The CPRL Virtual Machine

See Appendix E of the textbook for additional details on the definition of CVM.

CVM (CPRL Virtual Machine)

- CVM
  - is a hypothetical computer designed to simplify the code generation phase of a compiler for CPRL
  - uses a stack architecture; i.e., most instructions either expect values on the stack, place results on the stack, or both
  - has 4 internal or special purpose registers, but no general purpose registers
- Memory is organized into 8-bit bytes. Each byte is directly addressable.
- A word is a logical grouping of 4 consecutive bytes in memory. The address of a word is the address of its first (low) byte.

Representing Primitive Types

- Boolean values are represented in a single byte.
  - 0 means false.
  - Any nonzero value is interpreted as true.
- Character values (Unicode) use 2 bytes.
  - Unicode Basic Multilingual Plane (Plane 0)
  - Code points range from U+0000 to U+FFFF
- Integer values use a word.
  - 32-bit 2's complement

CVM Instructions

- Each CVM instruction operation code (opcode) occupies one byte of memory.
- Some instructions take one or two arguments, which are always located in the words immediately following the instruction in memory.
- Depending on the opcode, an argument can be
  - a single byte
  - two bytes (e.g., for a char)
  - four bytes (e.g. for an integer or a memory address)
  - multiple bytes (e.g., for a string literal)

CVM Instructions (continued)

- Most instructions get their operands from the stack.
- In general, the operands are removed from the stack whenever the instruction is executed, and any results are left on the top of the stack.

Examples: CVM Instructions

- `ADD`: Remove two integers from the top of the stack and push their sum back onto the stack.
- `INC`: Add 1 to the integer at the top of the stack.
- `LOADW` (load word): Load/push a word (four consecutive bytes) onto the stack. The address of the first byte of the word is obtained by popping it off the top of the stack.
- CMP (compare): Remove two integers from the top of the stack and compare them. Push a byte representing -1, 0, or 1 back onto the stack depending on whether the first integer is less than, equal to, or greater than the first integer, respectively.

Registers

Four 32-bit internal registers (no general-purpose registers)

- `PC` (program counter; a.k.a. instruction pointer) - holds the address of the next instruction to be executed.
- `SP` (stack pointer) - holds the address of the top of the stack. The stack grows from low-numbered memory addresses to high-numbered memory addresses.
- `SB` (stack base) – holds the address of the bottom of the stack. When a program is loaded, `SB` is initialized to the address of the first free byte in memory.
- `BP` (base pointer) - holds the base address of the subprogram currently being executed.

Relative Addressing Using the `SB` and `BP` Registers

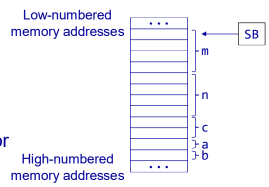
- Variables declared at program scope are addressed relative to the `SB` register.
- Variables declared at subprogram scope are addressed relative to the `BP` register.
- Example: If `SB` has the value 112, and program scoped variable x has the relative address 8, then the actual address of x is `[SB]` + relAddr(x) or 120.
- When preparing for code generation, the compiler needs to determine the relative address of every variable.
- For programs that don't have subprograms, both `SB` and `BP` will point to the same memory location.

Relative Addressing Example

- Suppose a program contains the following declarations:

```
var m, n : Integer;
var c : Char;
var a, b : Boolean;
```

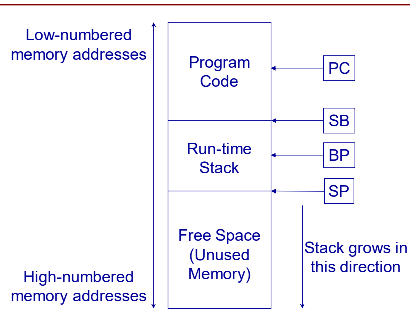
- The relative addresses of the variables are as follows:
  - `m` has relative address 0
  - n has relative address 4
  - c has relative address 8
  - a has relative address 10
  - b has relative address 11
- The total variable length for the program is 12.



Loading a Program

- The object code is loaded into the beginning of memory
- Register `PC` is initialized to 0, the address of the first instruction.
- Registers `SB` and `BP` are initialized to the address following the last instruction.
- Register `SP` is initialized to `BP` - 1.
- The first instruction usually has the form `program n`. When executed it allocates n bytes on the top of the stack for global variables.

Program Loaded in Memory
(after several instructions have been executed)



Opcodes `LDGADDR` and `LDLADDR`

- `LDGADDR n`
  - load global address for variable at offset n
  - pushes `SB` + n onto the stack
  - used for variables declared at program scope
- `LDLADDR n`
  - load local address for variable at offset n
  - pushes `BP` + n onto the stack
  - used for variables declared at subprogram scope

CPRL Example

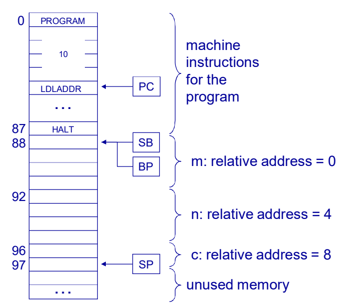
```
var   m, n : Integer;
var   c : Char;
const five := 5;

begin

   m := 7;
   n := five*m;
   c := 'X';
   writeln "n = ", n;
   writeln "c = ", c;

end.
```


CPRL Example Disassembled

```
 0: PROGRAM 10                43: LDCSTR  "n = "
 5: LDGADDR 0                 56: PUTSTR
10: LDCINT 7                  57: LDGADDR 4
15: STOREW                    62: LOADW
16: LDGADDR 4                 63: PUTINT
21: LDCINT 5                  64: PUTEOL
26: LDGADDR 0                 65: LDCSTR  "c = "
31: LOADW                     78: PUTSTR
32: MUL                       79: LDGADDR 8
33: STOREW                    84: LOAD2B
34: LDGADDR 8                 85: PUTCH
39: LDCCH 'X'                 86: PUTEOL
42: STORE2B                   87: HALT
```

```
m: relative address = 0, absolute address = 88
n: relative address = 4, absolute address = 92
c: relative address = 8, absolute address = 96
```


CPRL Example in Memory
(after execution of first instruction)



Using the Stack to Hold Temporary Values

- The part of memory below the CVM instructions and global variables is used as a run-time stack that holds subprogram activation records (see Chapter 13) and temporary, intermediate values.
- As machine instructions are executed, the stack grows and shrinks.
- The run-time stack is empty at both the start and end of the each CPRL statement in the main program.

Example: Using the Stack to Hold Temporary Values

- Assume
  - register `SB` has the value `100`
  - integer variable x has relative address `0`
  - integer variable y has value `5` and relative address `4`
  - integer variable z has value `13` and relative address `8`
- The CPRL assignment statement

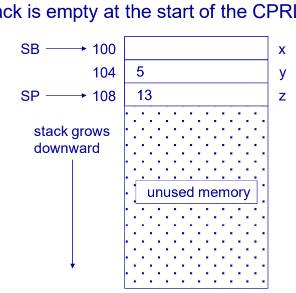
  `x := 2*y + z;`

  will compile to the following CVM instructions:

```
LDGADDR 0        LDGADDR 8
LDCINT 2         LOADW
LDGADDR 4        ADD
LOADW            STOREW
MUL
```


Example: Using the Stack to Hold Temporary Values (continued)

Stack is empty at the start of the CPRL statement.



Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LDGADDR 0`

SB →	100		x
	104	5	y
	108	13	z
SP →	112	100 (address of x)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LDCINT 2`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
SP →	116	2 (constant integer)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LDGADDR 4`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
	116	2 (constant integer)	
SP →	120	104 (address of y)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LOADW`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
	116	2 (constant integer)	
SP →	120	5 (value of y)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `MUL`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
SP →	116	10 (product)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LDGADDR 8`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
	116	10 (product)	
SP →	120	108 (address of z)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `LOADW`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
	116	10 (product)	
SP →	120	13 (value of z)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `ADD`

SB →	100		x
	104	5	y
	108	13	z
	112	100 (address of x)	
SP →	116	23 (sum)	

Example: Using the Stack to Hold Temporary Values (continued)

After execution of `STOREW`

SB →	100	23	x
	104	5	y
SP →	108	13	z

x now has the value 23

stack is empty again