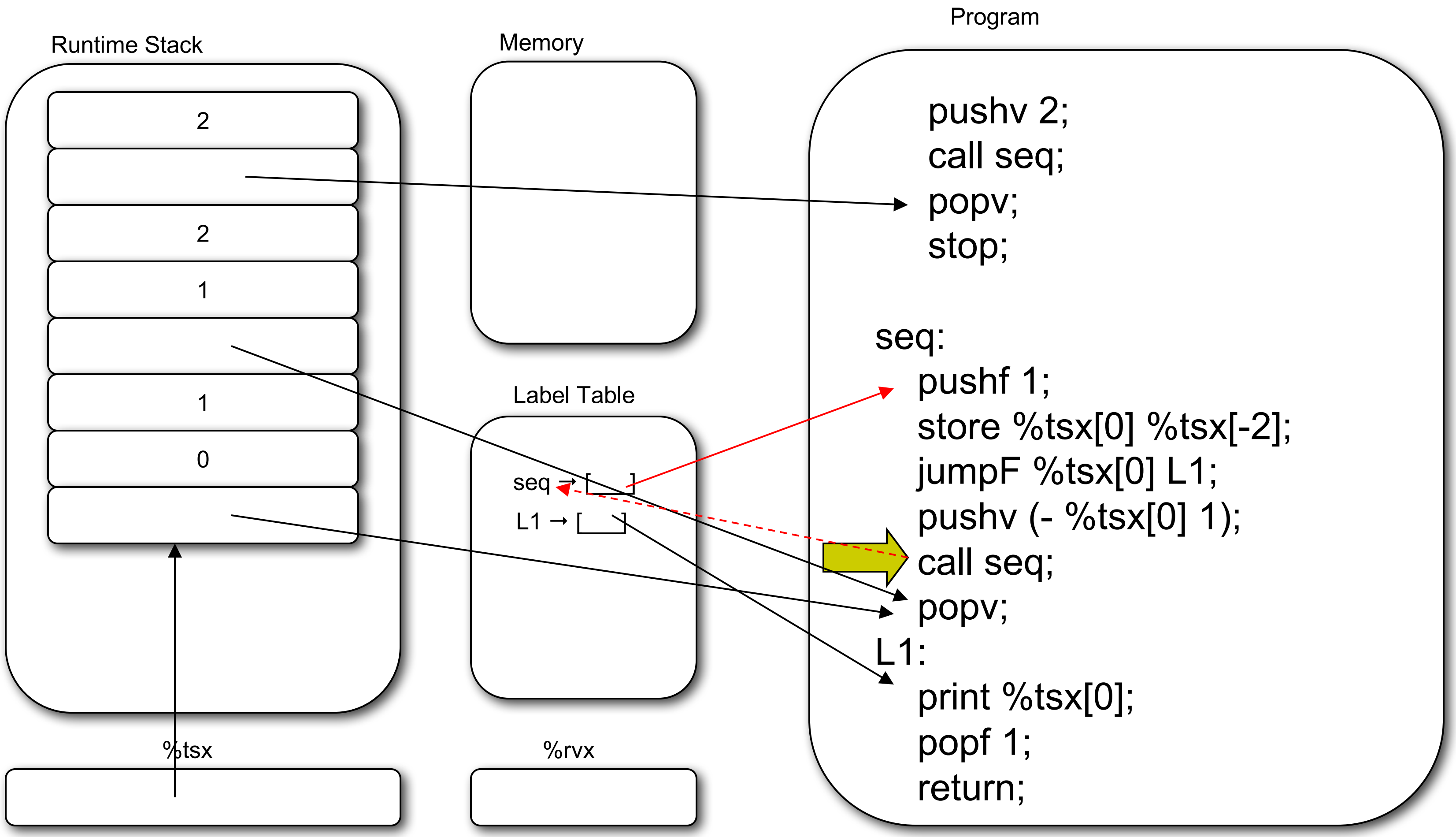
Virtual Machine Design



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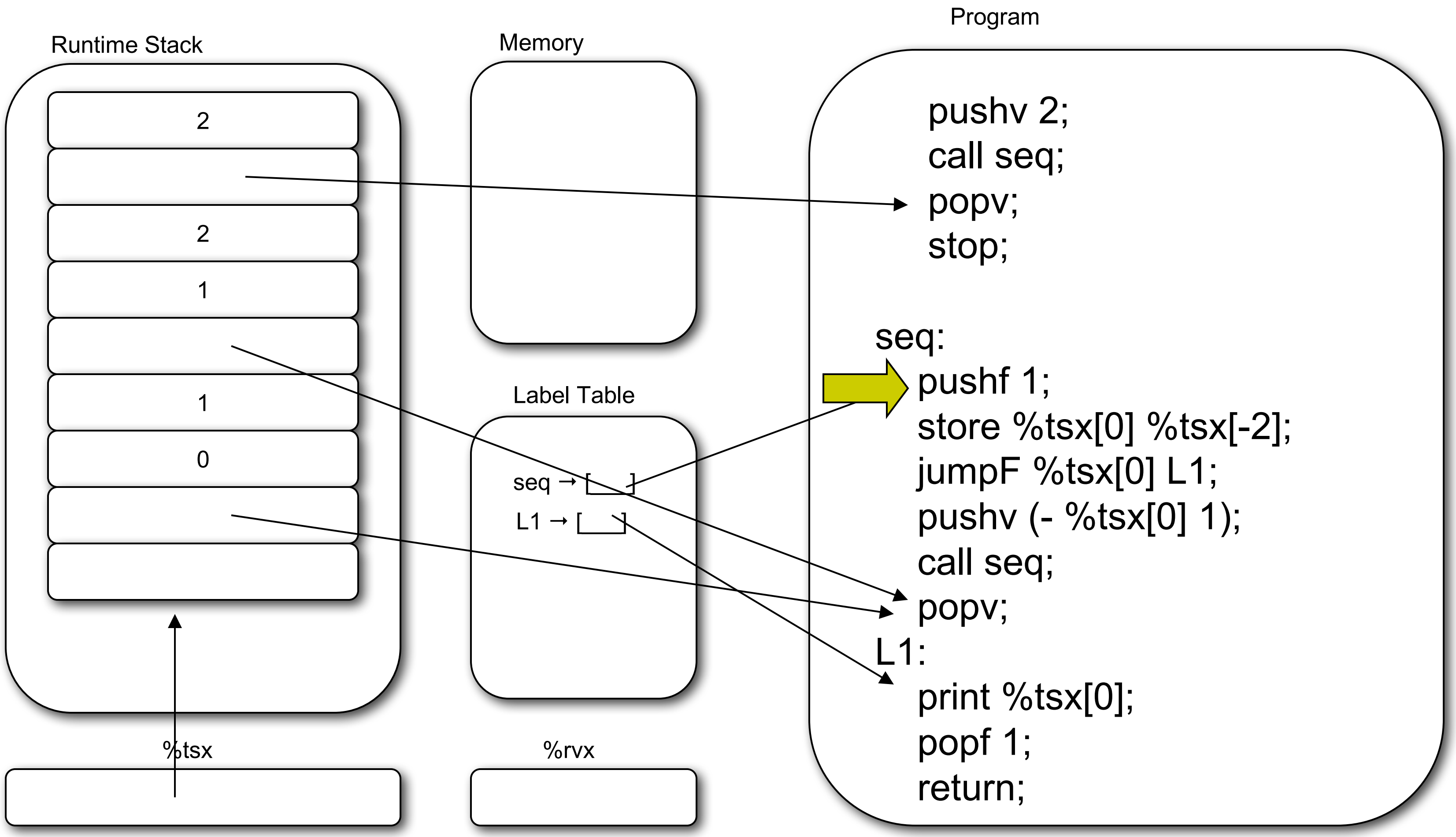
```

Virtual Machine Design



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L1:
  print %tsx[0];
  popf 1;
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```
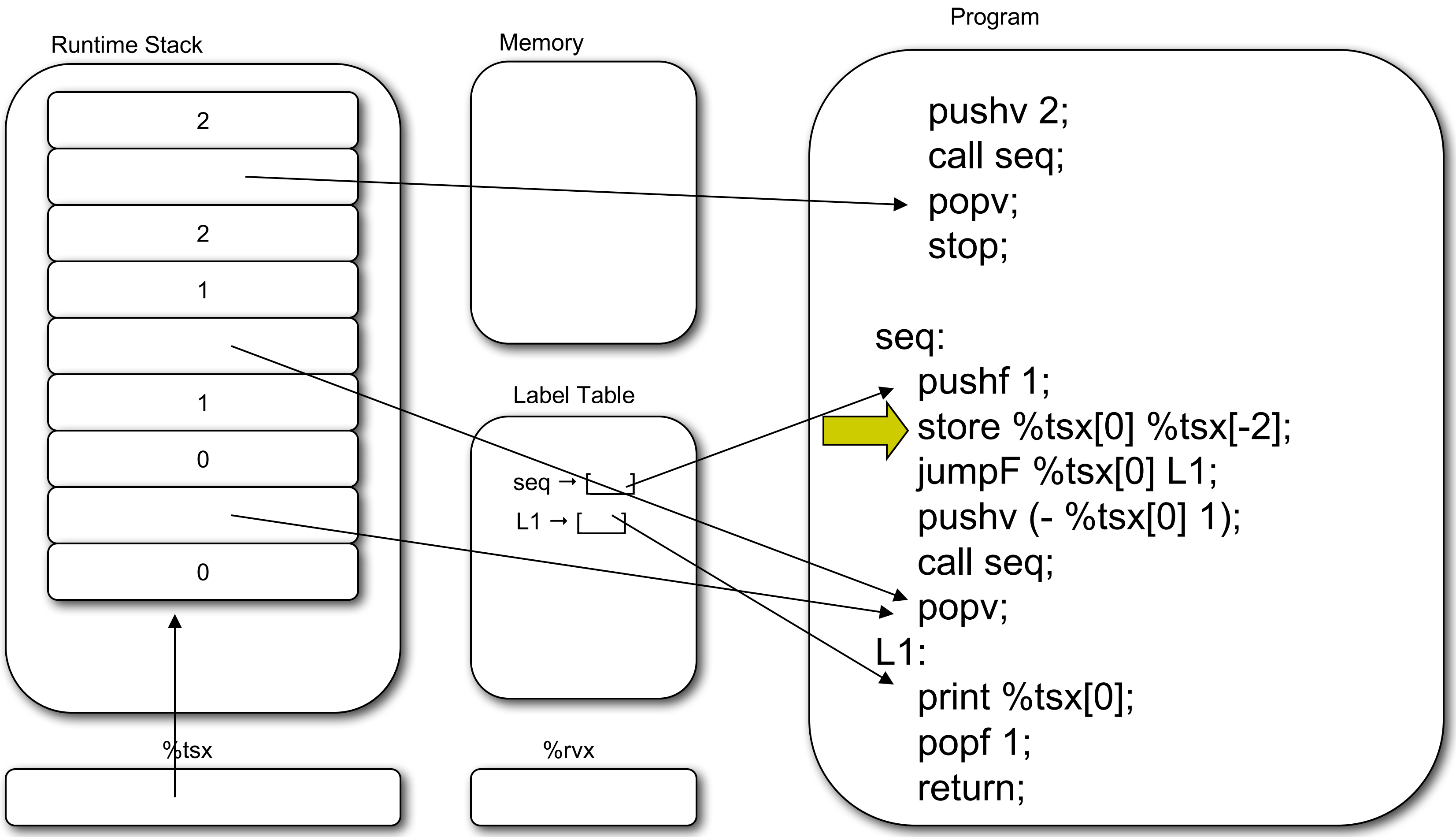

Virtual Machine Design



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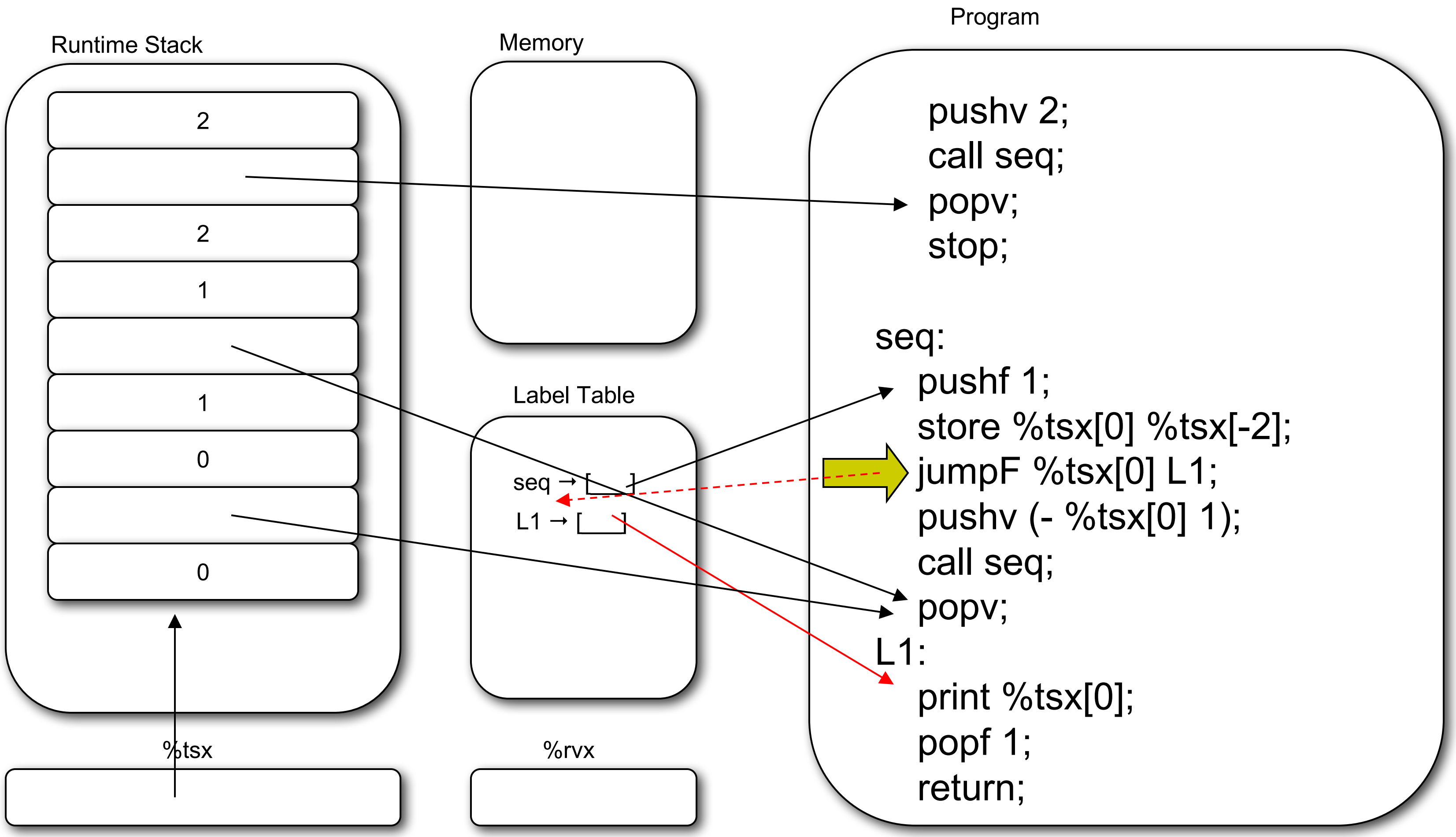
Virtual Machine Design



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   popv;
L1:
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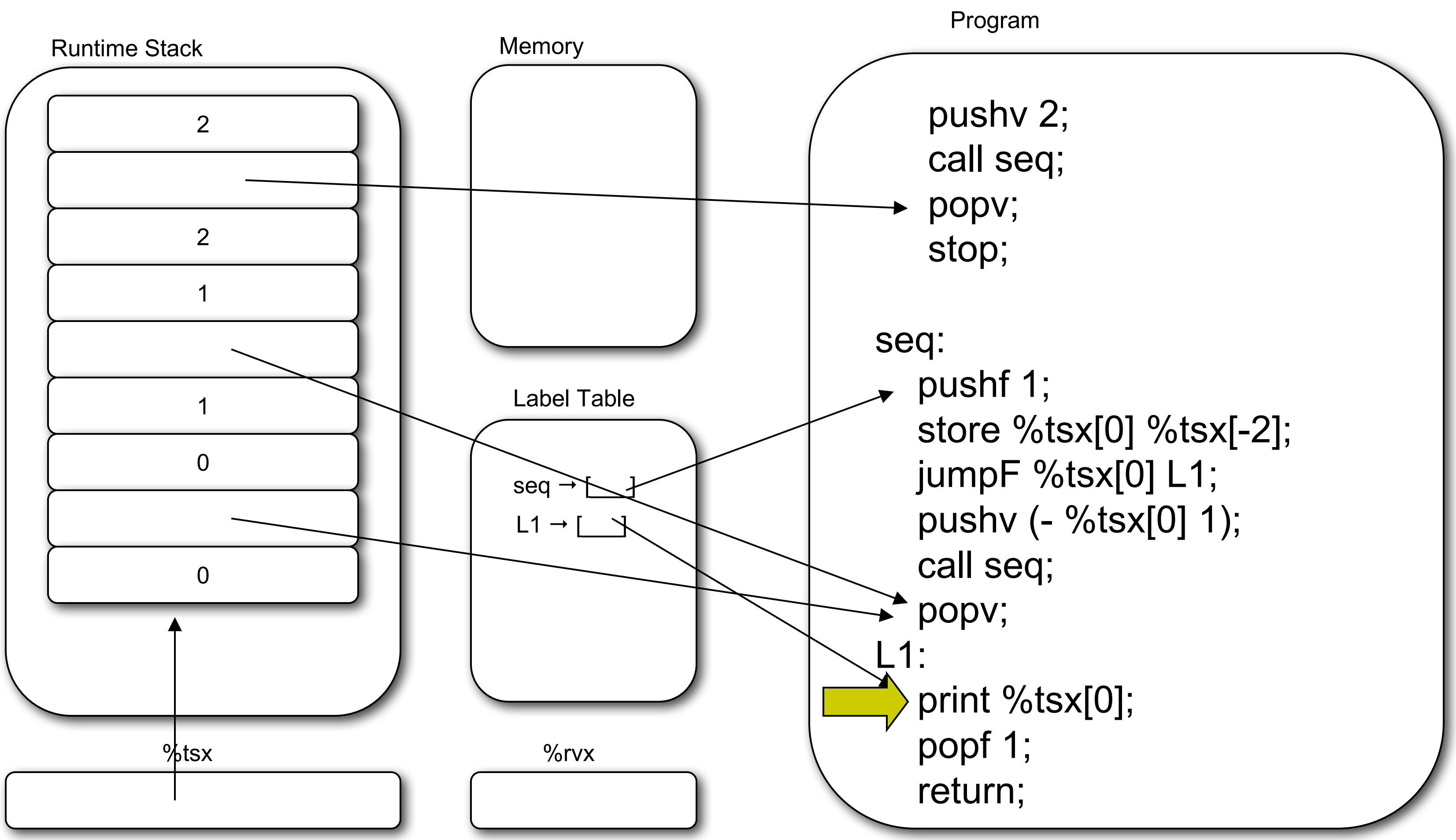
   popf 1;
   return;
```

Virtual Machine Design

0



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```
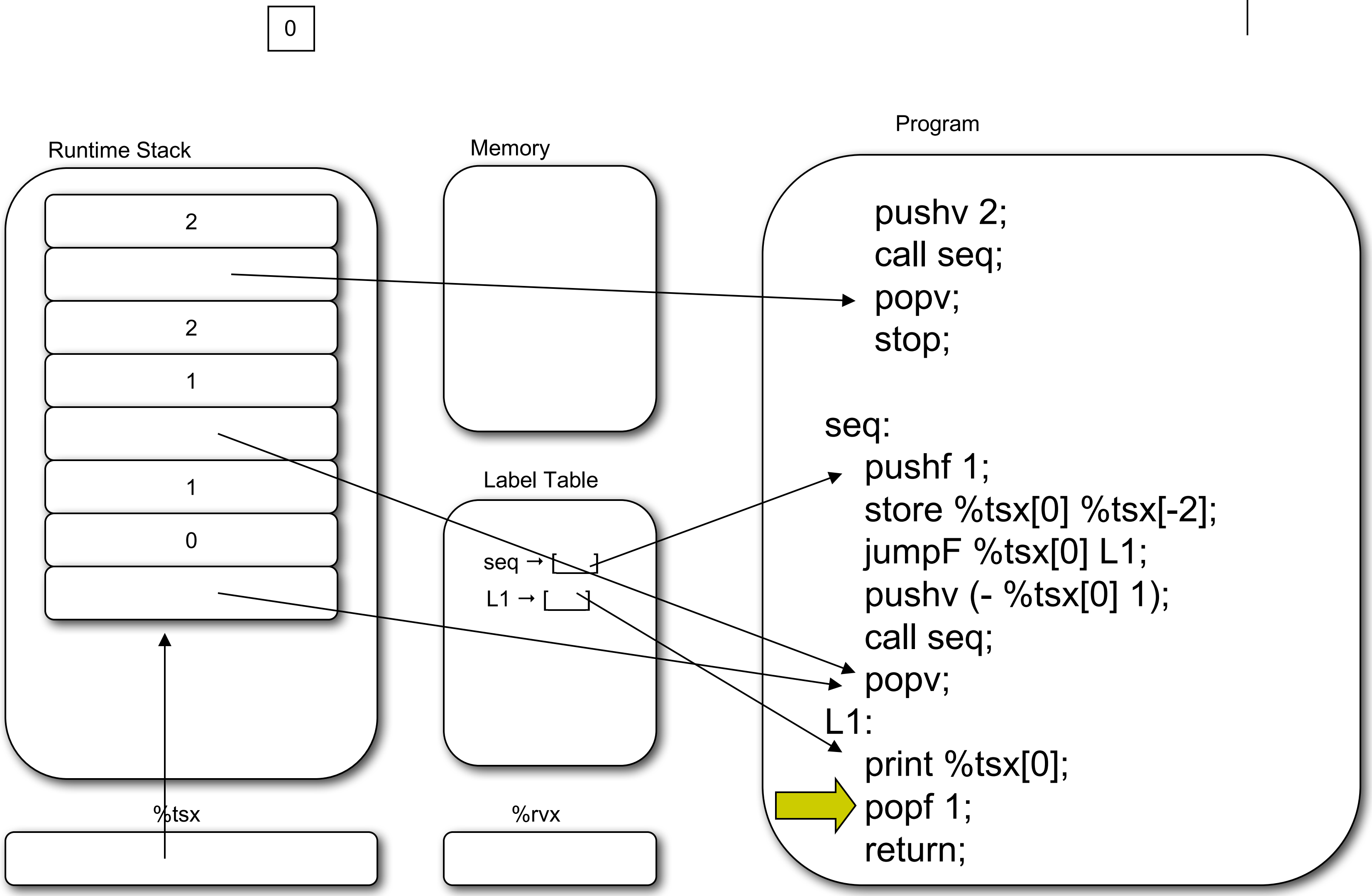

Virtual Machine Design



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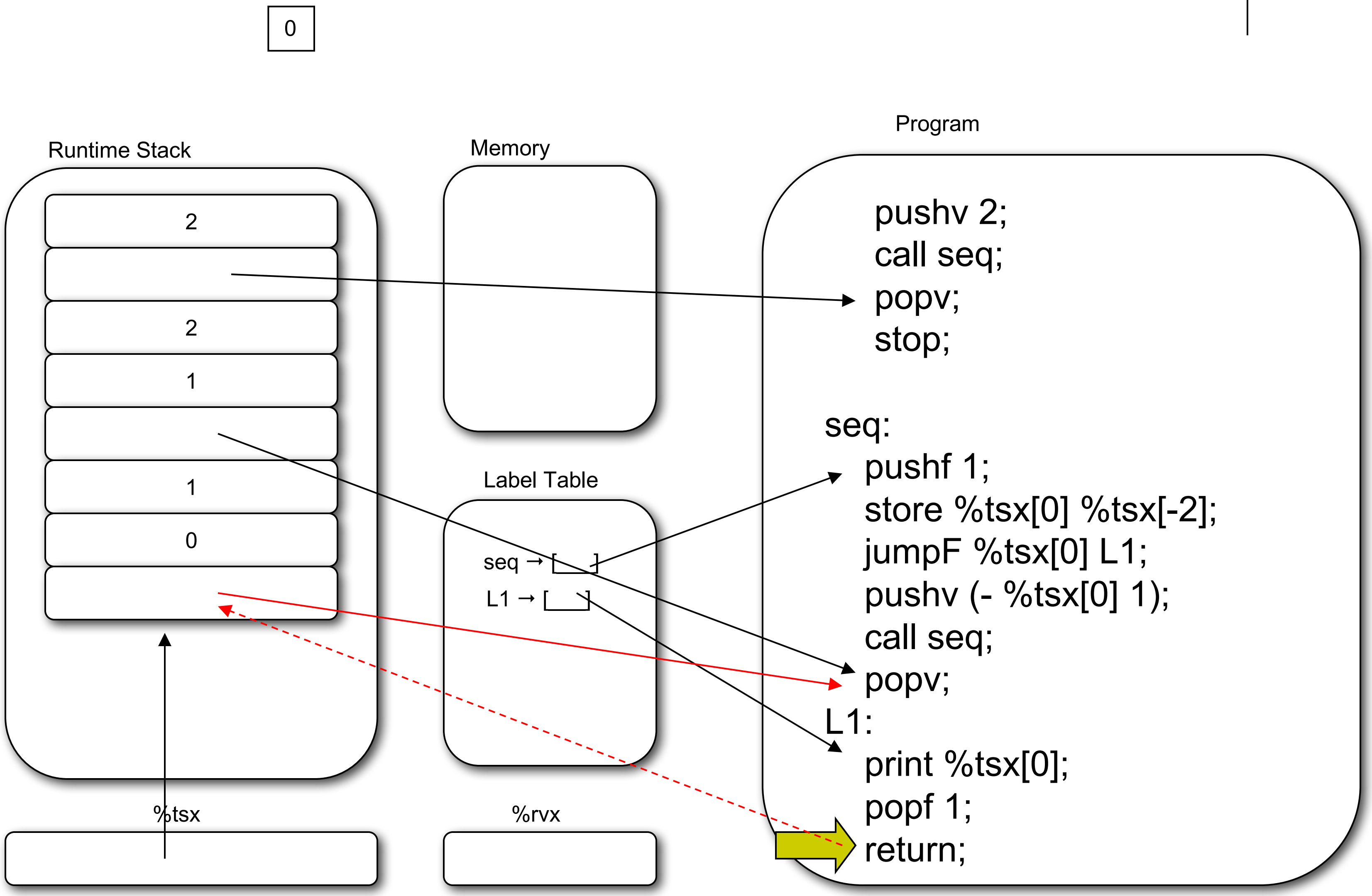
Virtual Machine Design



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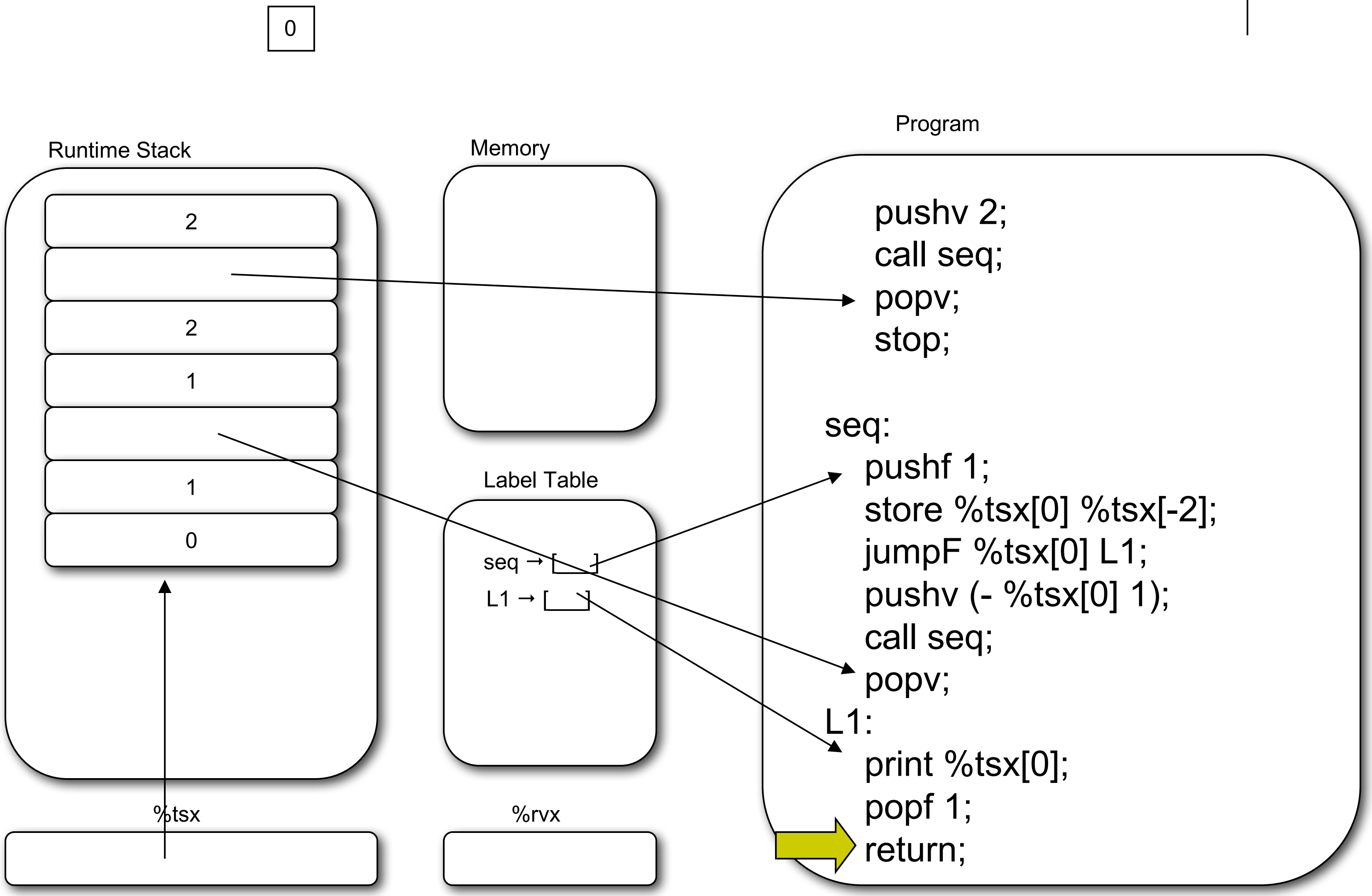
Virtual Machine Design



```
   pushv 2;
   call seq;
   popv;
   stop;

seq:
   pushf 1;
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   jumpF %tsx[0] L1;
   pushv (- %tsx[0] 1);
   call seq;
   popv;
L1:
   print %tsx[0];
   popf 1;
   return;
```
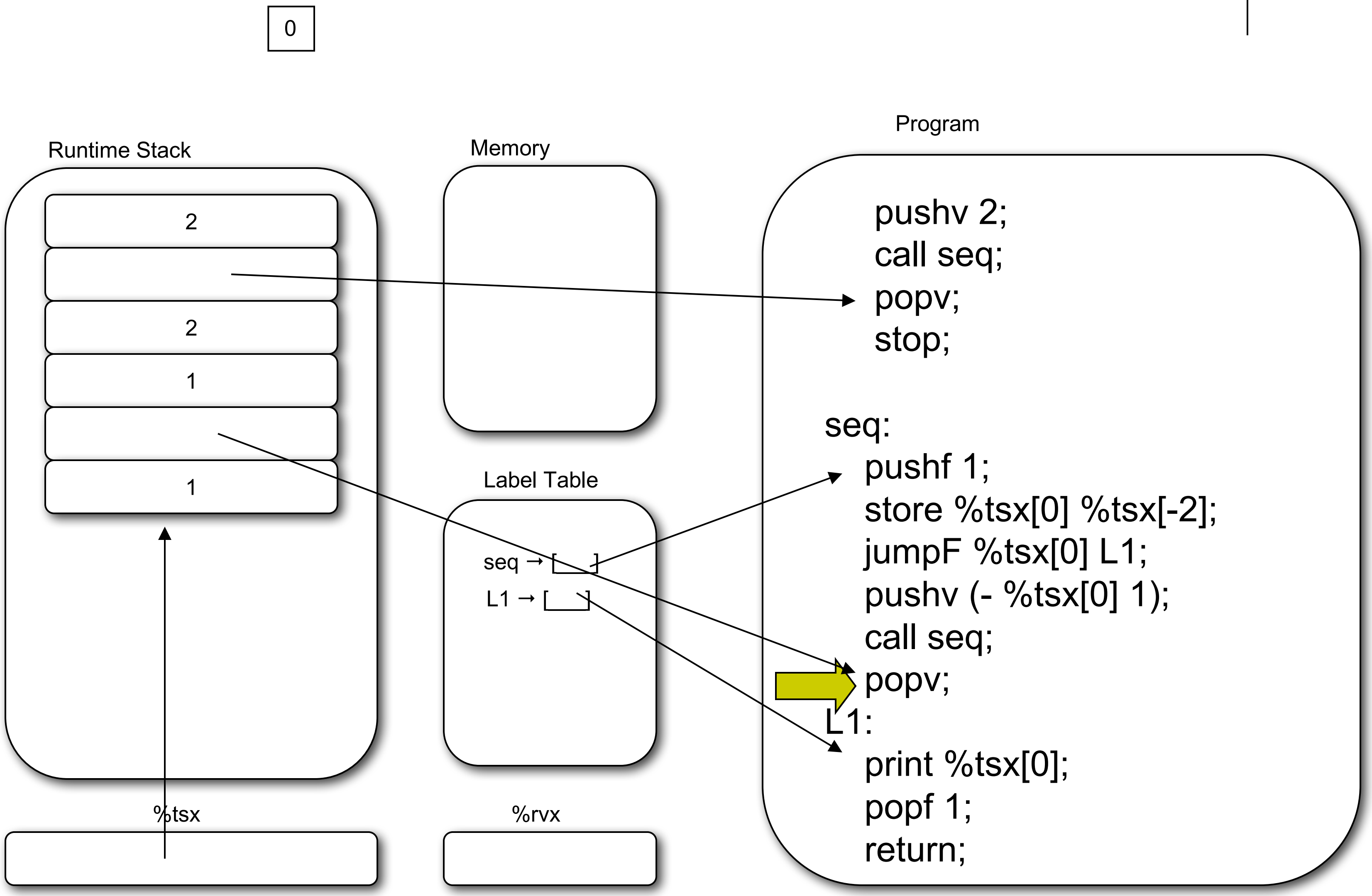

Virtual Machine Design



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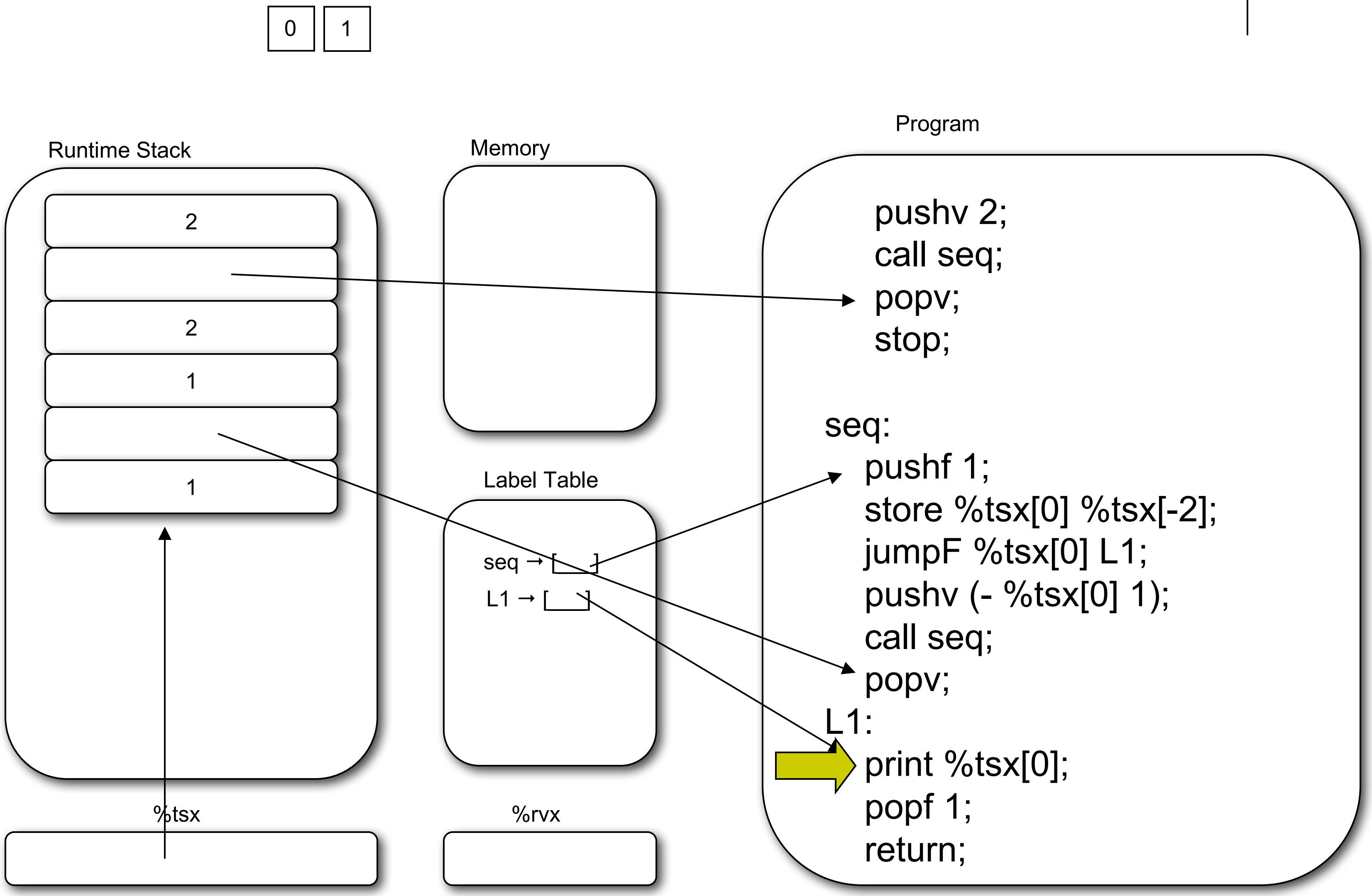
Virtual Machine Design



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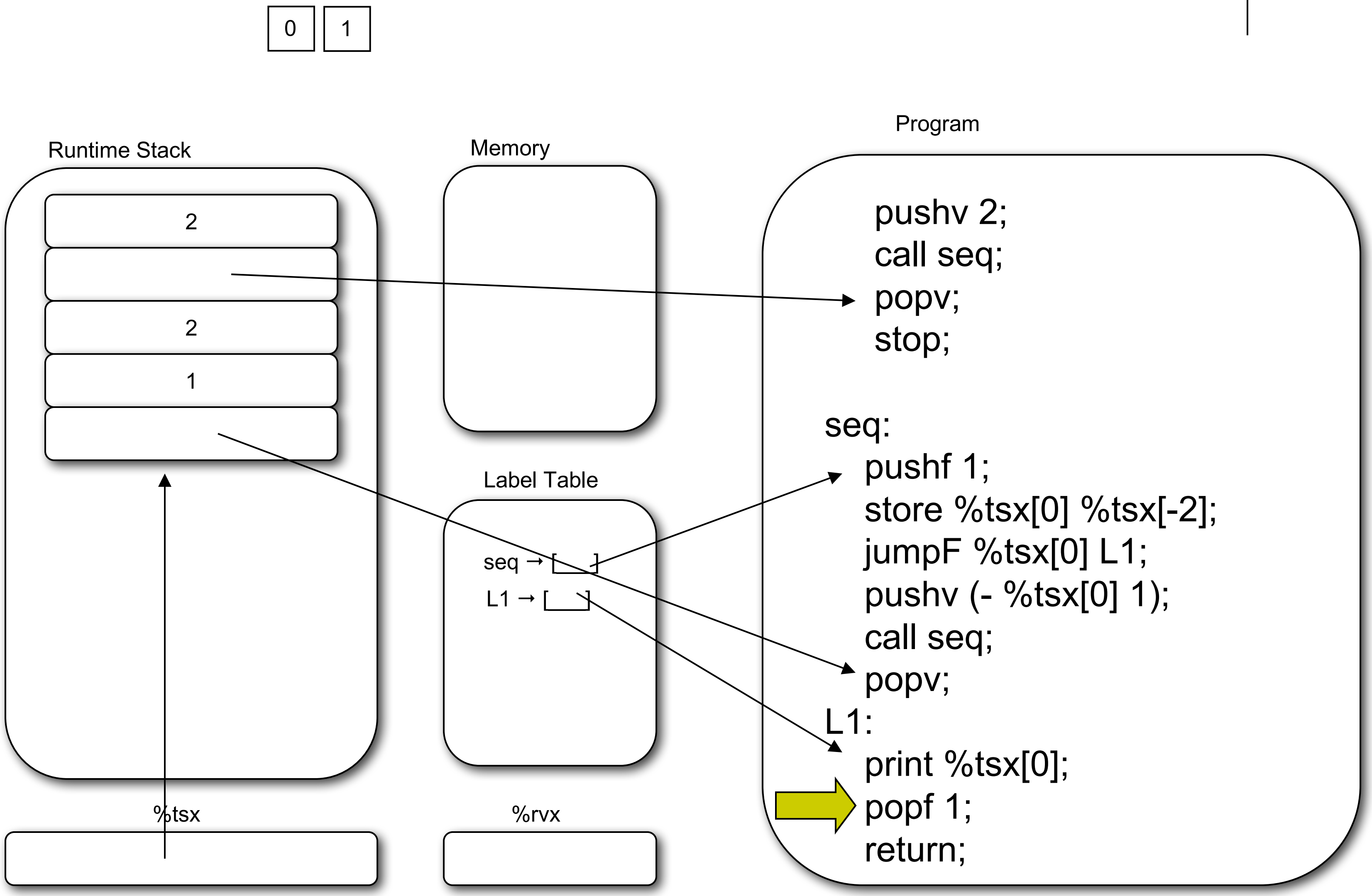
Virtual Machine Design



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  popv;
L1:
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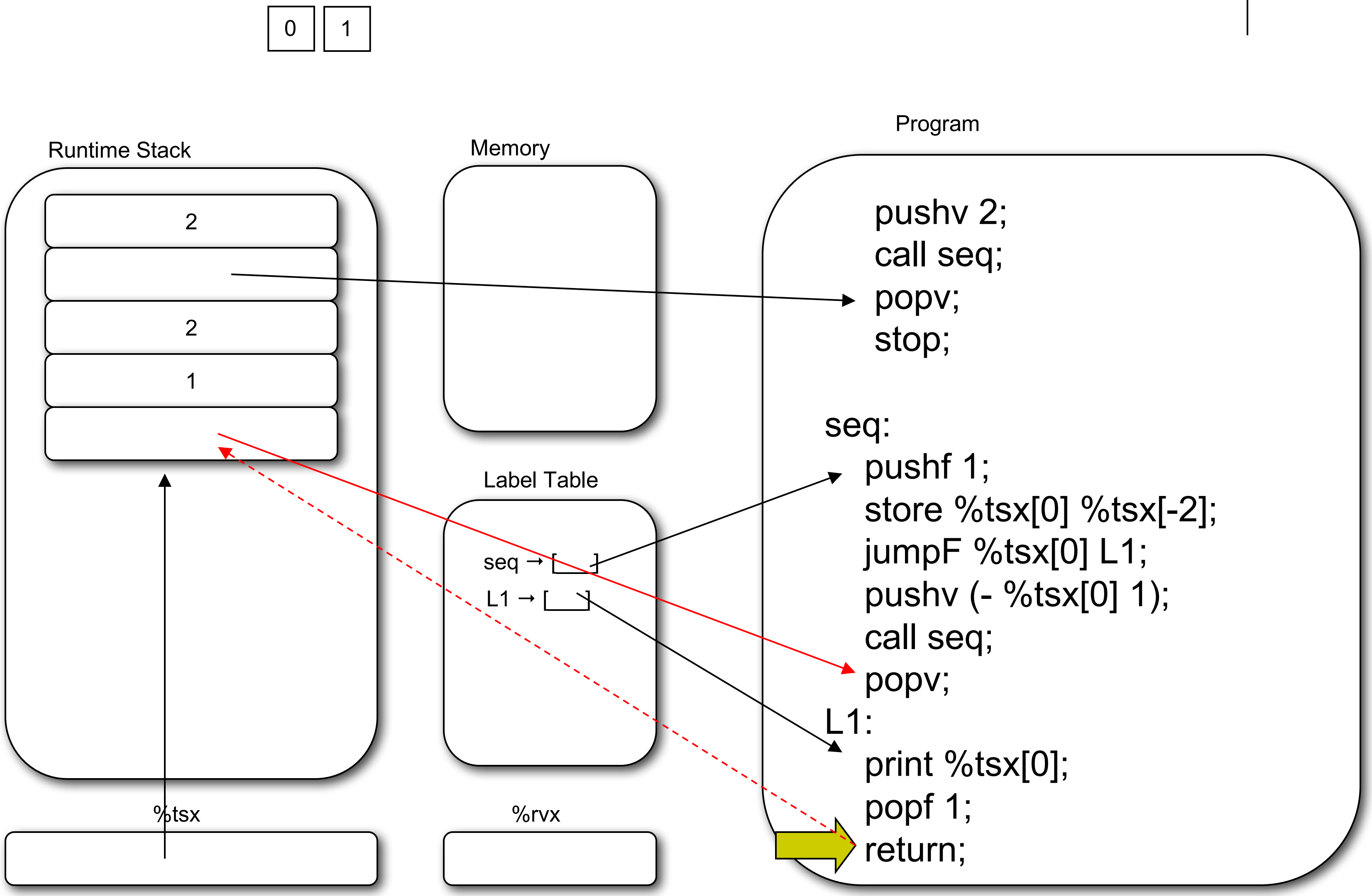
Virtual Machine Design



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   call seq;
   popv;
L1:
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   popf 1;
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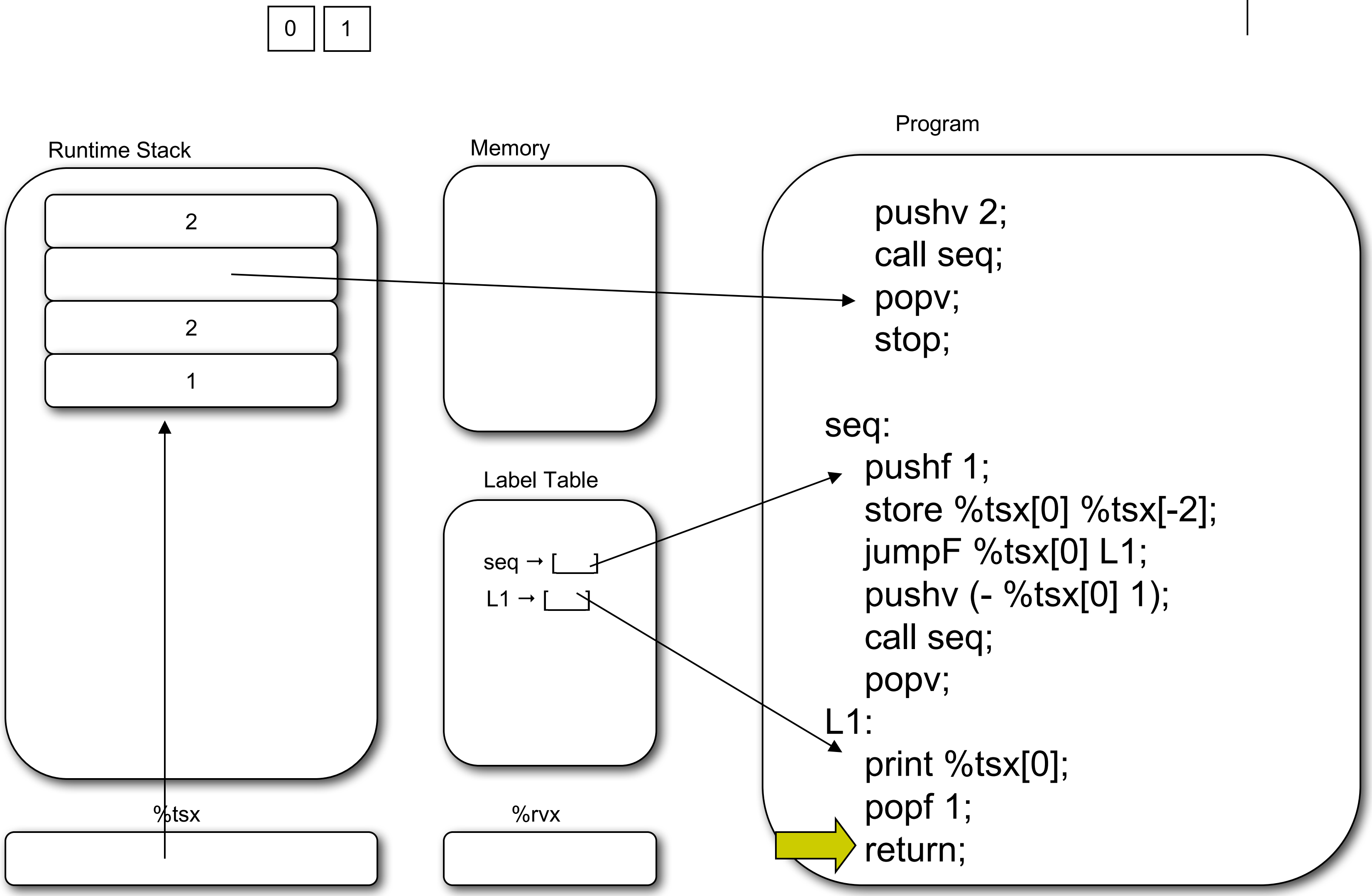
```

Virtual Machine Design



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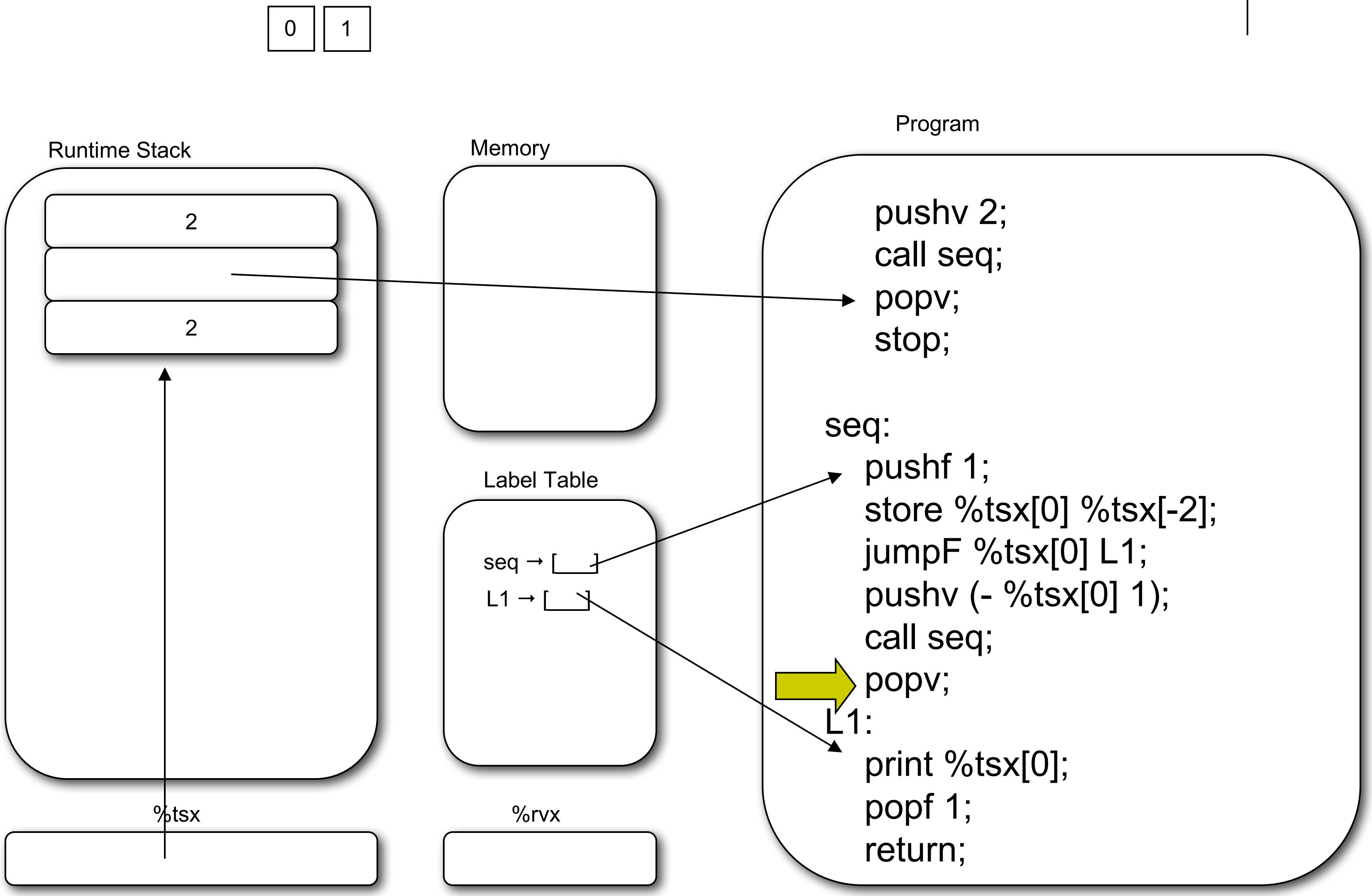
Virtual Machine Design



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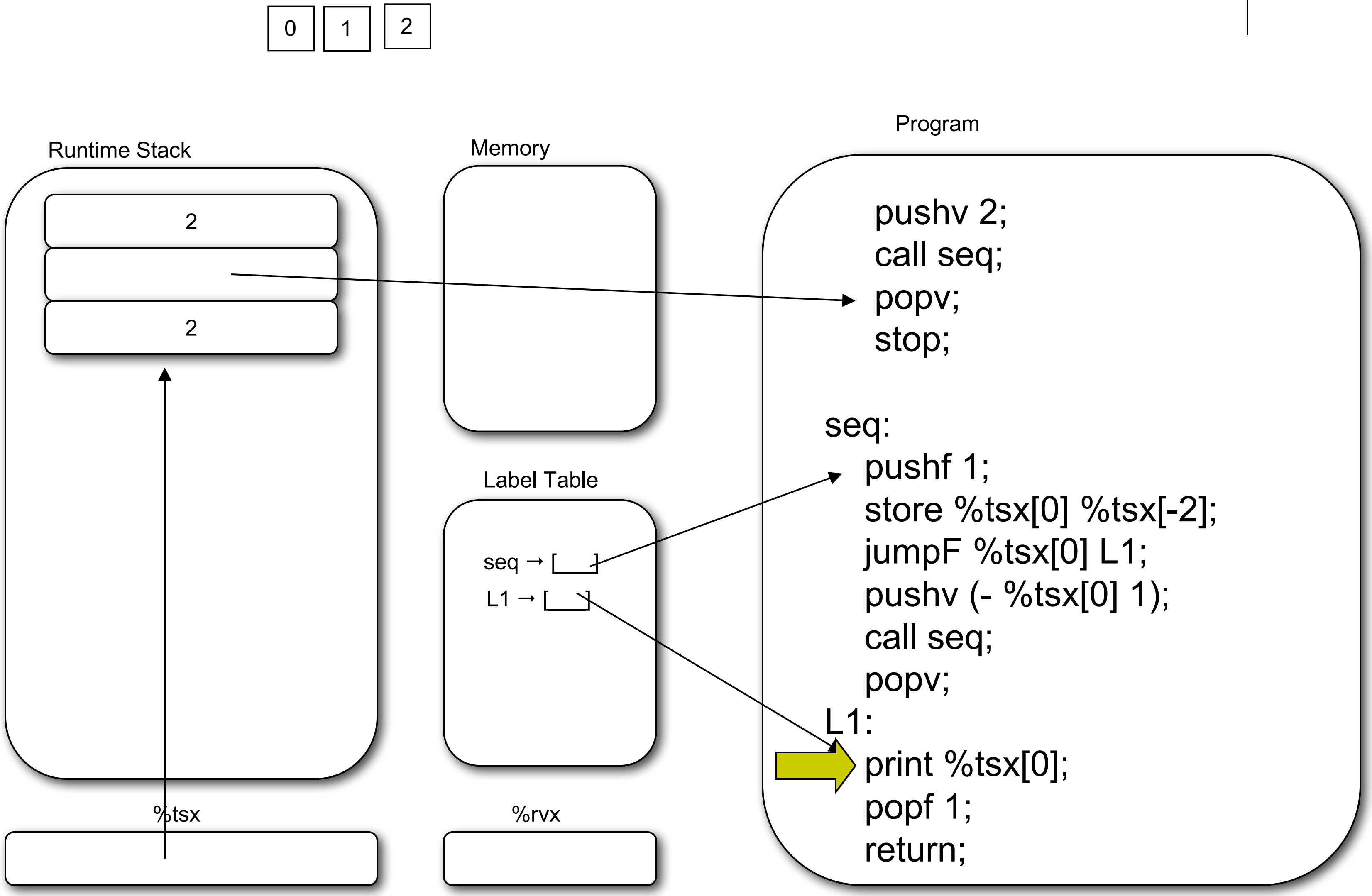
Virtual Machine Design



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    popv;
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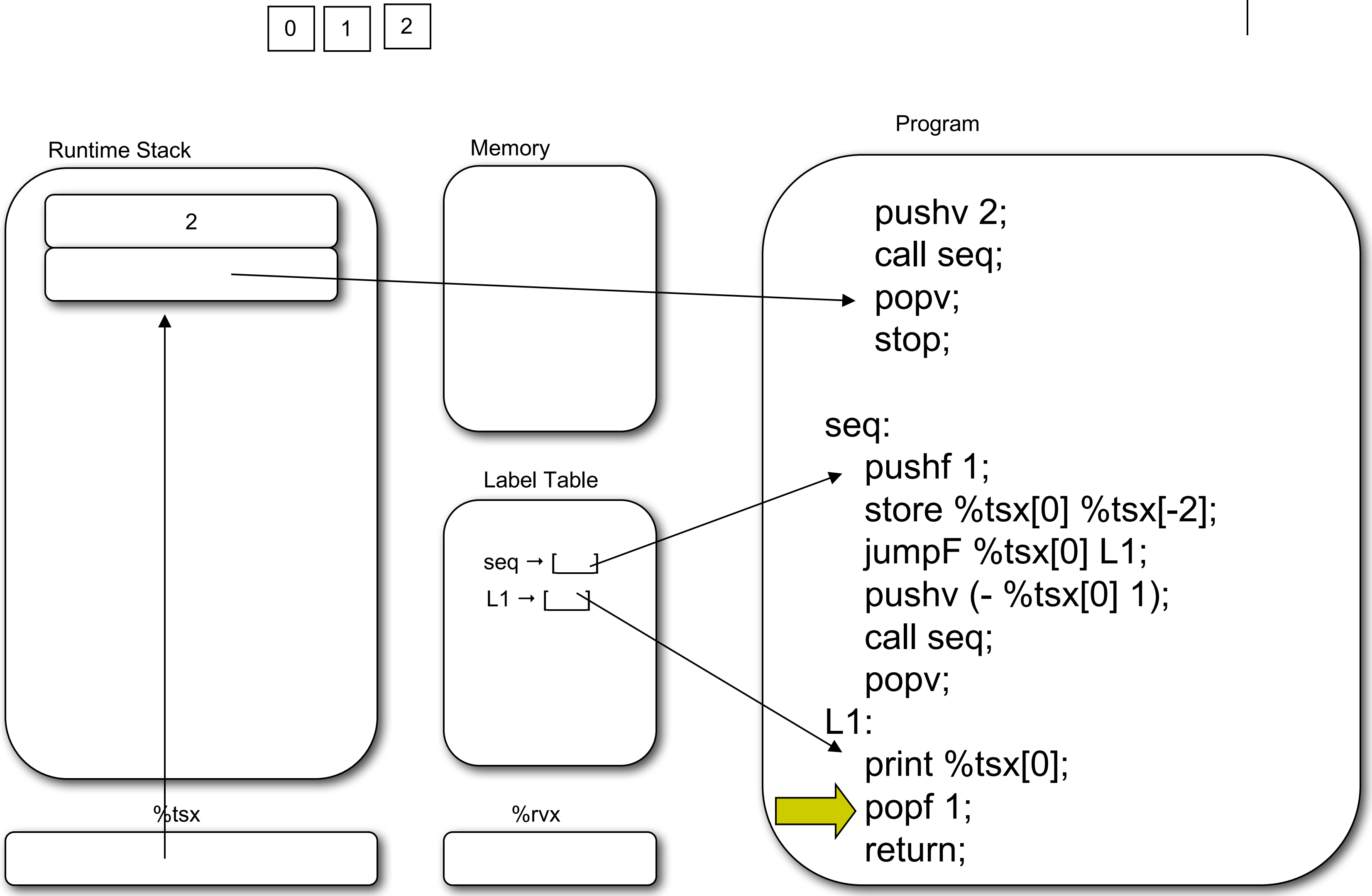
Virtual Machine Design



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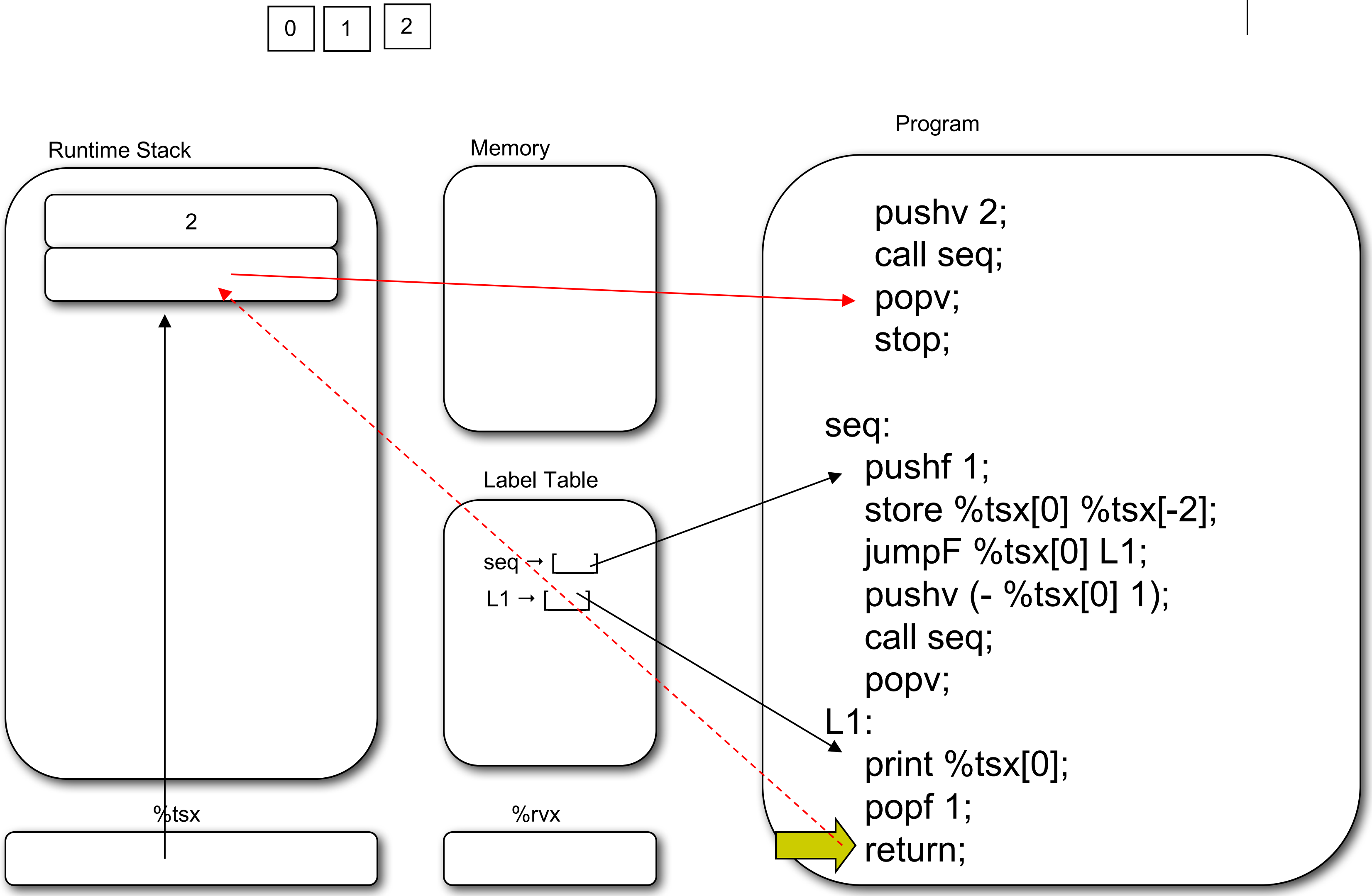
Virtual Machine Design



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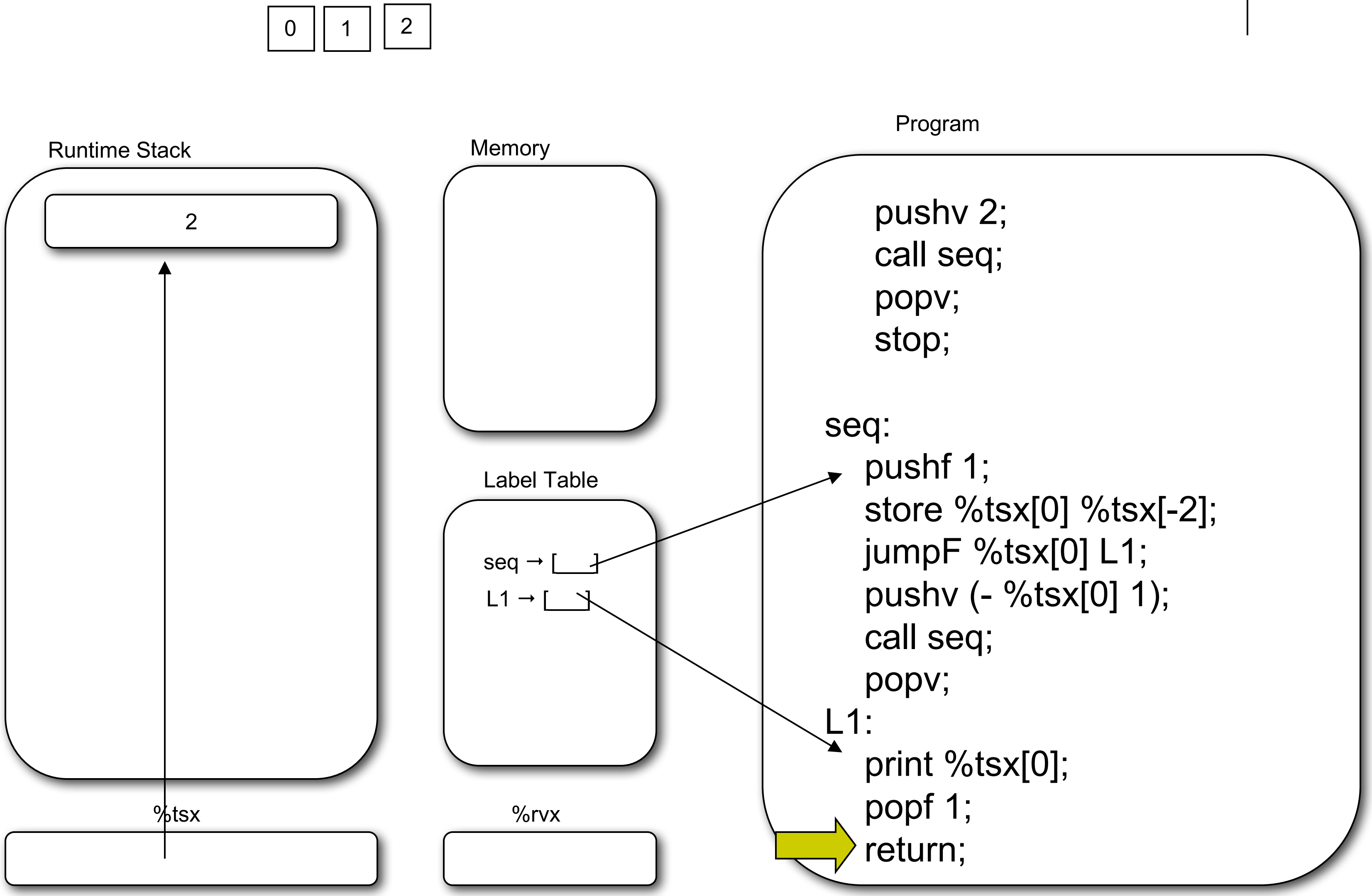
Virtual Machine Design



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```
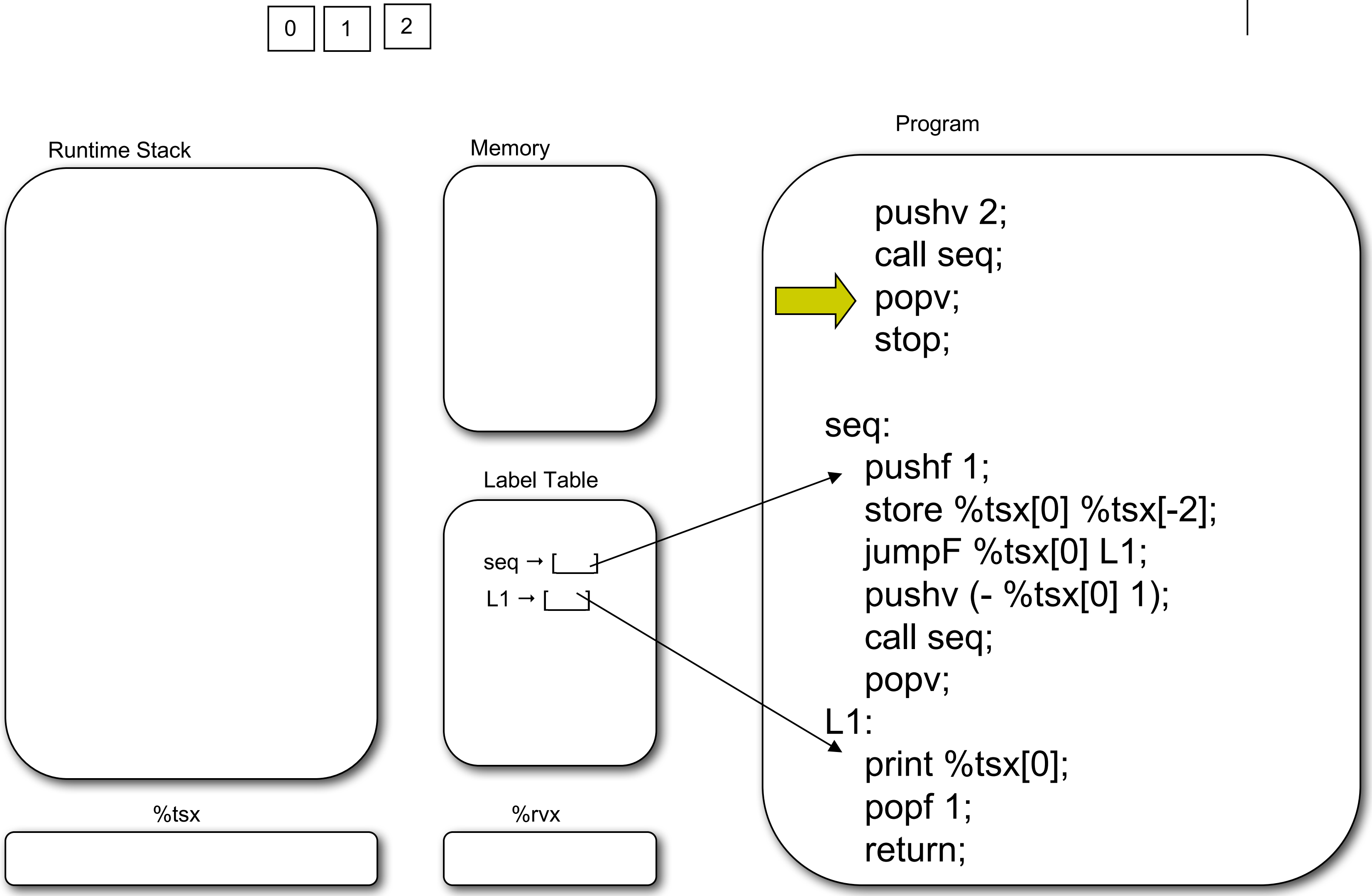

Virtual Machine Design



```
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```
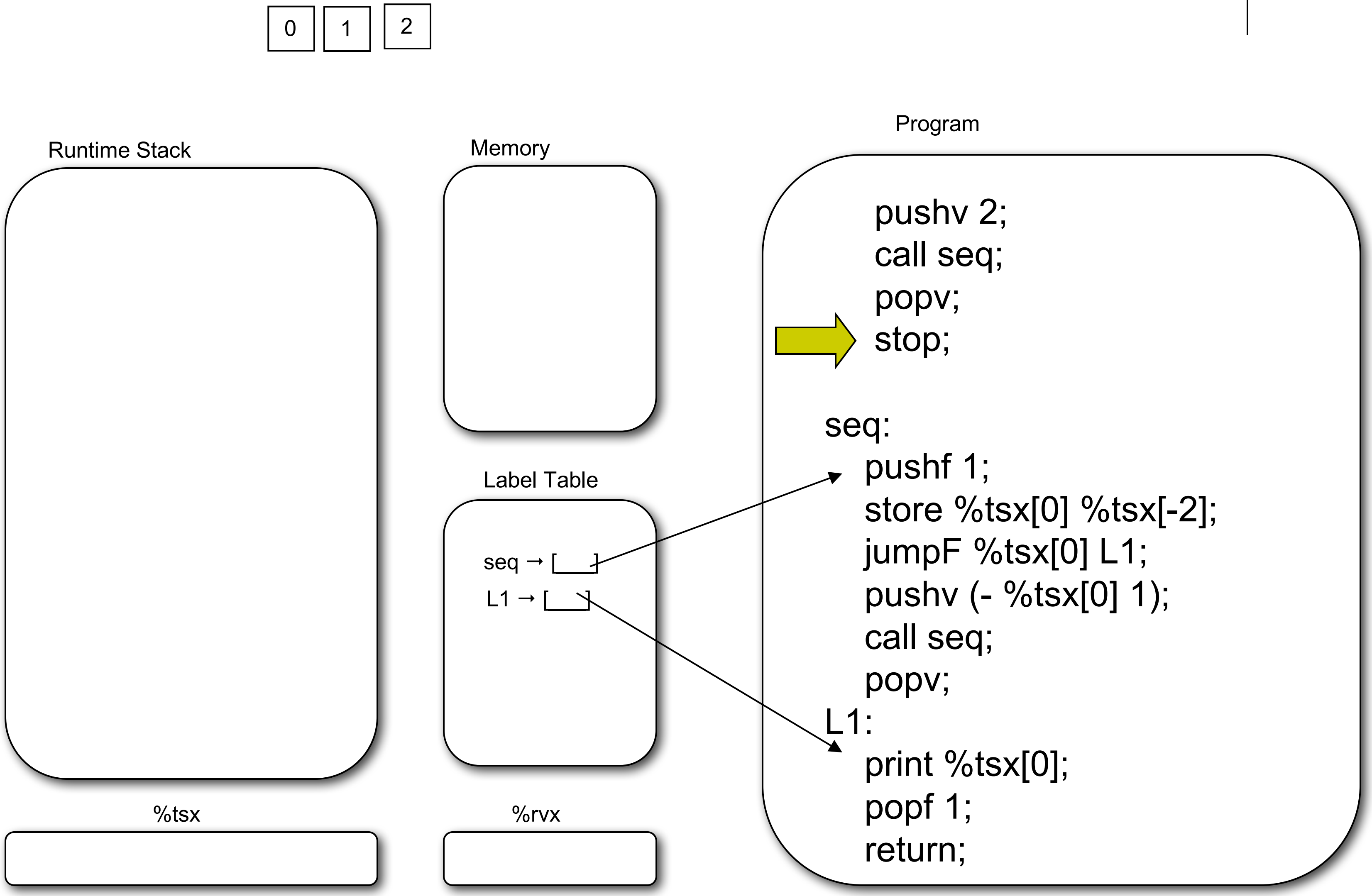

Virtual Machine Design



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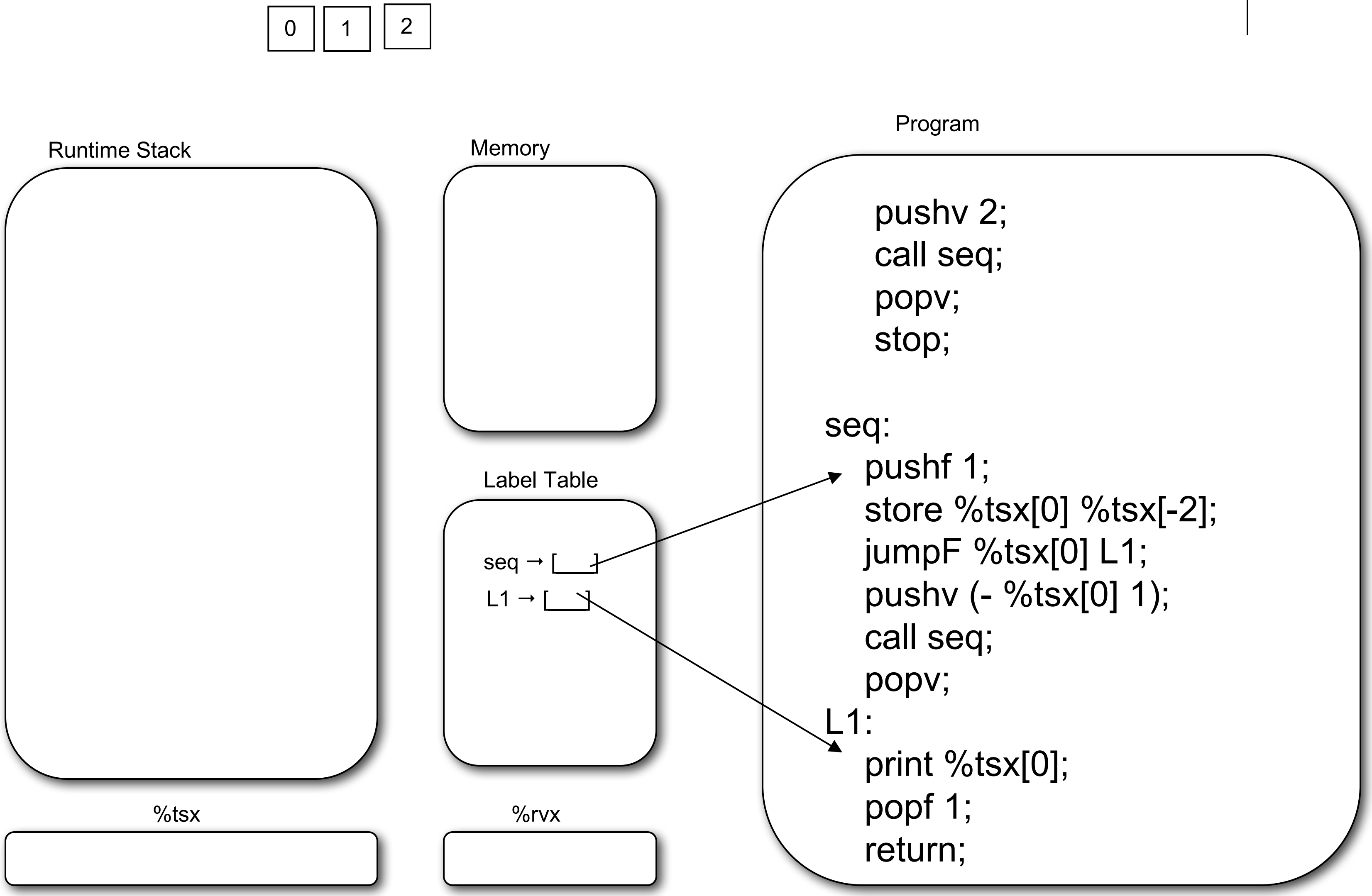
```

Virtual Machine Design



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    pushf 1;
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    call seq;
    popv;
L1:
    print %tsx[0];
    popf 1;
    return;
```
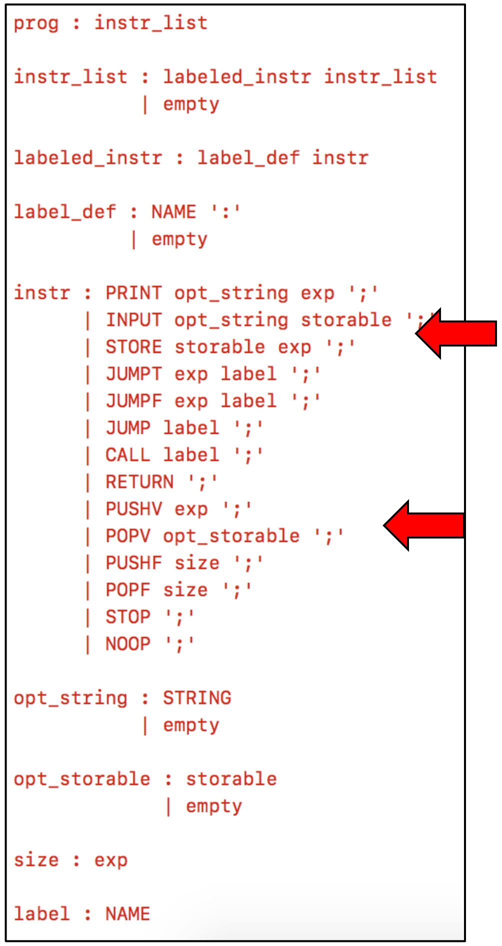
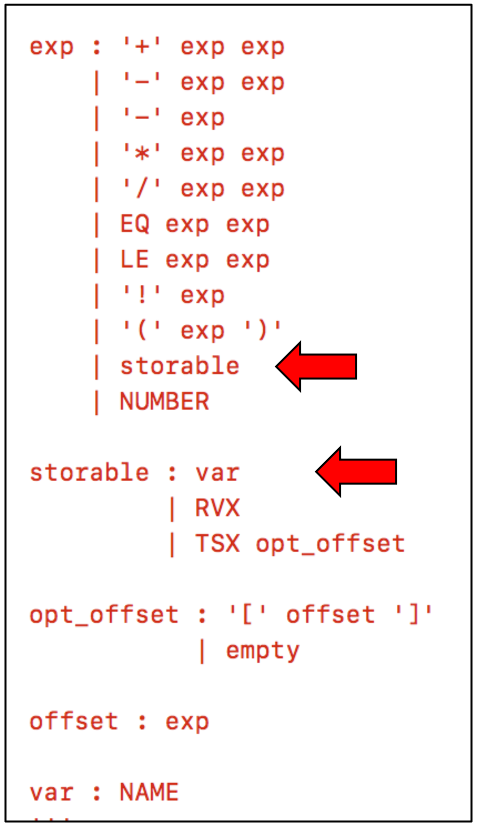

Exp2Bytecode – Abstract Machine

- Exp2bytecode introduces ‘storable’ in order to deal with different classes of memory.



```
prog : instr_list

instr_list : labeled_instr instr_list
           | empty

labeled_instr : label_def instr

label_def : NAME ':'
          | empty

instr : PRINT opt_string exp ';'
      | INPUT opt_string storable ';'
      | STORE storable exp ';'
      | JUMPT exp label ';'
      | JUMPF exp label ';'
      | JUMP label ';'
      | CALL label ';'
      | RETURN ';'
      | PUSHV exp ';'
      | POPV opt_storable ';'
      | PUSHF size ';'
      | POPF size ';'
      | STOP ';'
      | NOOP ';'

opt_string : STRING
           | empty

opt_storable : storable
             | empty

size : exp

label : NAME
```



```
exp : '+' exp exp
    | '-' exp exp
    | '-' exp
    | '*' exp exp
    | '/' exp exp
    | EQ exp exp
    | LE exp exp
    | '!' exp
    | '(' exp ')'
    | storable
    | NUMBER

storable : var
         | RVX
         | TSX opt_offset

opt_offset : '[' offset ']'
           | empty

offset : exp

var : NAME
```

Exp2Bytecode – A
Machine

```
# define and initialize the structures of our abstract machine

class State:

    def __init__(self):
        self.initialize()

    def initialize(self):
        self.program = []
        self.symbol_table = dict()
        self.label_table = dict()
        self.runtime_stack = []
        self.instr_ix = 0
        self.rvx = None # return value register

state = State()
```

```
def p_labeled_instr(p):
    '''
    labeled_instr : label_def instr
    '''
    # if label exists record it in the label table
    if p[1]:
        state.label_table[p[1]] = state.instr_ix
    # append instr to program
    state.program.append(p[2])
    state.instr_ix += 1
```

```
def p_instr(p):
    '''
    instr : PRINT opt_string exp ';'
          | INPUT opt_string NAME ';'
          | STORE storable exp ';'
          | JUMPT exp label ';'
          | JUMPF exp label ';'
          | JUMP label ';'
          | CALL label ';'
          | RETURN ';'
          | PUSHV exp ';'
          | POPV opt_storable ';'
          | PUSHF size ';'
          | POPF size ';'
          | STOP ';'
          | NOOP ';'
    '''
    # for each instr assemble the appropriate tuple
    if p[1] == 'print':
        p[0] = ('print', p[2], p[3])
    elif p[1] == 'input':
        p[0] = ('input', p[2], p[3])
    elif p[1] == 'store':
        p[0] = ('store', p[2], p[3])
    elif p[1] == 'jumpT':
        p[0] = ('jumpT', p[2], p[3])
    elif p[1] == 'jumpF':
        p[0] = ('jumpF', p[2], p[3])
    elif p[1] == 'jump':
        p[0] = ('jump', p[2])
    elif p[1] == 'call':
        p[0] = ('call', p[2])
    elif p[1] == 'return':
        p[0] = ('return',)
    elif p[1] == 'pushv':
        p[0] = ('pushv', p[2])
    elif p[1] == 'popv':
        p[0] = ('popv', p[2])
    elif p[1] == 'pushf':
        p[0] = ('pushf', p[2])
    elif p[1] == 'popf':
        p[0] = ('popf', p[2])  ...
```

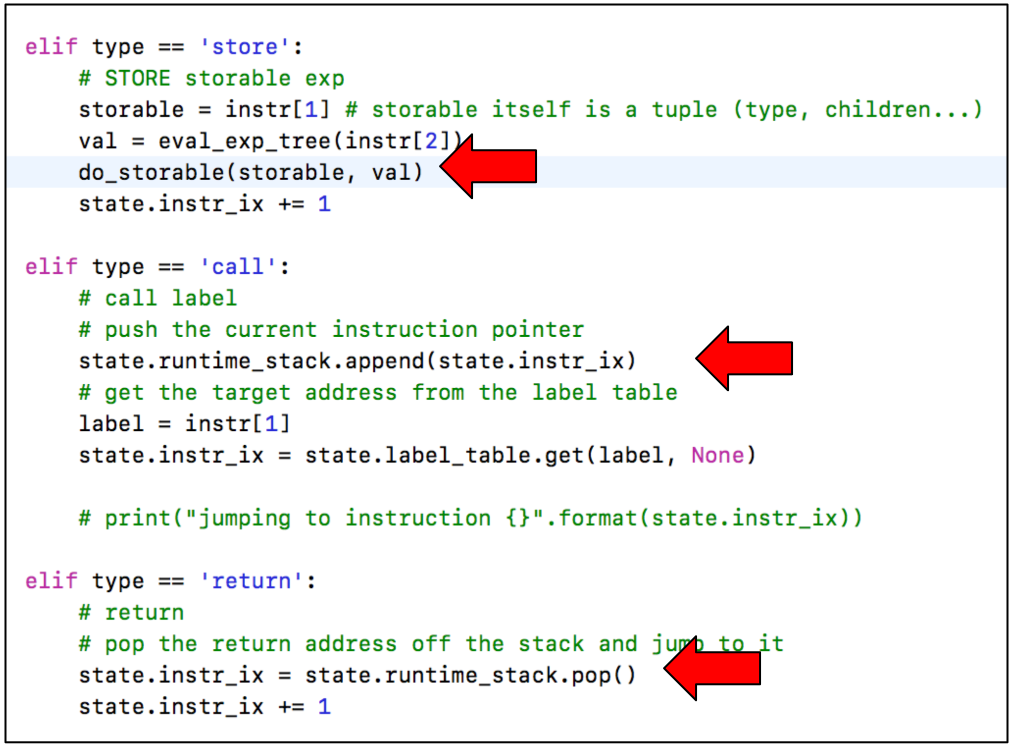
Exp2Bytecode – Abstract Machine

- As in exp1bytecode – the interpreter is just one big loop that interprets the instructions on the program list.

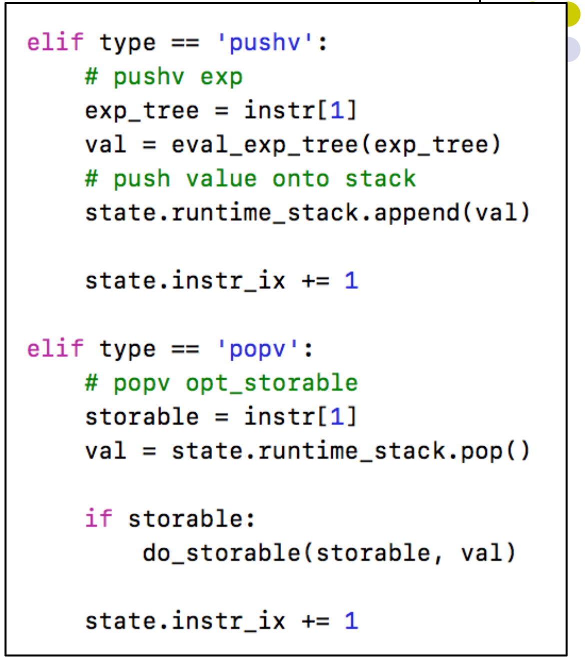
```
def interp_program():
    'execute abstract bytecode machine'

    # We cannot use the list iterator here because we
    # need to be able to interpret jump instructions

    # start at the first instruction in program
    state.instr_ix = 0

    # keep interpreting until we run out of instructions
    # or we hit a 'stop'
    while True:
        if state.instr_ix == len(state.program):
            # no more instructions
            break
        else:
            # get instruction from program
            instr = state.program[state.instr_ix]

        # instruction format: (type, [arg1, arg2, ...])
        type = instr[0]
```

Interpret instructions here…

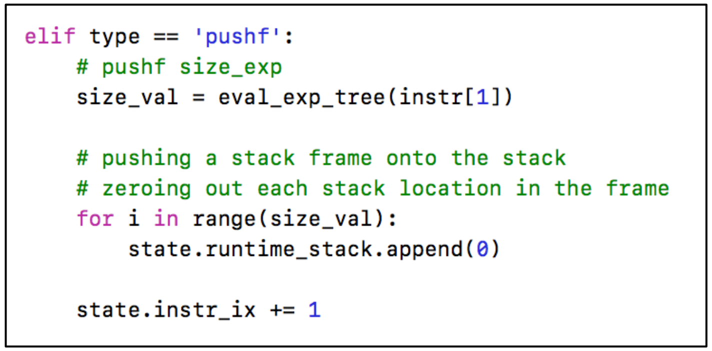
Exp2Bytecode – Abstract Machine



```python
elif type == 'store':
    # STORE storable exp
    storable = instr[1] # storable itself is a tuple (type, children...)
    val = eval_exp_tree(instr[2])
    do_storable(storable, val)
    state.instr_ix += 1

elif type == 'call':
    # call label
    # push the current instruction pointer
    state.runtime_stack.append(state.instr_ix)
    # get the target address from the label table
    label = instr[1]
    state.instr_ix = state.label_table.get(label, None)

    # print("jumping to instruction {}".format(state.instr_ix))

elif type == 'return':
    # return
    # pop the return address off the stack and jump to it
    state.instr_ix = state.runtime_stack.pop()
    state.instr_ix += 1
```

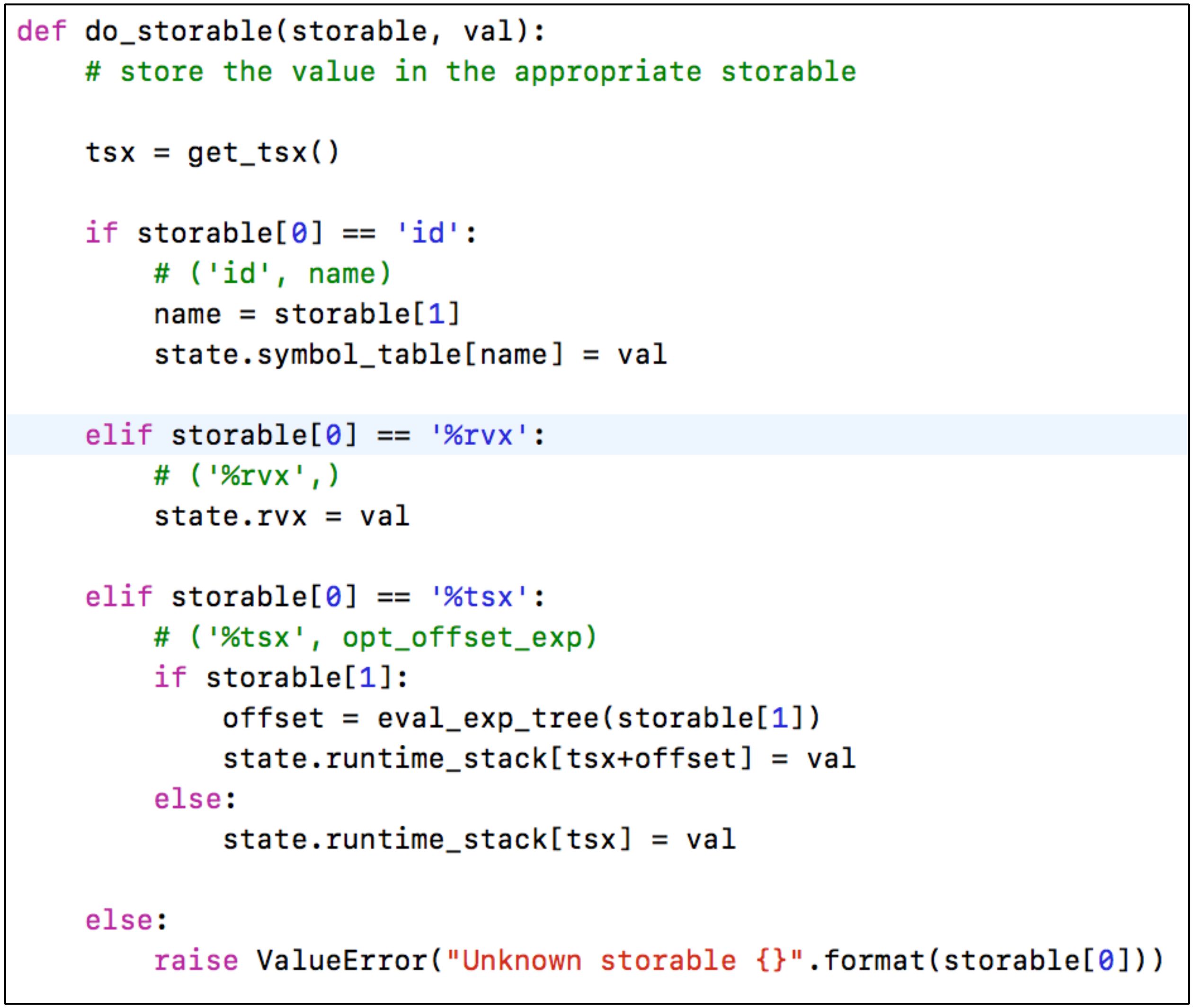


```python
elif type == 'pushv':
    # pushv exp
    exp_tree = instr[1]
    val = eval_exp_tree(exp_tree)
    # push value onto stack
    state.runtime_stack.append(val)

    state.instr_ix += 1

elif type == 'popv':
    # popv opt_storable
    storable = instr[1]
    val = state.runtime_stack.pop()

    if storable:
        do_storable(storable, val)

    state.instr_ix += 1
```



```python
elif type == 'pushf':
    # pushf size_exp
    size_val = eval_exp_tree(instr[1])

    # pushing a stack frame onto the stack
    # zeroing out each stack location in the frame
    for i in range(size_val):
        state.runtime_stack.append(0)

    state.instr_ix += 1
```

Exp2Bytecode – Abstract Machine



```python
def do_storable(storable, val):
    # store the value in the appropriate storable

    tsx = get_tsx()

    if storable[0] == 'id':
        # ('id', name)
        name = storable[1]
        state.symbol_table[name] = val

    elif storable[0] == '%rvx':
        # ('%rvx',)
        state.rvx = val

    elif storable[0] == '%tsx':
        # ('%tsx', opt_offset_exp)
        if storable[1]:
            offset = eval_exp_tree(storable[1])
            state.runtime_stack[tsx+offset] = val
        else:
            state.runtime_stack[tsx] = val

    else:
        raise ValueError("Unknown storable {}".format(storable[0]))
```

Function Calls on Real Machines

- Function calls on real machines work similar to the function calls on our bytecode virtual machine.
- The main difference is the level of abstraction of the instruction set.
- We show examples of programs compiled on an Intel Mac.

Function Calls on Real Machines

- Functions on real machines are broken into three parts:
  - Function prologue - set up the stack environment in which the function executes
  - Function code - the code in the body of the function
  - Function epilogue - clean up the stack.
- On the Intel chip the function prologue looks something like this:
  - pushl %ebp // push the basepointer/framepointer on the stack
  - movl %esp, %ebp // make the current stack pointer the current frame pointer
  - subl $n, %esp // make a new frame of size n

Function Calls on Real Machines

- The function epilogue usually looks like this:
  - movl %ebp, %esp
  - popl %ebp
  - ret
- The x86 processor contains a built-in instruction which performs part of the epilogue. The following code is equivalent to the above code:
  - leave
  - ret

The Add Program

Compiling a C program on an Intel Mac.

call.c

```
int add(int a, int b)
{
  return a+b;
}

int main() {
  int x = add(3,2);
}
```

gcc -S

call.s

```
.text
.globl _add
_add:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $8, %esp
        movl    12(%ebp), %eax
        addl    8(%ebp), %eax
        leave
        ret

.globl _main
_main:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $40, %esp
        movl    $2, 4(%esp)
        movl    $3, (%esp)
        call    _add
        movl    %eax, -12(%ebp)
        leave
        ret
  .subsections_via_symbols
```

The Add Program

```
.text
.globl _add
_add:
        pushl   %ebp                          // save base ptr onto stack
        movl    %esp, %ebp                    // move stack ptr to base ptr
        subl   $8, %esp                       // make a new frame on stack
        movl    12(%ebp), %eax                // get parameter a at offset 12 from base ptr, store in register %eax
        addl   8(%ebp), %eax                  // get parameter b at offset 8 from base pts, add to %eax
        leave                                 // remove frame
        ret                                   // return from call

.globl _main
_main:
         pushl   %ebp                          // save base ptr onto stack
         movl    %esp, %ebp                   // move stack ptr to base ptr
         subl    $40, %esp                    // make a new frame on stack
         movl    $2, 4(%esp)                  // move constant 2 to TOS offset 4
         movl    $3, (%esp)                   // move constant 3 to TOS
         call    _add                         // call function add
         movl    %eax, -12(%ebp)              // retrieve result from eax register and store it at the ‘location’ for x.
         leave                                // clean up the stack
          ret                                 // return to OS
   .subsections_via_symbols
```

See http://en.wikipedia.org/wiki/Function_prologue and http://en.wikipedia.org/wiki/X86

The Recursive Seq Program

seq.c

```
void seq(int x) {
  if (1<=x)
    seq(x-1);
  print(x);
}

int main() {
  seq(2);
}
```

gcc -S

seq.s

```
 .text
.globl _seq
_seq:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $24, %esp
        cmpl    $0, 8(%ebp)
        jle     L2
        movl    8(%ebp), %eax
        decl    %eax
        movl    %eax, (%esp)
        call    _seq
L2:
        movl    8(%ebp), %eax
         movl    %eax, (%esp)
         call    L_print$stub
         leave
         ret
.globl _main
_main:
          pushl   %ebp
          movl    %esp, %ebp
          subl    $24, %esp
          movl    $2, (%esp)
          call    _seq
          leave
          ret
```

We have more to say about this when we
look at compiling programs for actual machines.