CS 11 C track: lecture 8

- Last week: hash tables, C preprocessor
- This week:
  - Other integral types: **`short`**, **`long`**, **`unsigned`**
  - bitwise operators
  - **`switch`**
  - "fun" assignment: virtual machine

Integral types (1)

- Usually use `int` to represent integers
- But many other integral (integer-like) types exist:
  - `short`
  - `long`
  - `char`
  - `unsigned int`
  - `unsigned short`
  - `unsigned long`
  - `unsigned char`

Integral types (2)

- Two basic things that can vary:
  - `unsigned` vs. signed (default)
  - length: `char`, `short`, `int`, `long`
- Note that `char` is an integral type
  - can always treat char as an 8-bit integer
- Two basic questions:
  - Why use `unsigned` types?
  - When should we use shorter/longer integral types?

Integral types (2)

- Why use **`unsigned`** types?
  - may be used for something that can't be negative
    - *e.g.* a length
    - gives you 2x the range due to last bit
  - may want to use it as an array of bits
    - so sign is irrelevant
    - C has lots of bitwise operators

Integral types (3)

- When should we use shorter/longer integral types?
  - to save space when we know range is limited
  - when we know the exact number of bits we need
- `char` always 8 bits
- `short` usually 16 bits
- `int` usually 32 bits (but sometimes 64)
- `long` usually 32 bits (but sometimes 64)
- guaranteed: length(`char`) < length(`short`) <= length (`int`) <= length(`long`)

Integral types (4)

- **`unsigned`** by itself means unsigned **`int`**
- Similarly it's legal to say
  - **`short int`**
  - **`unsigned short int`**
  - **`long int`**
  - **`unsigned long int`**
- but usually we shorten by leaving off the **`int`**

Bitwise operators (1)

- You don't need to know this for this lab!
- But a well-rounded C programmer should know this anyway...
- There are several "bitwise operators" that do logical operations on integral types bit-by-bit
  - OR (`|`) (note difference from logical or: `||`)
  - AND (`&`) (note difference from logical and: `&&`)
  - XOR (`^`)
  - NOT (`~`) (note difference from logical not: `!`)

Bitwise operators (2)

- bitwise OR (`|`) and AND (`&`) work bit-by-bit
- `01110001 | 10101010` = ?
  - `11111011`
- `01110001 & 10101010` = ?
  - `00100000`
- NOTE: They don't do short-circuit evaluation like logical OR (`||`) and AND (`&&`) do
  - because that wouldn't make sense

Bitwise operators (3)

- bitwise XOR (`^`) also works bit-by-bit
- `01110001 ^ 10101010` = ?
  - `11011011`
- Bit is set if one of the operand's bits is 1 and the other is 0 (not both 1s or both 0s)

Bitwise operators (4)

- bitwise NOT (`~`) also works bit-by-bit
- `~10101010` = ?
  - `01010101` (duh)
- Substitute 0 for 1 and 1 for 0

Bitwise operators (5)

- Two other bitwise operators:
  - bitwise left shift (`<<`)
  - bitwise right shift (`>>`)
- `00001111 << 2` = ?
  - `00111100`
- `00111100 >> 2` = ?
  - `00001111`
- Can use to multiply/divide by powers of 2

`switch` (1)

- Minor language feature: `switch`
- Used to choose from multiple integer-valued possibilities
- Cleaner than a series of `if`/`else if`/`else` statements

switch (2)

- Common coding pattern:

```
void do_stuff(int i) {
    if (i == 0) {
        printf("zero\n");
    } else if (i == 1) {
        printf("one\n");
    } else {
        printf("something else\n");
    }
}
```

switch (3)

```
void do_stuff(int i) {
    switch (i) {
        case 0:
            printf("zero\n");
            break;
        case 1:
            printf("one\n");
            break;
        default:
            printf("something else\n");
            break;
    }
}
```

`switch` (4)

- `switch` statements more convenient than `if/else if/else` for many integer-valued cases
  - but not as general -- can only be used on integral types (`int`, `char`, etc.)
- Lab 8 code contains one `switch` statement that you don't have to write
  - but you should understand it anyway

switch (5)

```
switch (i) {
    case 0:  /* Start here if i == 0 */
        printf("zero\n");
        break;  /* Exit switch here. */
    ... /* other cases: 1, 2, 42 etc. */
    default: /* if no case matches i */
        printf("no match\n");
        break;
}
```

`switch` (6) -- fallthrough

```
switch (i) {
    case 0:  /* Start here if i == 0 */
        printf("zero\n");
        /* oops, forgot the break */
    case 1:  /* "fall through" from case 0 */
        printf("one\n");
        break;
}
```

- Now, if `i` is `0` then prints "zero" and also "one"!
- Sometimes this is desired, but usually just a bug

Lab 8: Virtual machine (1)

- Where have you heard the term "virtual machine" before?
  - Java virtual machine
- A "virtual microprocessor"
- You define simple instructions for a mythical computer's assembly language
- Program interprets them

Virtual machine (2)

- Our virtual machine is very simple
- Only data type will be `int`
- All instructions will act on `int`s
- Instructions include
  - arithmetic
  - control flow
  - memory access
  - printing

Virtual machine (3)

- First need to define data structures for our virtual microprocessor:
  - instruction memory to hold instructions of program
  - registers to hold temporary results of computations
  - stack to hold results that are being operated on directly

Virtual machine (4)

- Instruction memory contains 2^{16} locations
  - = 65536
- Each location is a single byte (`unsigned char`)
- How many bits do we need to represent all possible locations in instruction memory?
  - 16
- Can use an `unsigned short` for this
  - Called the "instruction pointer" or IP
- Don't confuse with C's pointers! Not the same thing!
  - It's just an index into the instruction memory

Virtual machine (5)

- 16 registers (temporary storage locations)
- How many bits do we need to represent all possible locations in registers?
  - 4
- Can use an `unsigned char` for this
- Registers are just an array of 16 `int`s

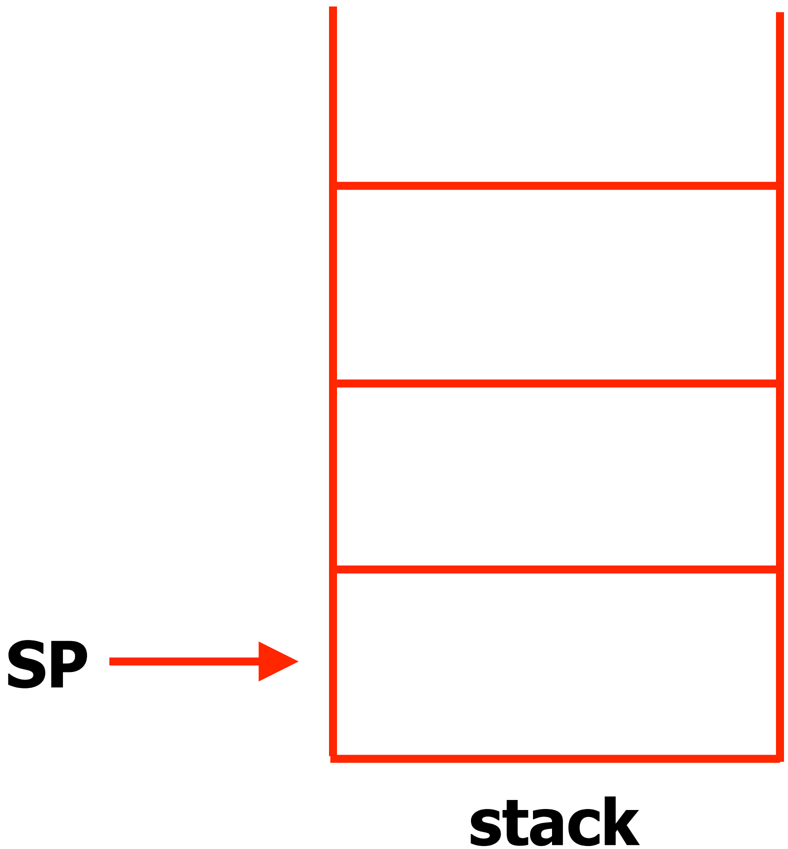
Virtual machine (6)

- Stack which is 256 deep
- How many bits do we need to represent all possible locations in stack?
  - 8
- Can use an **`unsigned char`** for this
  - called the "stack pointer" or SP
  - also not a pointer in the C sense, just an index
- Stack is just an array of 256 **`int`**s

Push and pop (1)

- Stack has two operations: push and pop
- push puts a new value onto the stack
- pop removes a value from the stack
- Have to adjust stack pointer (SP) after push and pop
- Stack pointer "points to" first UNUSED element of stack
  - starts at zero for empty stack
- Top filled element in stack is "top of stack" (TOS)

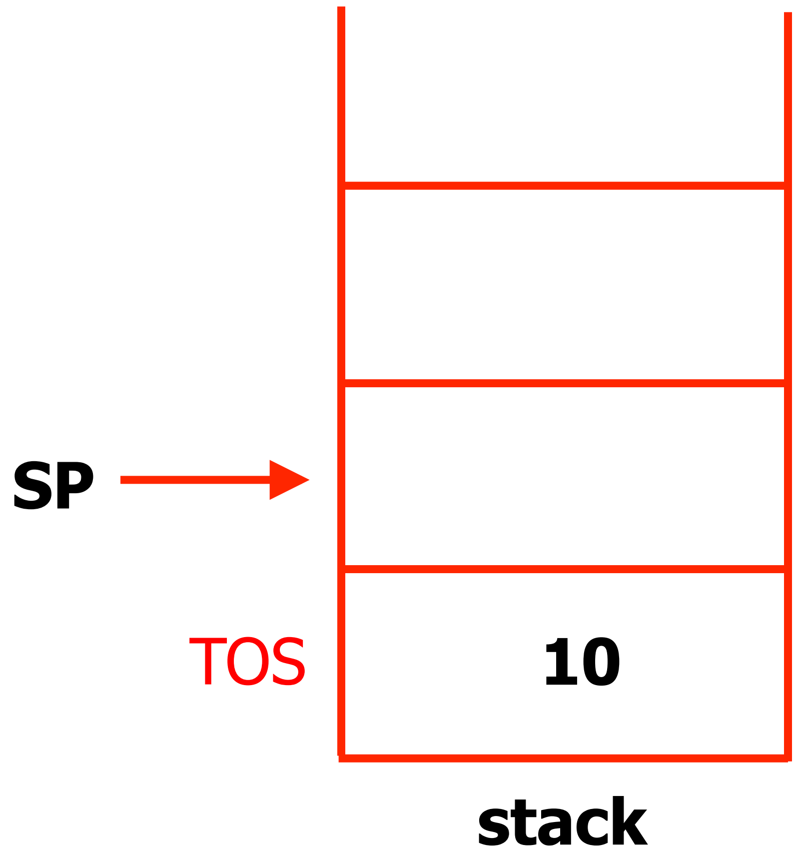
Push and pop (2)



Stack starts off empty;

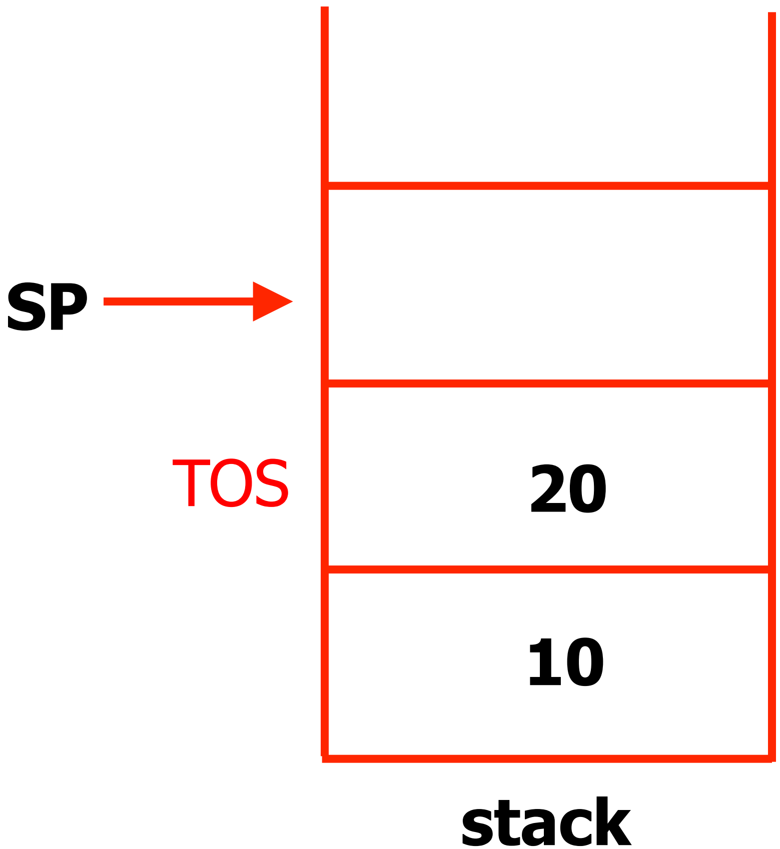
SP points to first unused location

Push and pop (3)



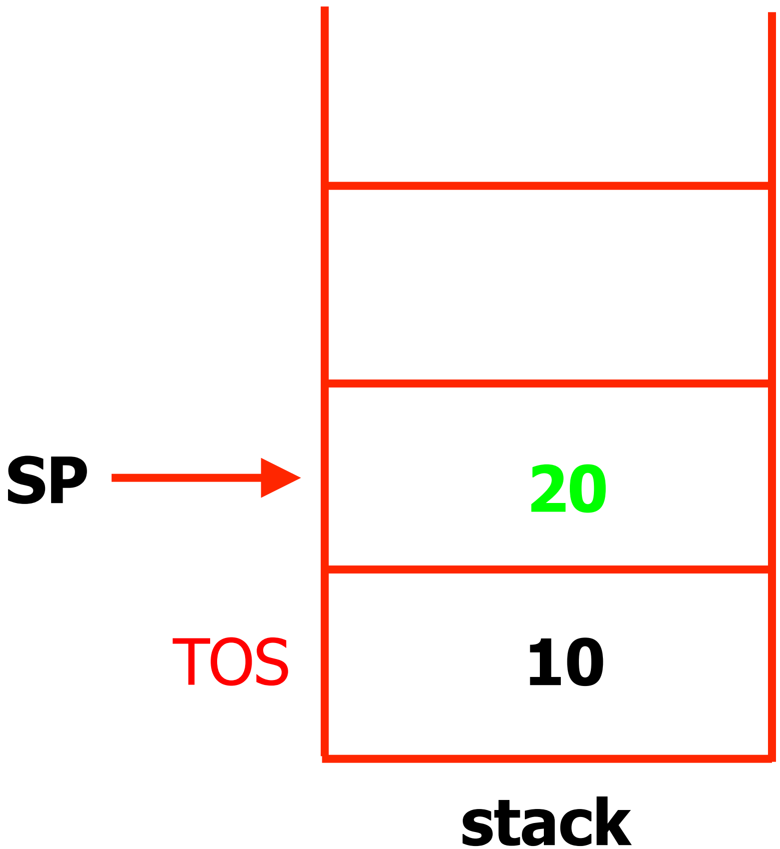
push 10 onto stack

Push and pop (4)



push 20 onto stack

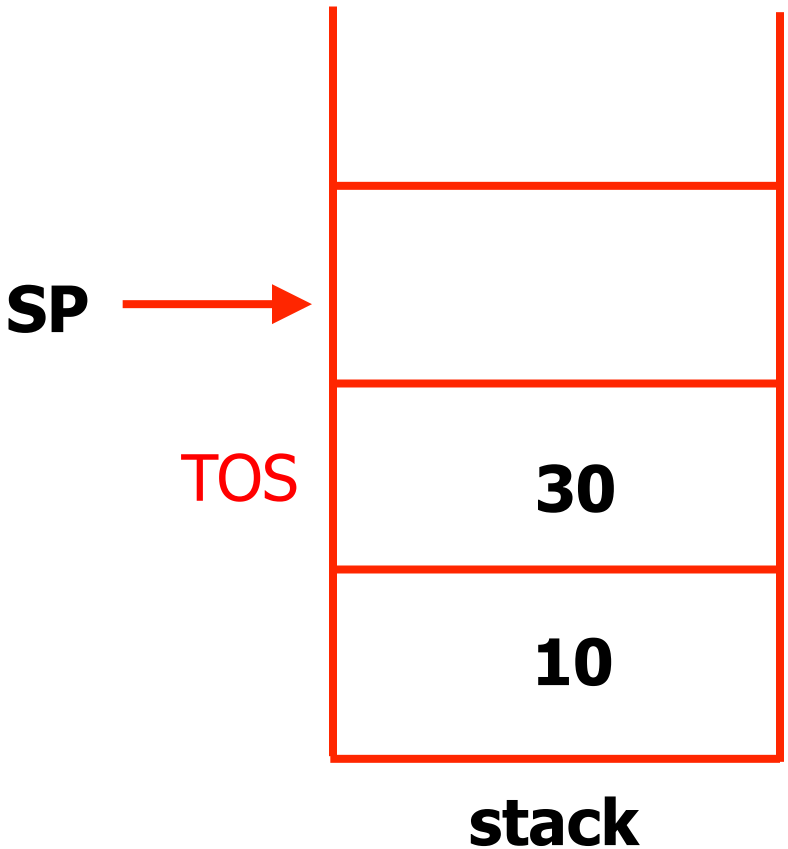
Push and pop (5)



pop stack;

20 still there, but will be overwritten next push

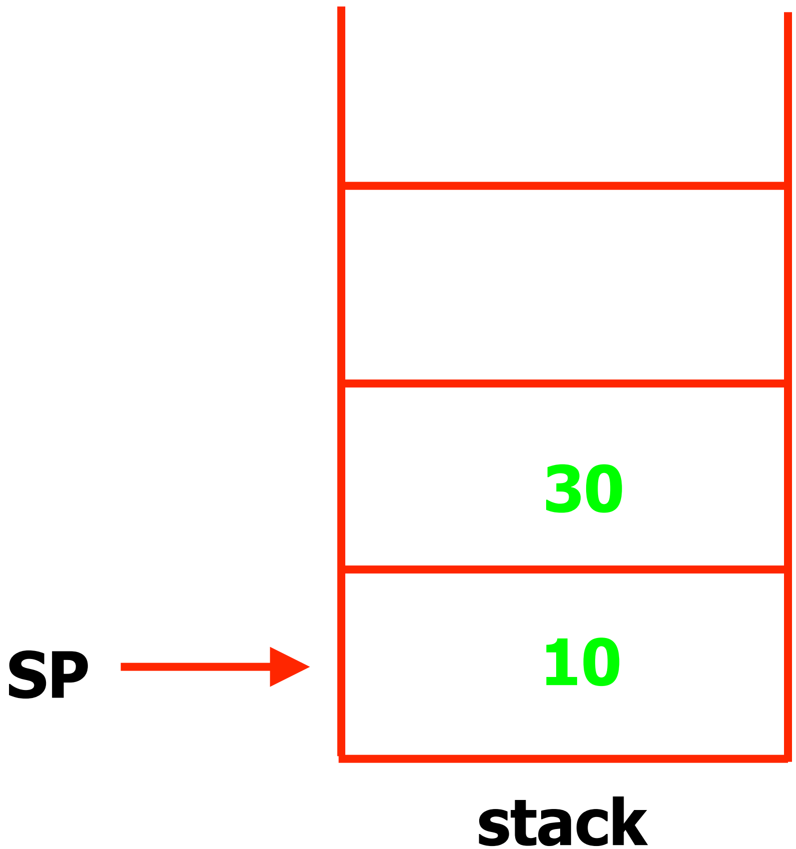
Push and pop (6)



push 30 onto stack;

old value (20) gets overwritten

Push and pop (7)



pop twice;

stack is now "empty" again

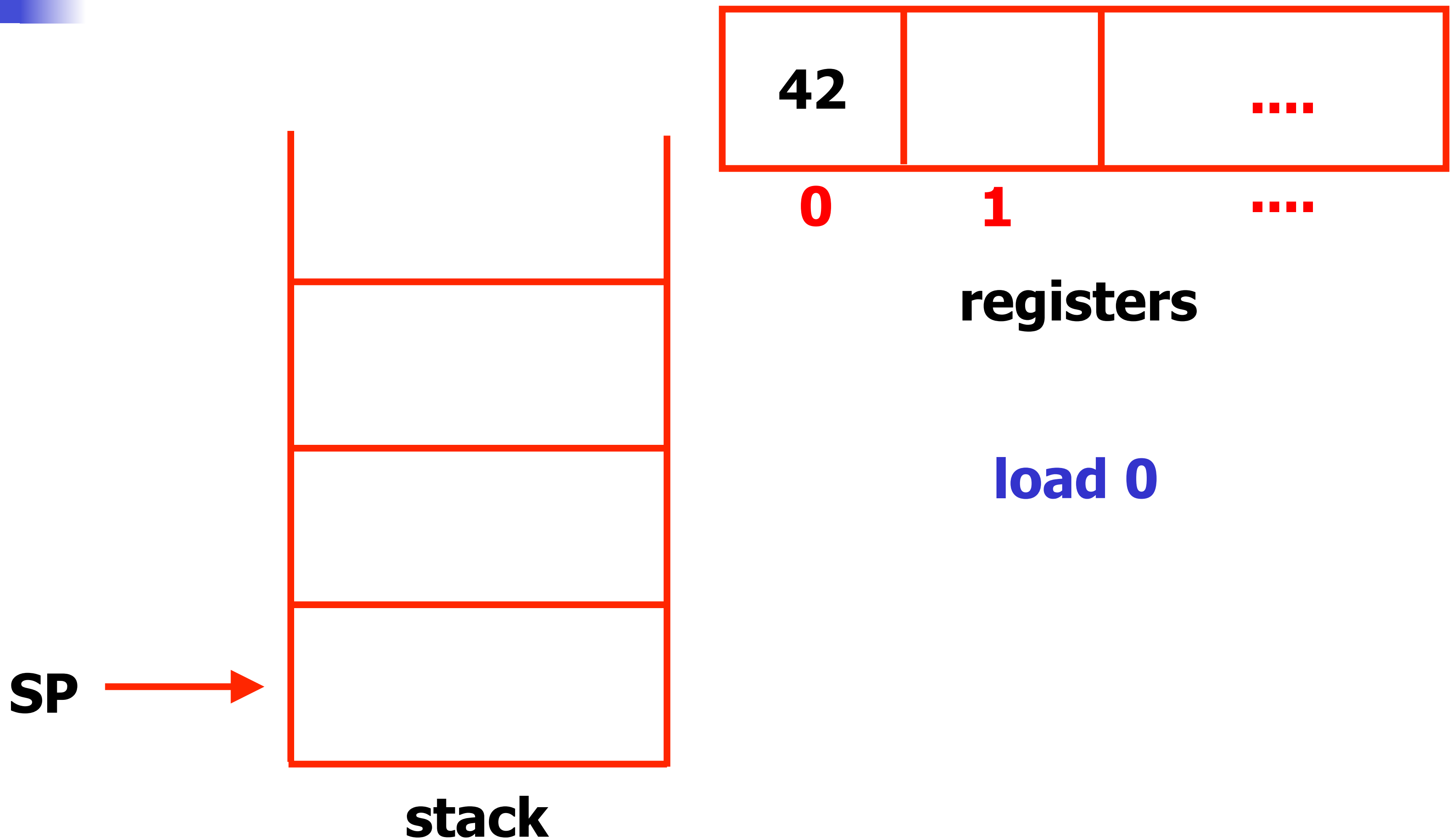
VM instruction set (1)

- VM instructions are often called "bytecode"
  - because they fit into a byte (8 bits)
  - represented as an **`unsigned char`**
- Our VM has 14 different instructions
  - some take operands (some number of bytes)
  - some don't

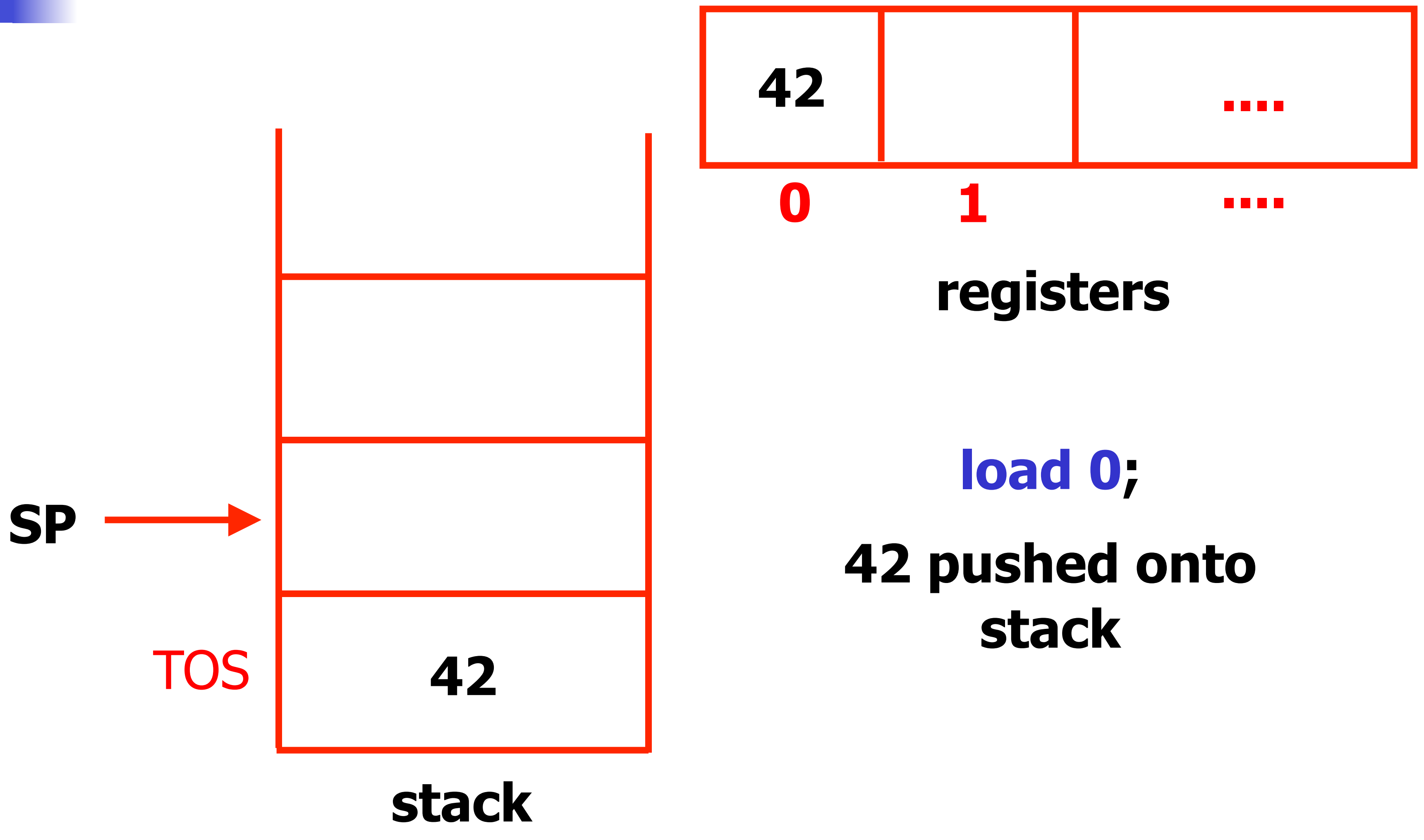
VM instruction set (2)

- Instructions:
  - NOP (0x00) – does nothing ("No OPeration")
  - PUSH (0x01) – PUSH <n> pushes the integer <n> onto the stack
  - POP (0x02) – removes the top element on the stack
  - LOAD (0x03) – LOAD <r> pushes contents of register <r> to the top of the stack
  - STORE (0x04) – STORE <r> pops top of stack and puts contents into register <r>

Load (1)



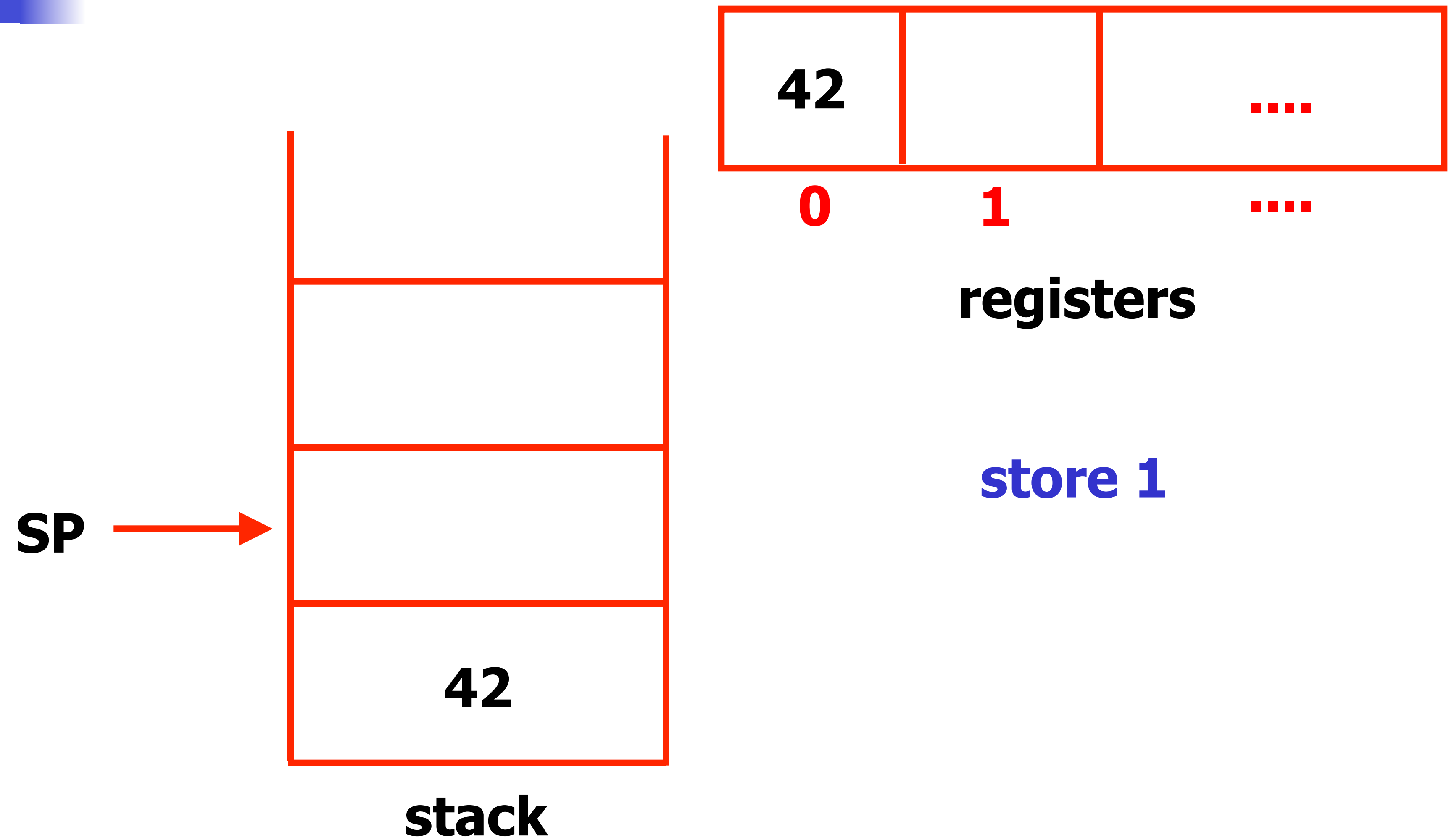
Load (2)



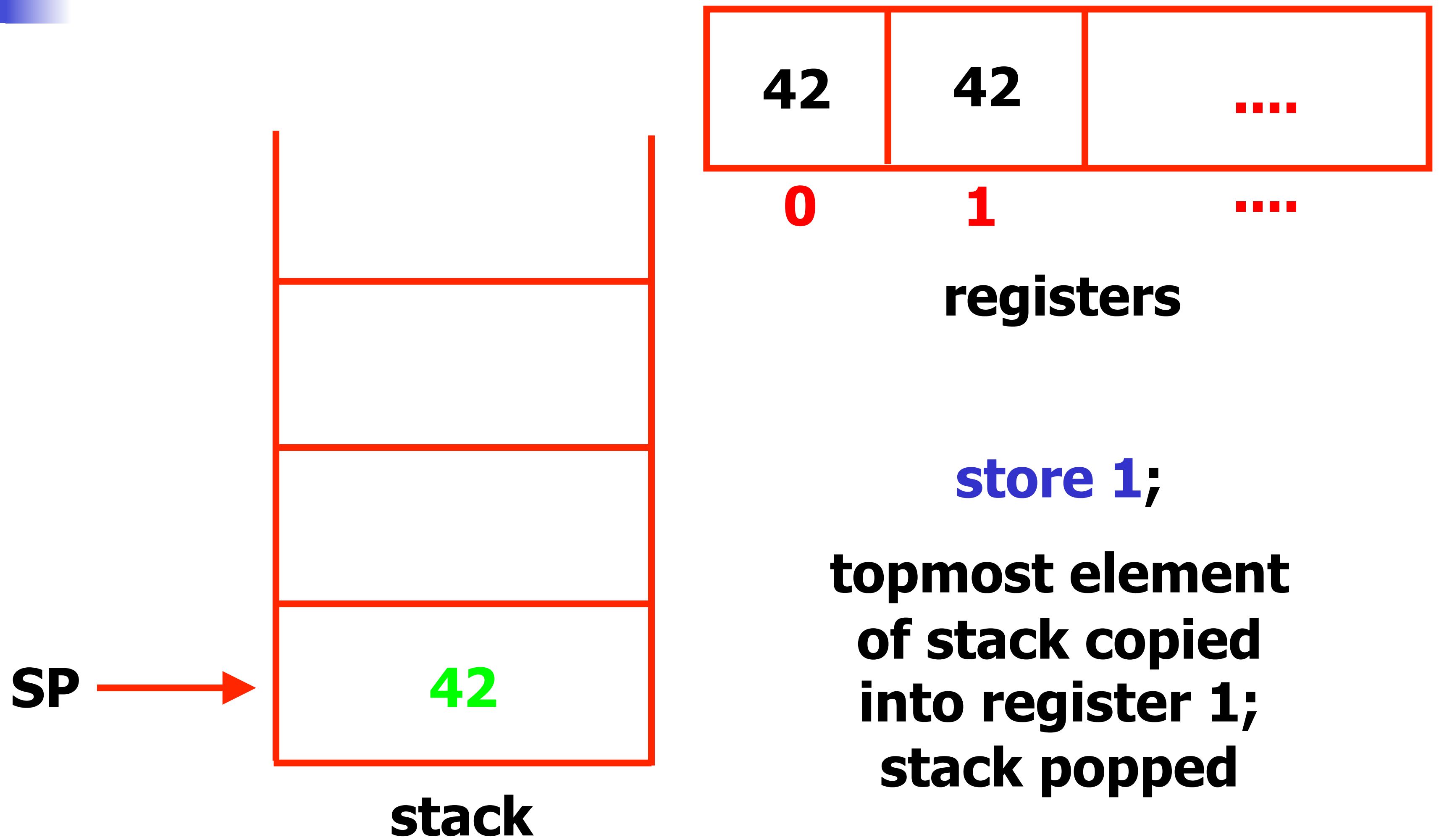
load 0;

42 pushed onto stack

Store (1)



Store (2)



store 1;

topmost element of stack copied into register 1; stack popped

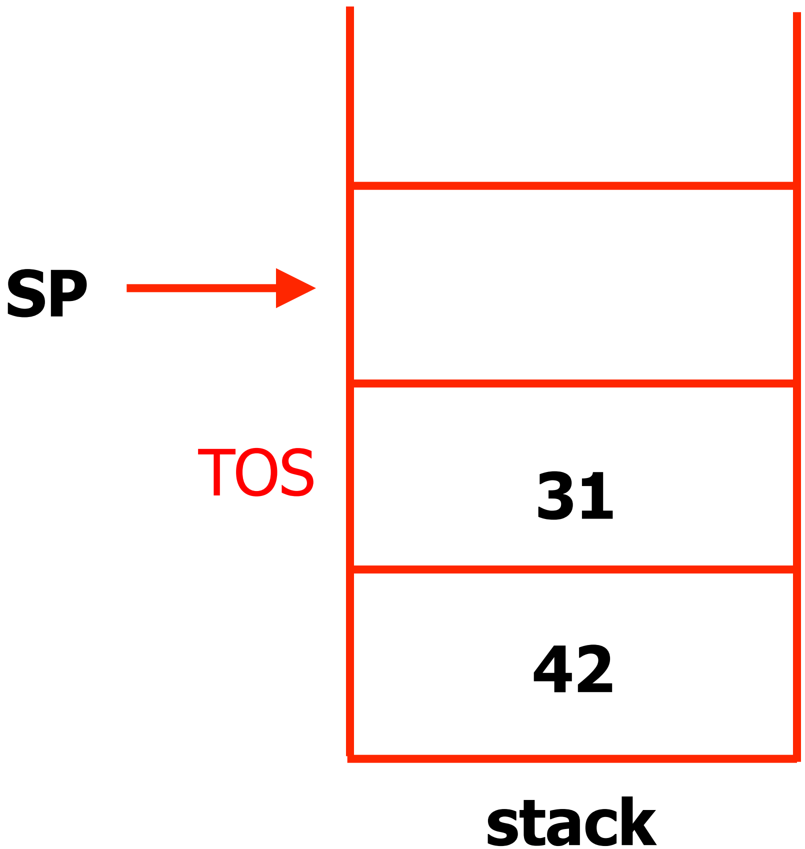
VM instruction set (3)

- Control flow instructions:
  - JMP (0x05) – JMP <i> sets the instruction pointer (IP) to <i> ("jump")
  - JZ (0x06) – JZ <i> sets IP to <i> only if the top value on the stack (TOS) is zero; also pops stack ("jump if zero")
  - JNZ (0x07) – JNZ <i> sets IP to <i> only if the TOS is not zero; also pops stack ("jump if nonzero")

VM instruction set (4)

- Arithmetic instructions:
  - ADD (0x08) – pops the top two entries in the stack, adds them, pushes result back
  - SUB (0x09) – pops the top two entries in the stack, subtracts them, pushes result back
    - Watch order! Should be S2 – S1 on TOS
  - MUL (0x0a) and DIV (0x0b) defined similarly

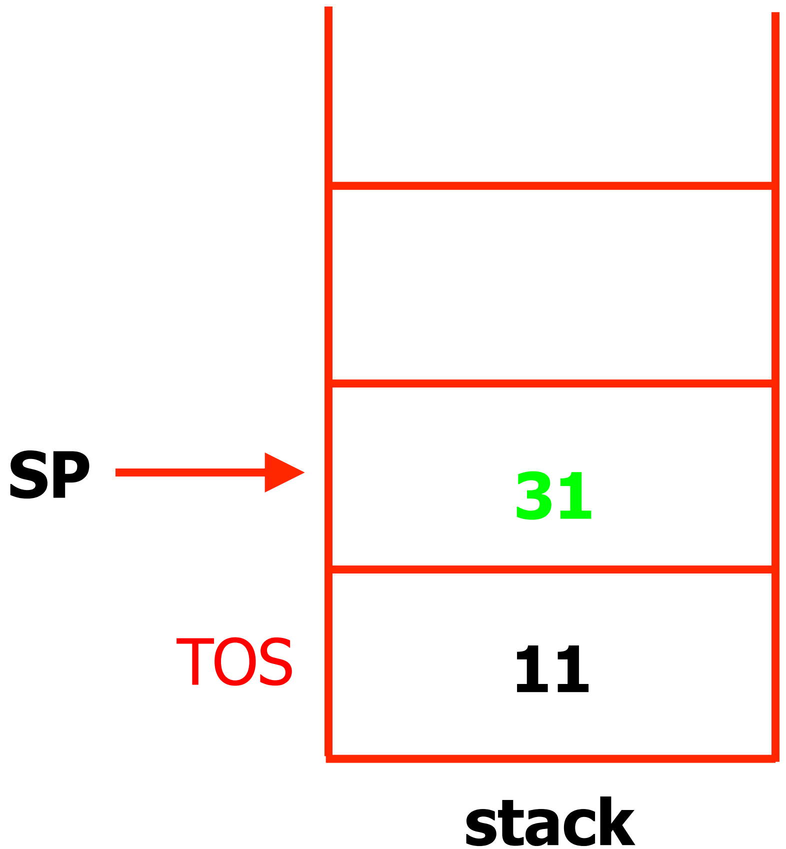
Sub (1)



sub

(before)

Sub (2)



sub

(after)

VM instruction set (5)

- Other instructions:
  - PRINT (0x0c) – prints the TOS to stdout and pop TOS
  - STOP (0x0d) – terminates the virtual program

Example program (1)

- Program to generate factorial of 10 (10!)
- Which means...?
  - 10 x 9 x 8 x 7 x 6 x 5 x 4 x 3 x 2 x 1
  - = 3628800
- But we'll write a program in our virtual machine's language

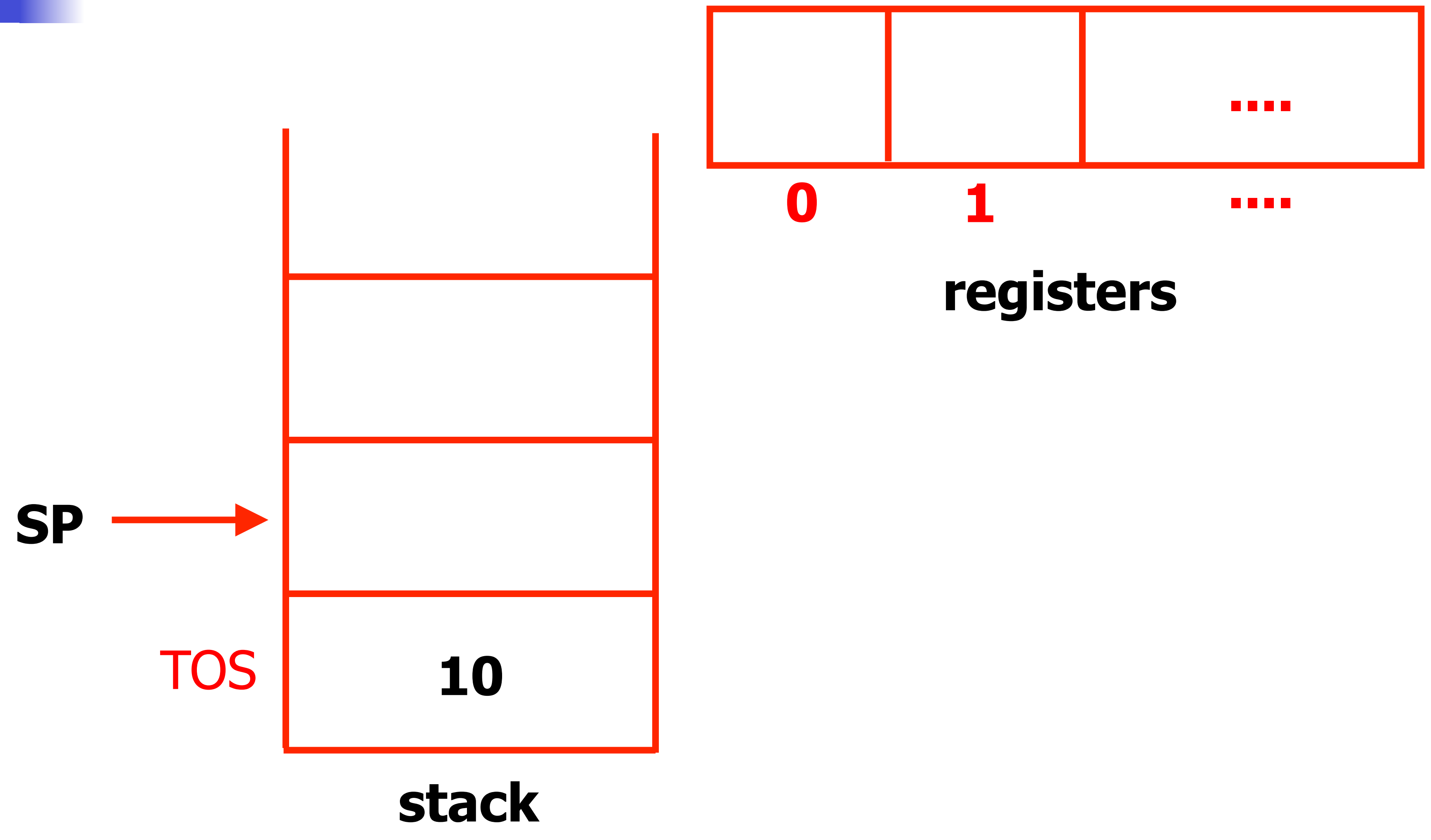
Example program (2)

- Register 0 will contain the count
- Register 1 will contain the running total
- Register 0 will start off at 10
  - each step, will decrease by 1
- Register 1 will start off at 1
  - each step, will be multiplied by register 0 contents
- Continue until register 0 has 0
  - result is in register 1

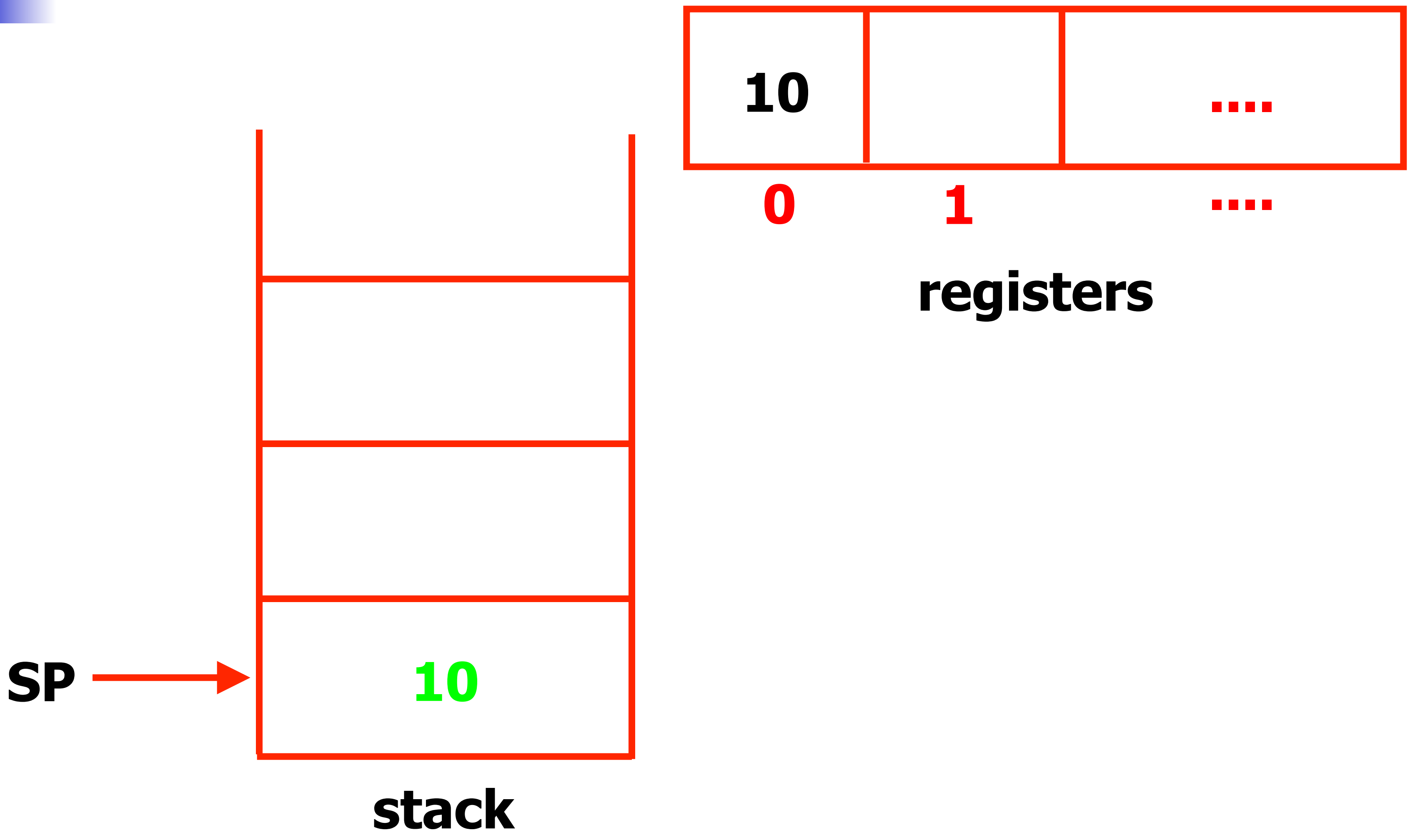
Example program (3)

```
/* Initialize the registers. */

1 push 10
2 store 0
3 push 1    /* Initialize result. */
4 store 1

/* continued on next slide... */
```

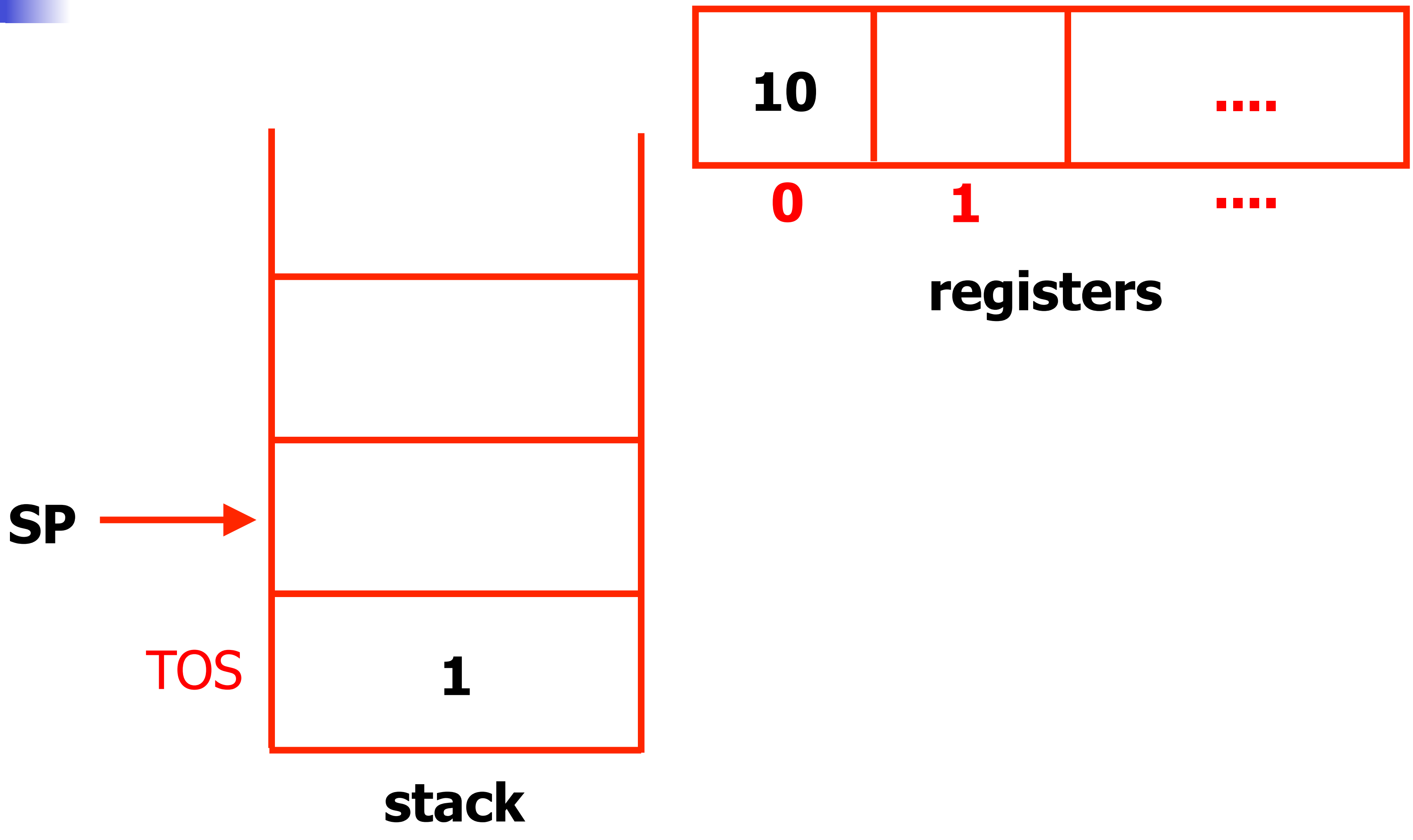
push 10



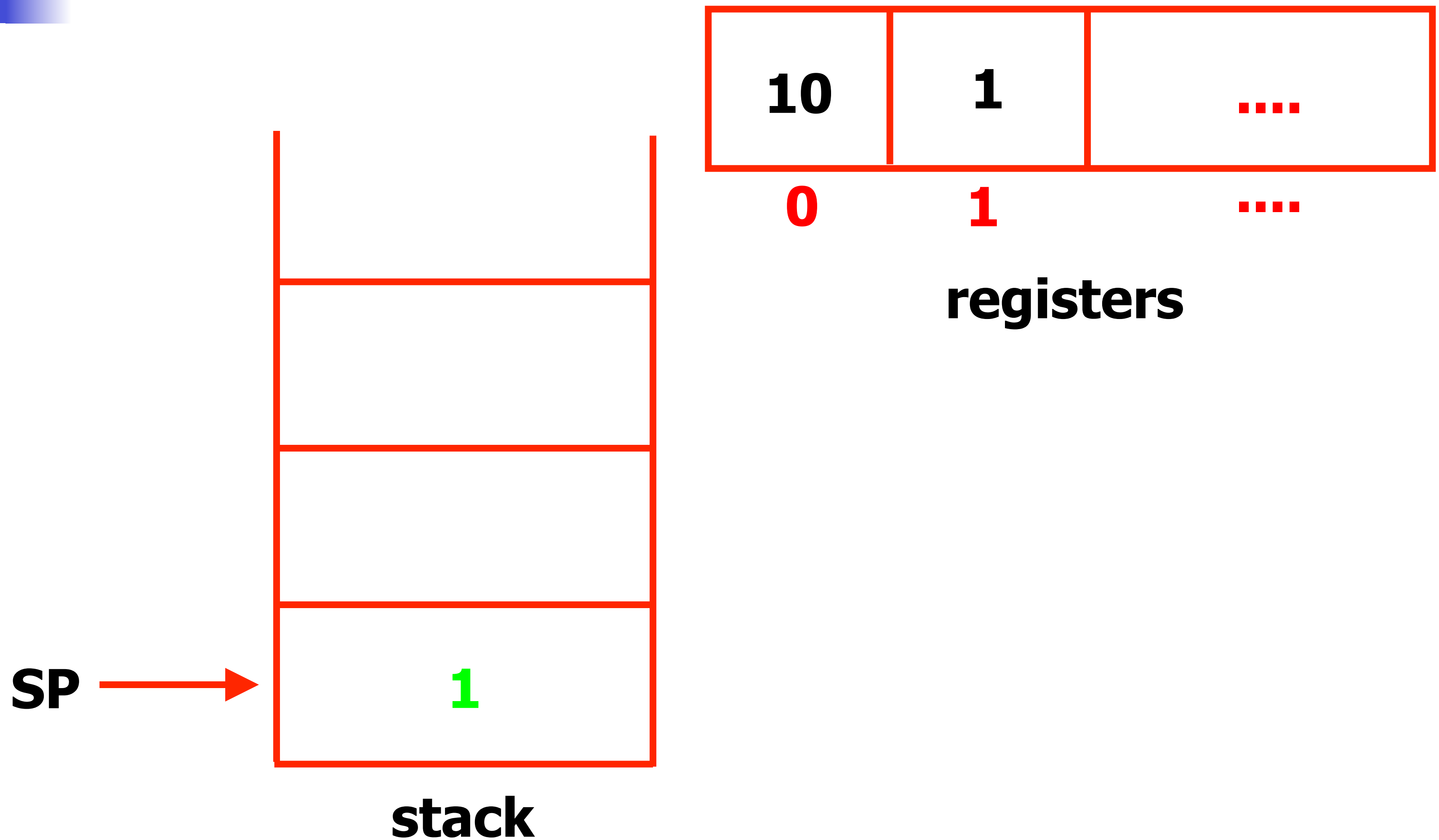
store 0



push 1



store 1



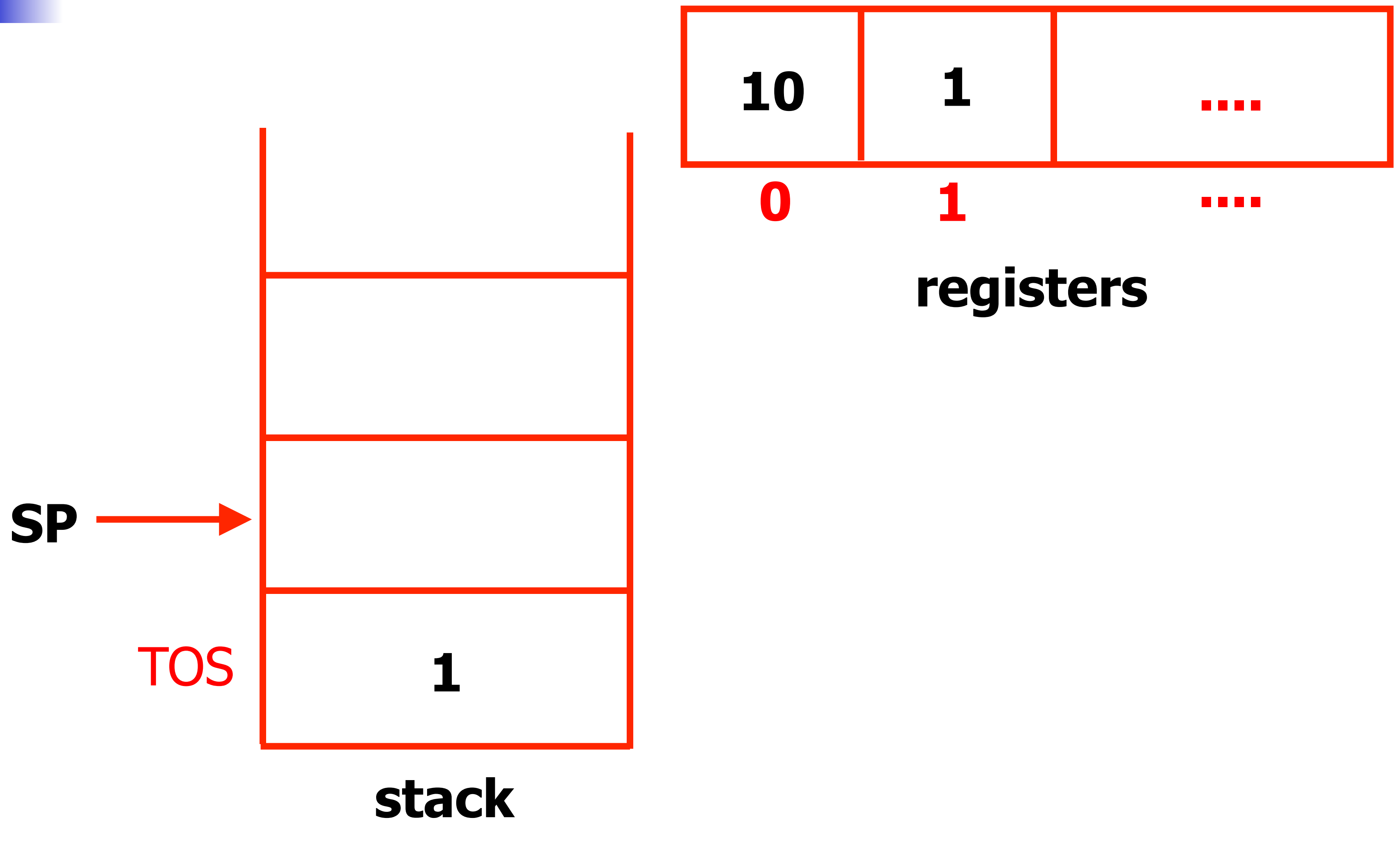
Example program (4)

```
/* Put counter value on stack.
 * If it's 0, we're done; register 1
 * contains the final value. */

5 load 0    /* Load current count. */
6 jz 16     /* if 0, jump to 2 */

/* 16 is the location of the instruction
   which is the target of the jz instruction
   i.e. where to jump to. */
```

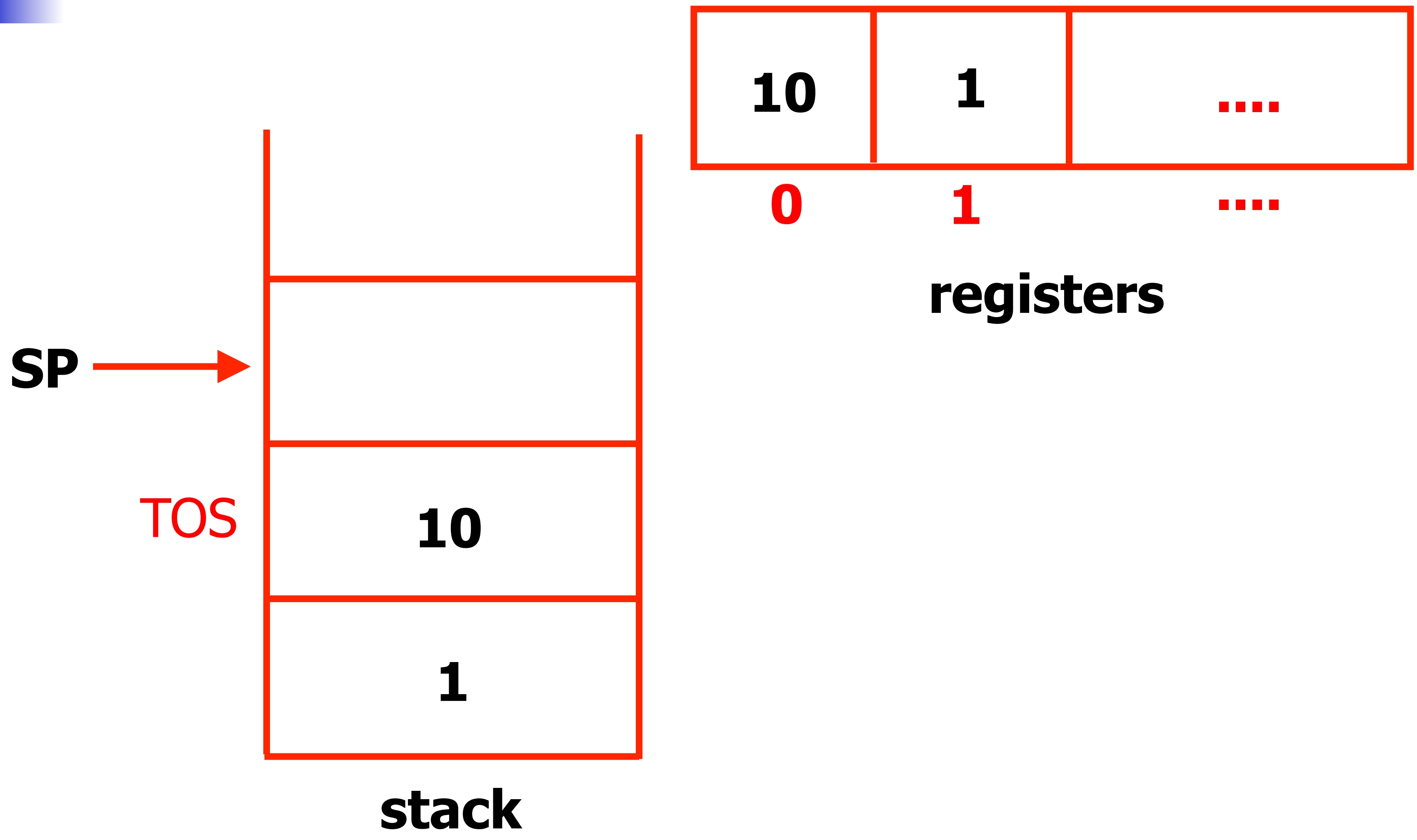
Example program (5)

```
/* result = result * count */
 7 load 1
 8 load 0
 9 mul
10 store 1
/* count = count - 1 */
11 load 0
12 push 1
13 sub
14 store 0
```

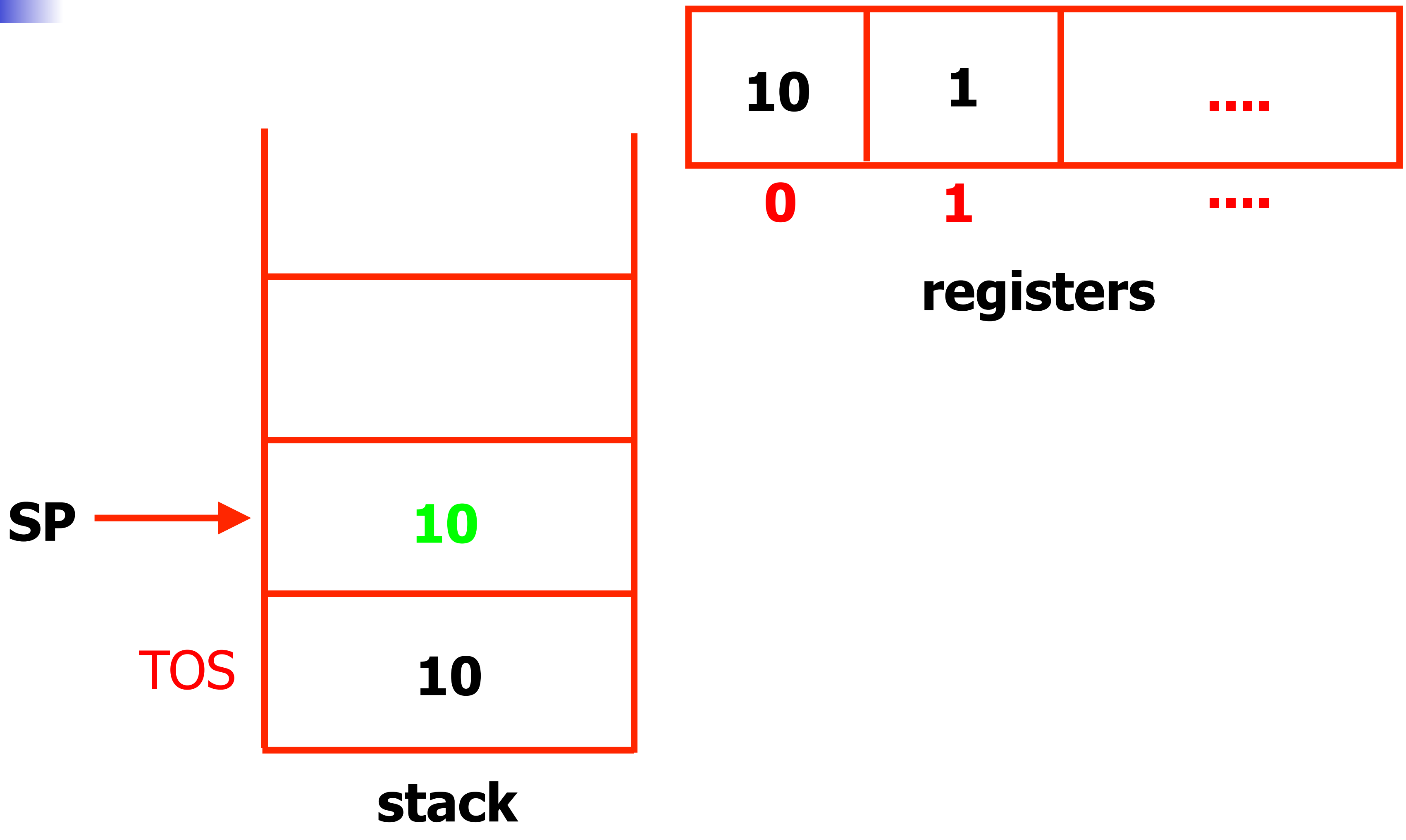
load 1



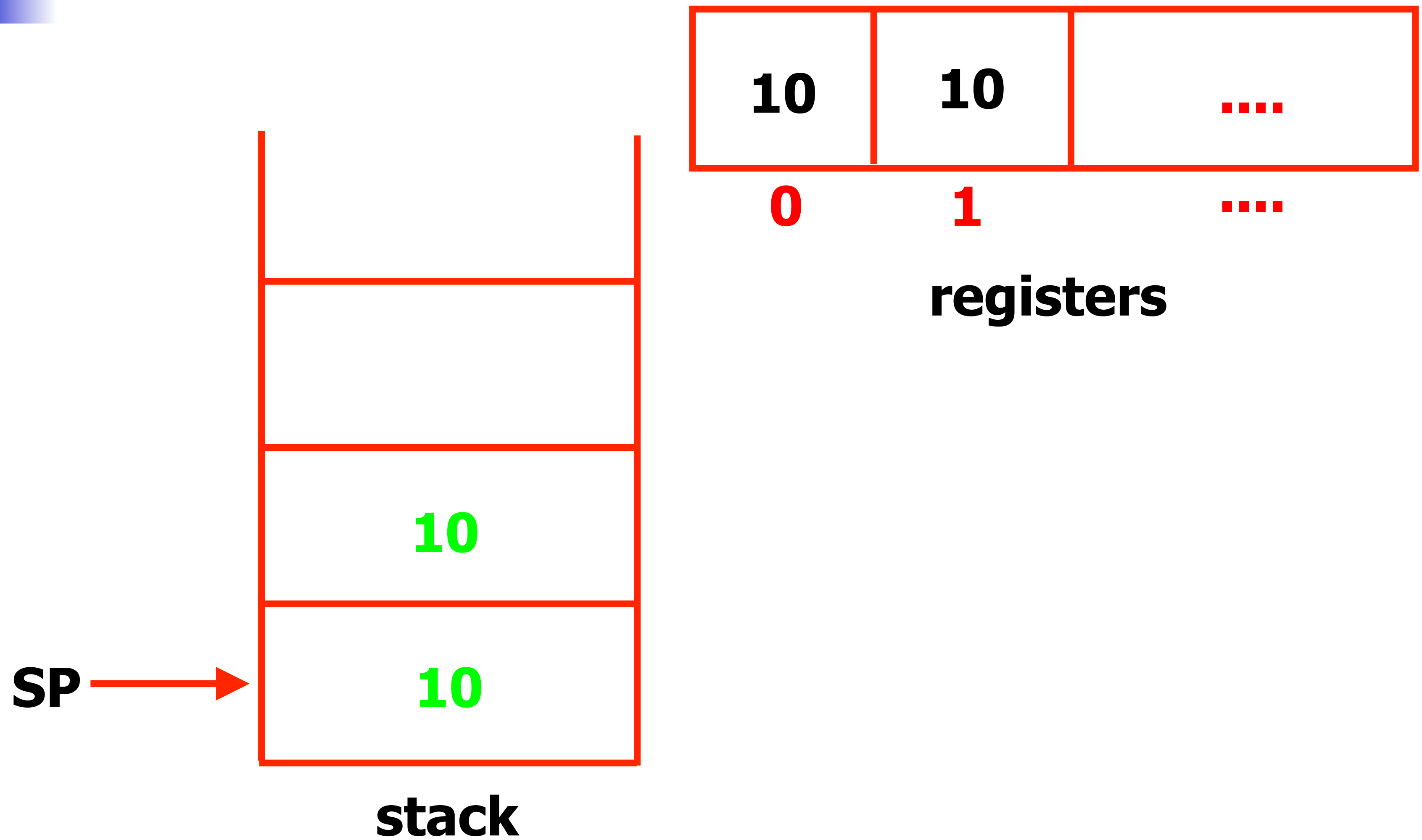
load 0



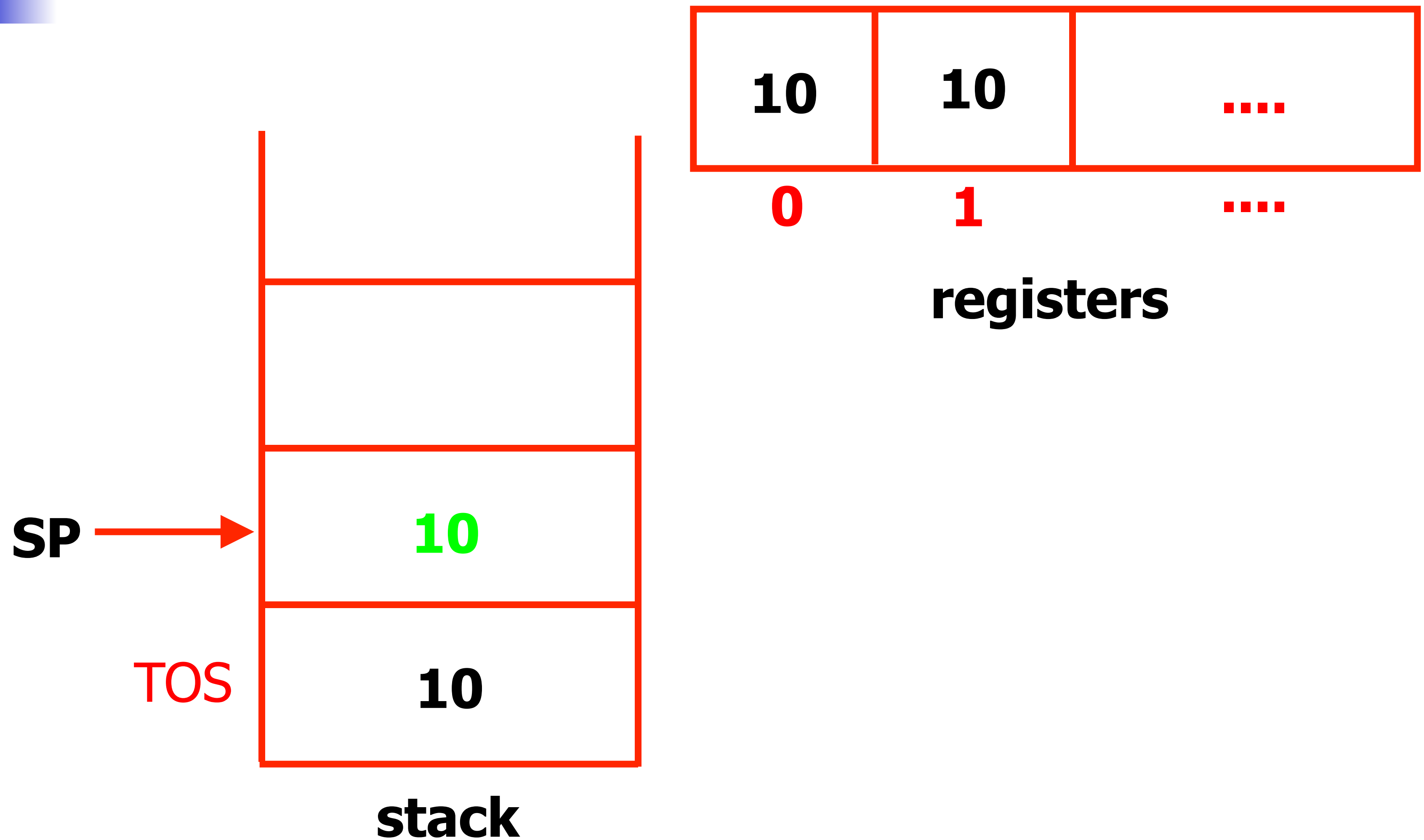
mul



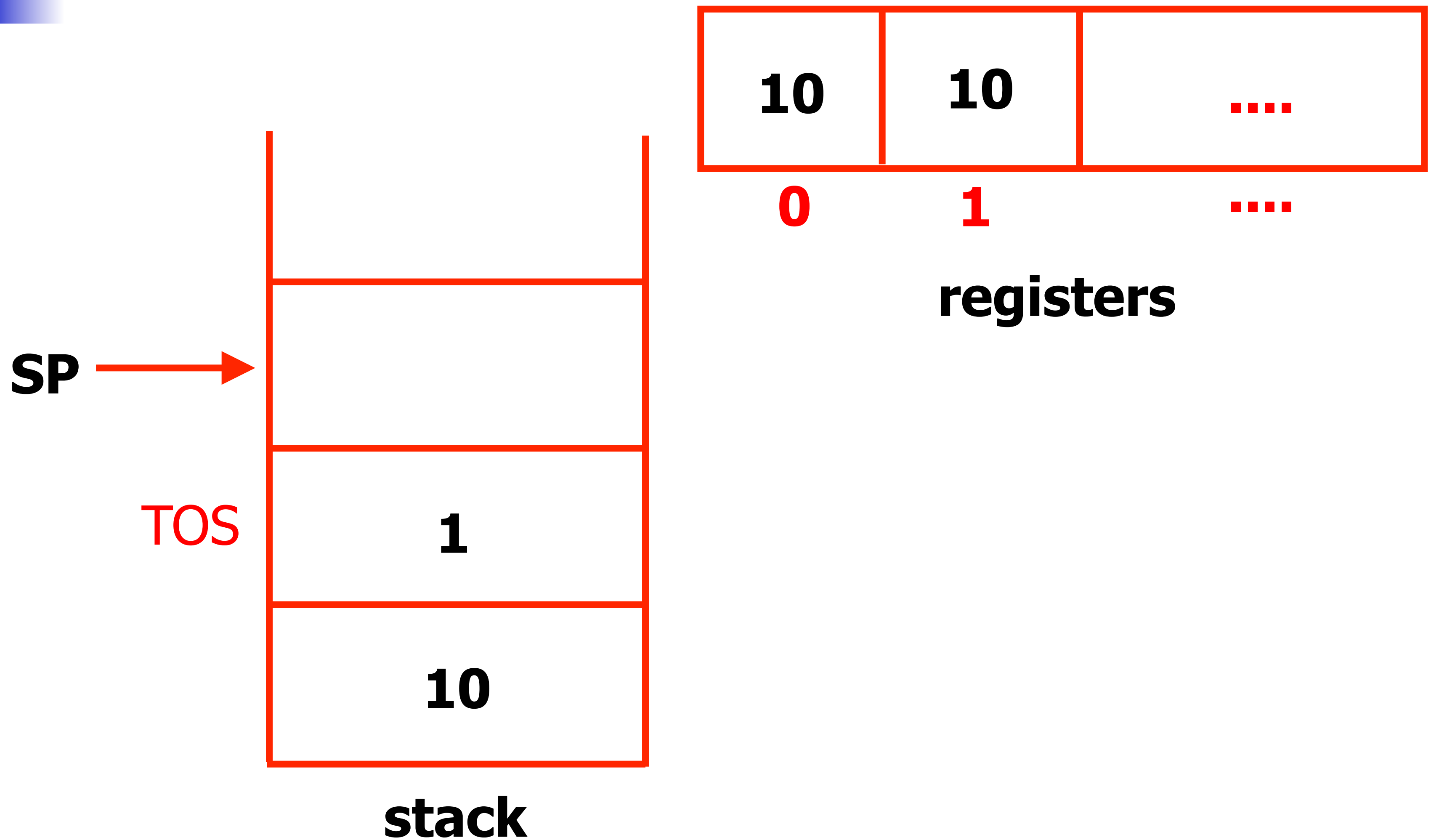
store 1



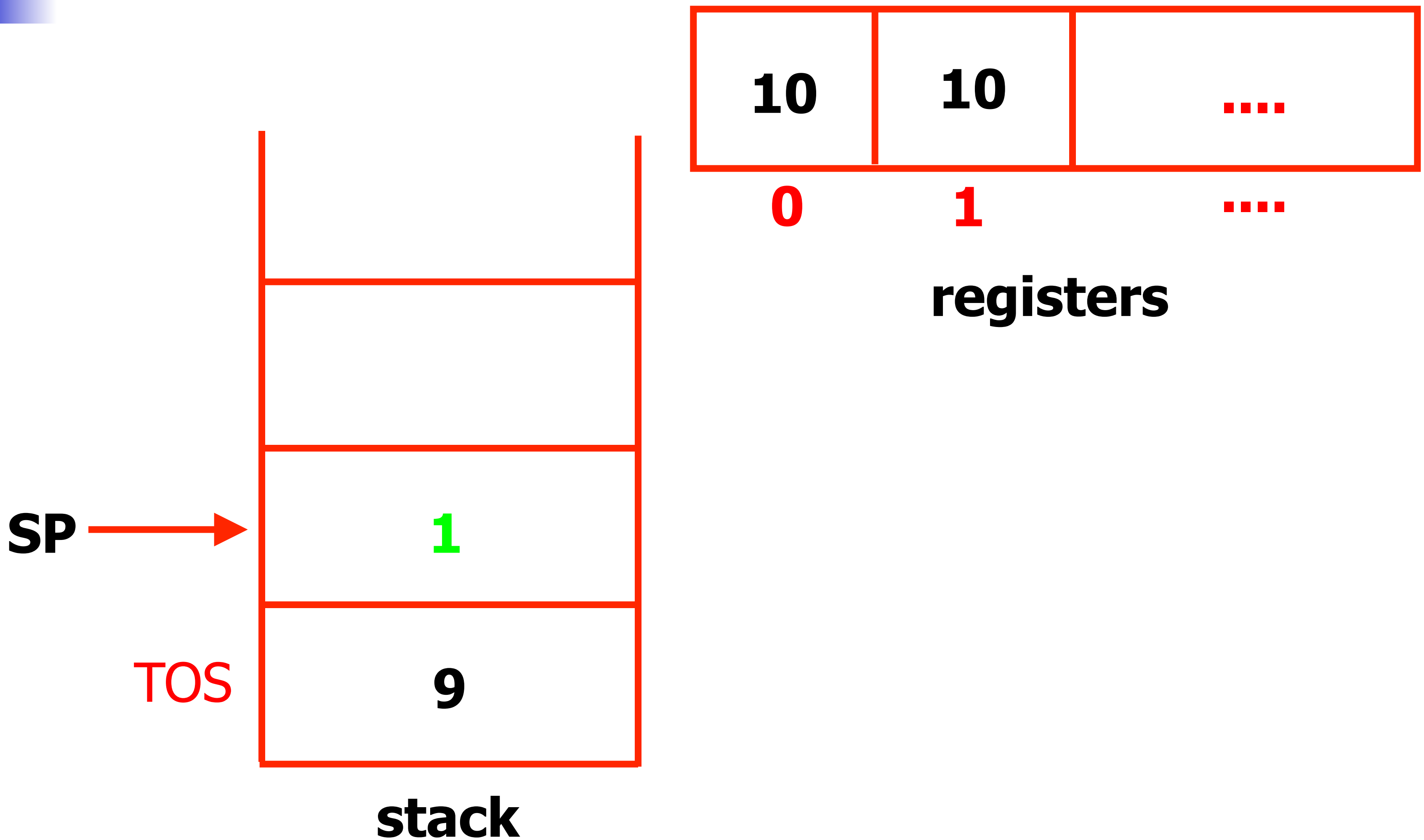
load 0



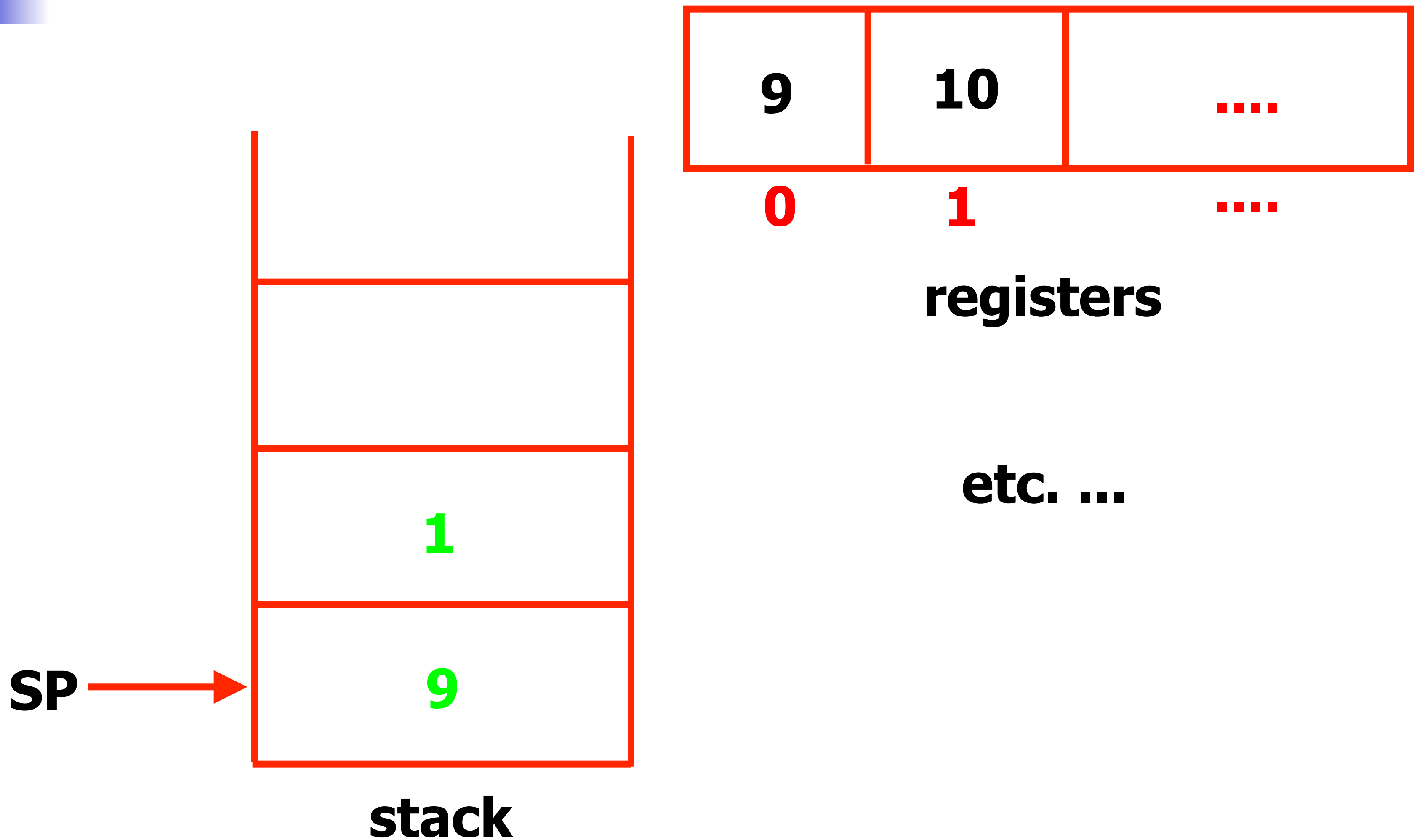
push 1



sub



store 0



Repeating...

- Registers start off as 10, 1
- Then become 9, 10
- 8, 10*9
- 7, 10*9*8
- ...
- 0, 10!
- ... and we're done.

Example program (6)

```
/* Go back and loop until done. */
15 jmp 5

/* When we get here, we're done. */
16 load 1
17 print
18 stop

/* End of program. */
```

Lab 8

- Program is given to you
- You need to write the byte-code interpreter
- Most of code is supplied; have to fill in the guts of the instruction-processing code
- Looks complicated but actually is pretty easy
- Watch out for error checking *e.g.*
  - popping an empty stack
  - pushing to a full stack
  - accessing non-existent register or instruction

Lab 8 -- error checking

- One subtlety with stack pushes
- If stack pointer is at 255, and you push onto stack, what is the new stack pointer value?
  - 0
  - (256 is too large for an `unsigned char`)
- But this is clearly incorrect
- How to detect "stack overflow"?
- Solution: If stack pointer is at location 255, a push is invalid

Finally…

- Hope you enjoyed the course!
- If so, consider taking
  - other CS 11 tracks
    - (C++, java, advanced C/C++/java, python, ocaml, haskell)
  - CS 11 project track
  - CS 24
  - CS 2, 3 for larger-scale software projects