香港中文大學
The Chinese University of Hong Kong

CSCI2510 Computer Organization
Lecture 05: Program Execution

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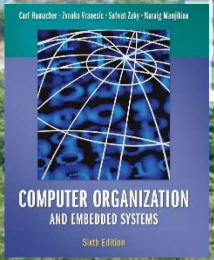

Reading: Chap. 2.3~2.7, 2.10, 4

Outline

- Revisit: Assembly Language Basics
- Program Execution
  - – Flow for Generating/Executing an Program
  - – Instruction Execution and Sequencing
  - – Branching
    - Condition Codes
  - – Subroutines
    - Stacks
    - Subroutine Linkage
    - Subroutine Nesting
    - Parameter Passing

Recall: Language Translation

High-level Language

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

```
TEMP = V(k);
V(k) = V(k+1);
V(k+1) = TEMP;
```

C/Java Compiler

Fortran Compiler

Assembly Language

`lw:` loads a word from **memory** into a register
`sw:` saves a word from a register into **RAM**
`0($2):` treats the value of register $2 + 0 bytes as a location
`4($2):` treats the value of register $2 + 4 bytes as a location

```
lw $t0, 0($2)
lw $t1, 4($2)
sw $t1, 0($2)
Sw $t0, 4($2)
```

MIPS Assembler

Machine Language

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```

https://gerardnico.com/code/lang/machine
https://clip2art.com/explore/Boy%20clipart%20teacher/

Assembly Language

- Machine instructions are represented by 0s and 1s.

→ Such patterns are *awkward* to deal with by humans!

→ We use symbolic names to represent 0/1 patterns!

- **Assembly Language**: a complete set of such symbolic names and rules for their use constitutes a programming language
  - **Syntax**: the set of rules for using the *mnemonics* or *notations* and for specifying complete instructions/programs
  - **Mnemonics**: acronyms to represent instruction operations
    - E.g. Load → **`LD`**, Store → **`ST`**, Add → **`ADD`**, etc.
  - **Notations**: shorthand for registers or memory locations
    - E.g. register 3 → **R3**, a particular memory location → **LOC**

Assembly Language Syntax

- **Three-operand Instruction**:

  `operation dest, src1, src2`

  - E.g. "**`Add A, B, C`**" means "A ← [B] + [C]"
    - Note: We use [X] to represent the content at location X.

- **Two-operand Instruction**:

  `operation dest, src`

  - E.g. "**`Move A, B`**" means "A ← [B]"
  - E.g. "**`Add A, B`**" means "A ← [A] + [B]"
    - Note: Operand A is like both the source and the destination.

Some machines may put destination last:

`operation src, dest`

- **One-operand Instruction**:
  - Some PCs have a special register called accumulator (ACC).
    - E.g. "**`Add B`**" means "ACC ← ACC + [B]"
    - E.g. "**`Load B`**" means "ACC ← [B]"
    - E.g. "**`Store B`**" means "B ← ACC"

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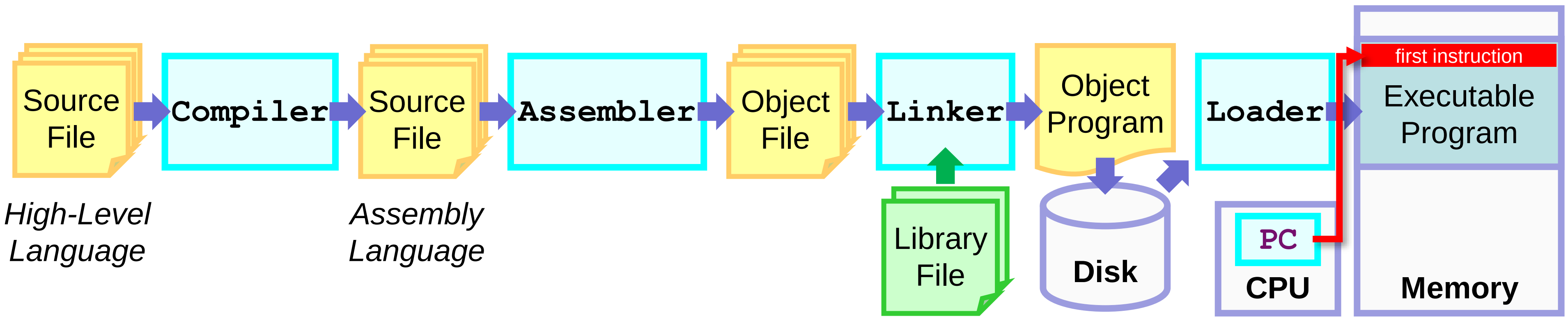
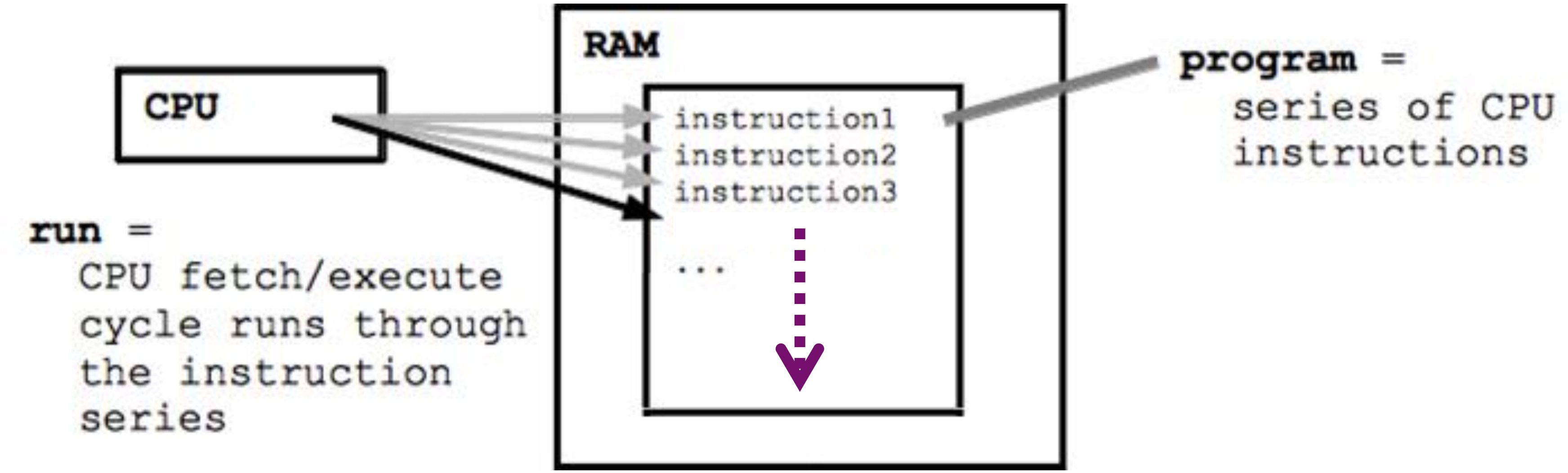
Generating/Executing a Program

- **Compiler**: Translate a high-level language source programs into assembly language source programs
- **Assembler**: Translate assembly language source programs into object files of machine instructions
- **Linker**: Combine the contents of object files and library files into one object/executable program
  - **Library File**: Collect useful subroutines of application programs
- **Loader**: Load the program into memory and load the address of the first instruction into program counter (PC)



Activities in a Computer: Instructions

- A computer is governed by instructions.
  - To perform a given task, a program consisting of a list of machine instructions is stored in the memory.
    - Data to be used as operands are also stored in the memory.
  - Individual instructions are brought from the memory into the processor, one after another, in a sequential way (normally).
  - The processor executes the specified operation/instruction.



An Example of Program Execution

- Considering a program of 3 instructions:

PC → I_0: `Load R0, LOC`

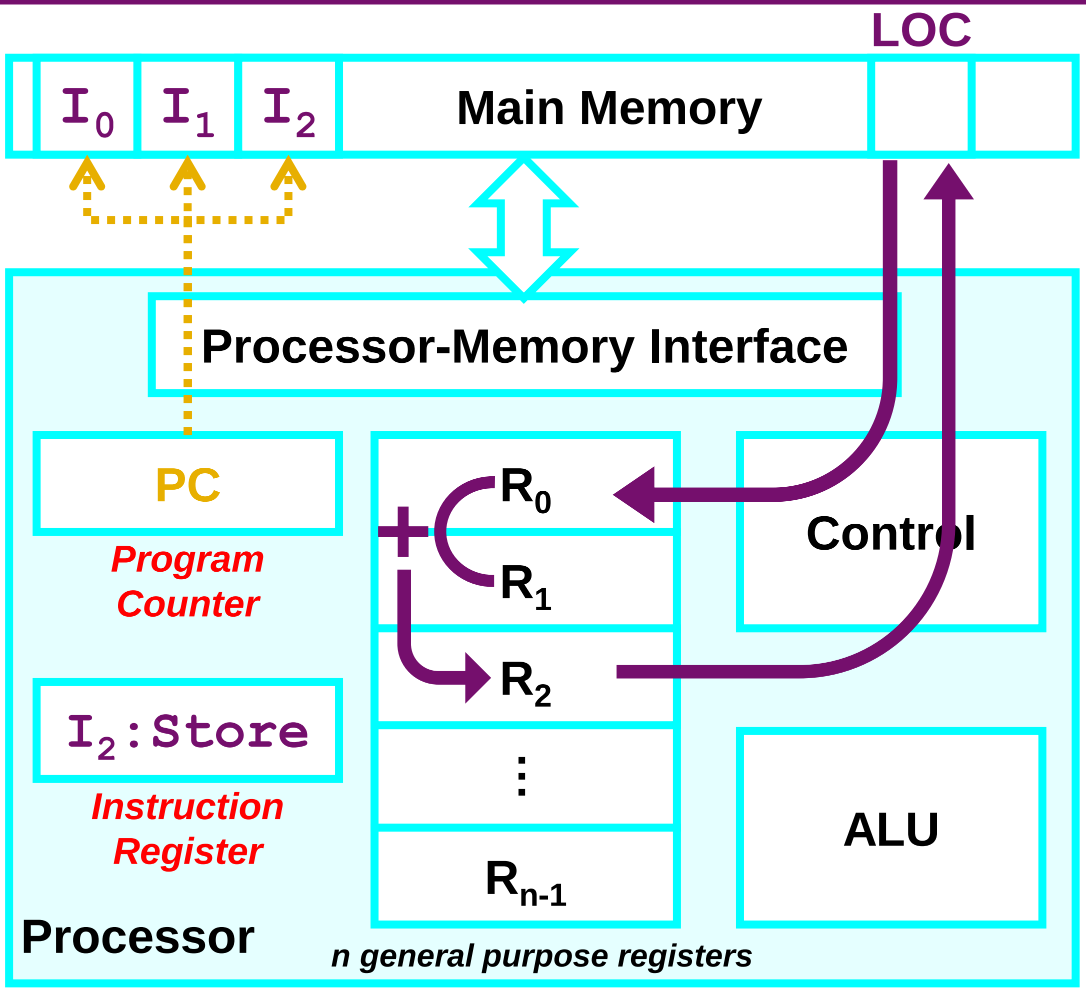
  - Reads the contents of a memory location LOC
  - Loads them into processor register R0

– I_1: `Add R2, R0, R1`

  - Adds the contents of registers R0 and R1
  - Places their sum into register R2

– I_2: `Store R2, LOC`

  - Copies the operand in register R2 to memory location LOC



PC: contains the memory address of the next instruction to be fetched and executed.
IR: holds the instruction that is currently being executed.
R_0~R_{n-1}: n general-purpose registers.

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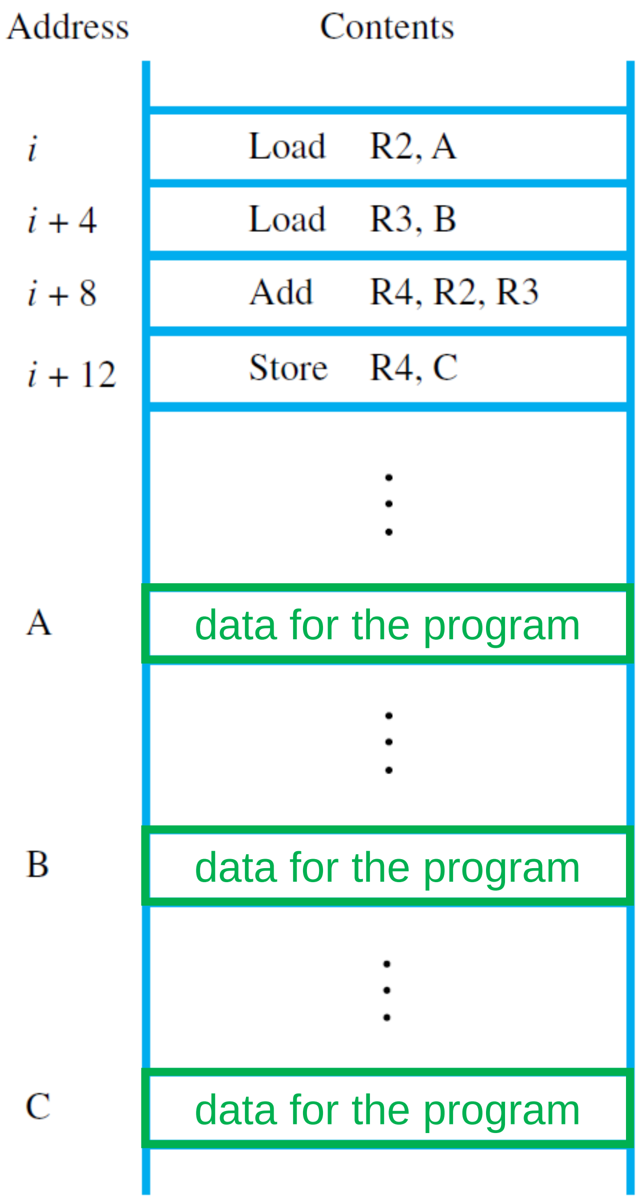
Instruction Execution & Sequencing (1/3)

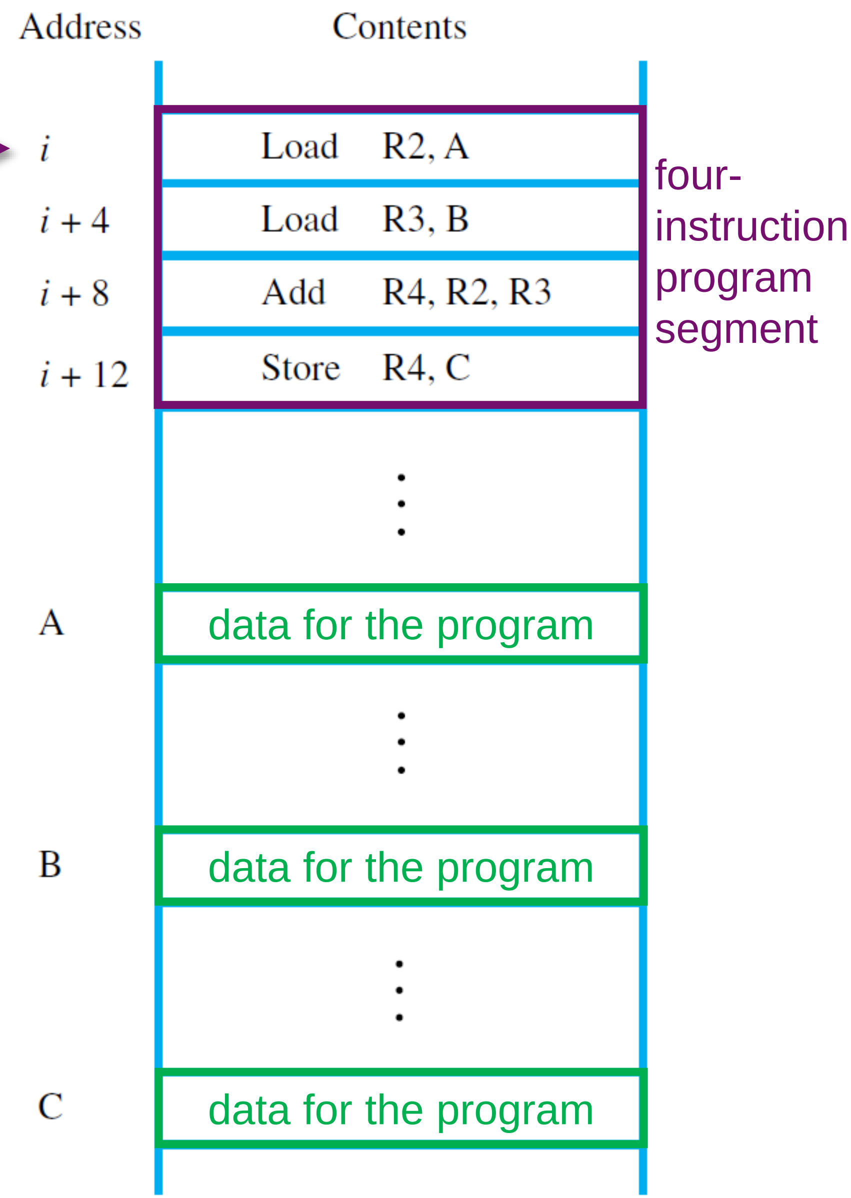
- Consider a machine:
  - RISC instruction set
  - 32-bit word, 32-bit instruction
  - Byte-addressable memory

- Given the task $C = A + B$ ($Lec04$)
  - Implemented as C ← [A] + [B]
  - Possible RISC-style program segment:
    - `Load R2, A`
    - `Load R3, B`
    - `Add R4, R2, R3`
    - `Store R4, C`



Instruction Execution & Sequencing (2/3)

- Assume the 4 instructions are loaded in successive memory locations:
  - Starting at location *i*
  - The 2nd, 3rd, 4th instructions are at $i + 4$, $i + 8$, and $i + 12$
    - Each instruction is 4 bytes
- To execute this program
  - The program counter (PC) register in the processor should be loaded with the address of the 1st instruction.
    - **PC**: holds the address of *the next instruction* to be executed.

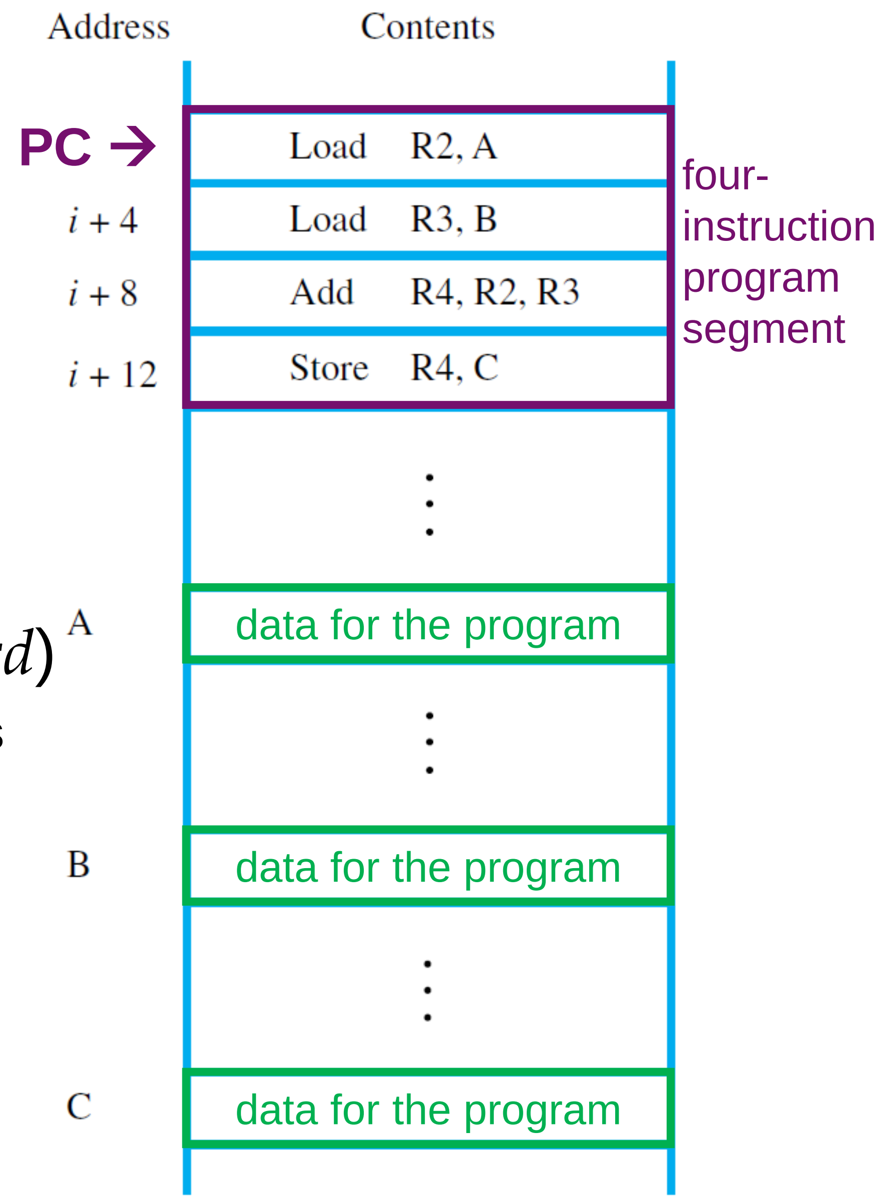


Instruction Execution & Sequencing (3/3)

- **Straight-Line Sequencing:**
  – CPU fetches and executes instructions indicated by PC, one at a time, in the order of increasing addresses.

  1) Instruction Fetch:
  - `IR ← [[PC]]`
  - `PC ← [PC] + 4` (*32-bit word*)
    - ✓ **PC** contains the memory address of the next instruction.
    - ✓ **IR** holds the current instruction.

  2) Instruction Execute:
  - Interpret (or decode) IR
  - Perform the operation



Class Exercise 5.1

Student ID: ____________ Date:
Name: ____________________ __________

- Consider a task of adding n num:
  - The symbolic memory addresses of the n numbers: NUM1, NUM2, …, NUMn
  - The result is in memory location SUM.
- Please write the program segment to add n num into R2.
- Answer:

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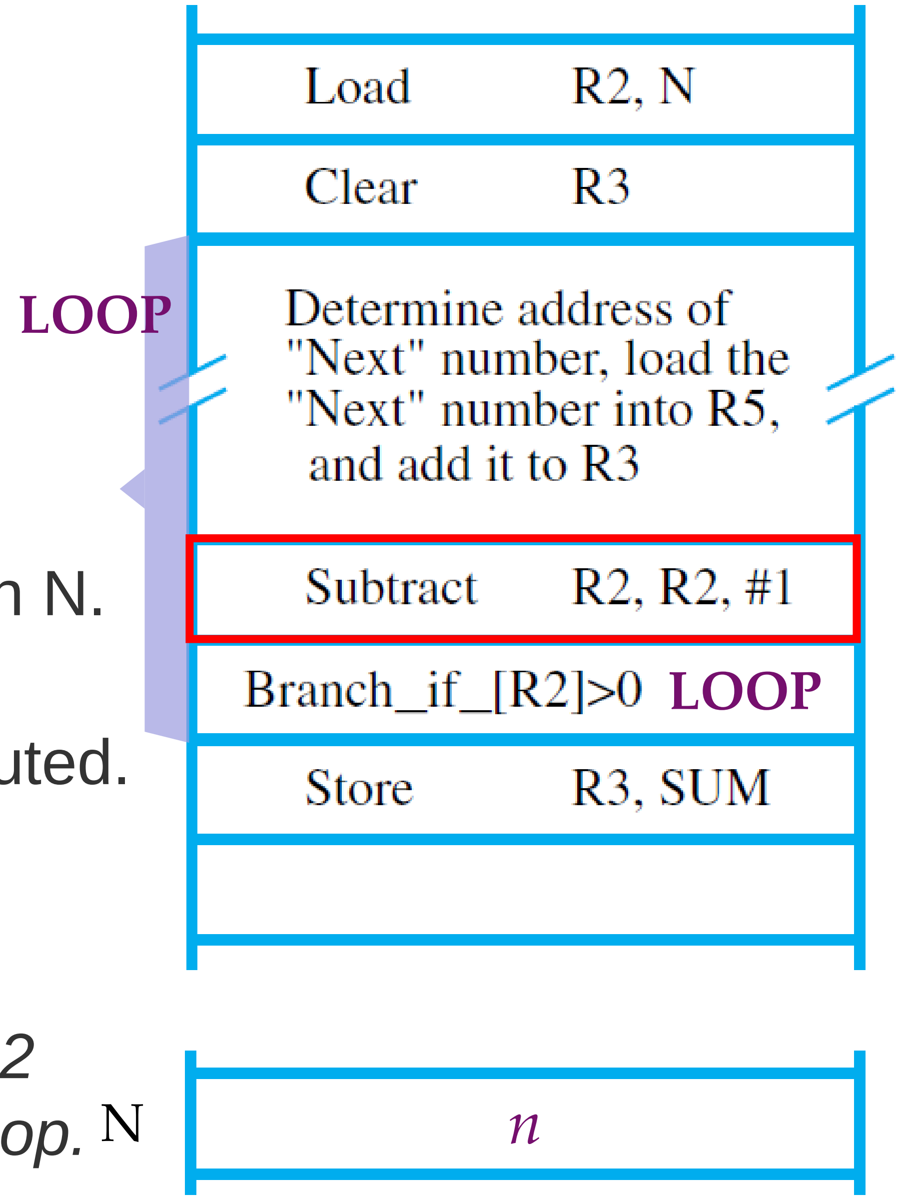
Branching: Implementing a Loop (1/2)

- The body of the **loop**:
  - **Start**: at location `LOOP`
  - **Body:** the repeated task
    - E.g. "`Load-Add`" instructions
  - **End**: at Branch_if_[R2]>0
- Assume that
  - *n* is stored in memory location N.
  - R2 represents <u>the number of times</u> (i.e. *n*) the loop is executed.
- Within the body of the loop,

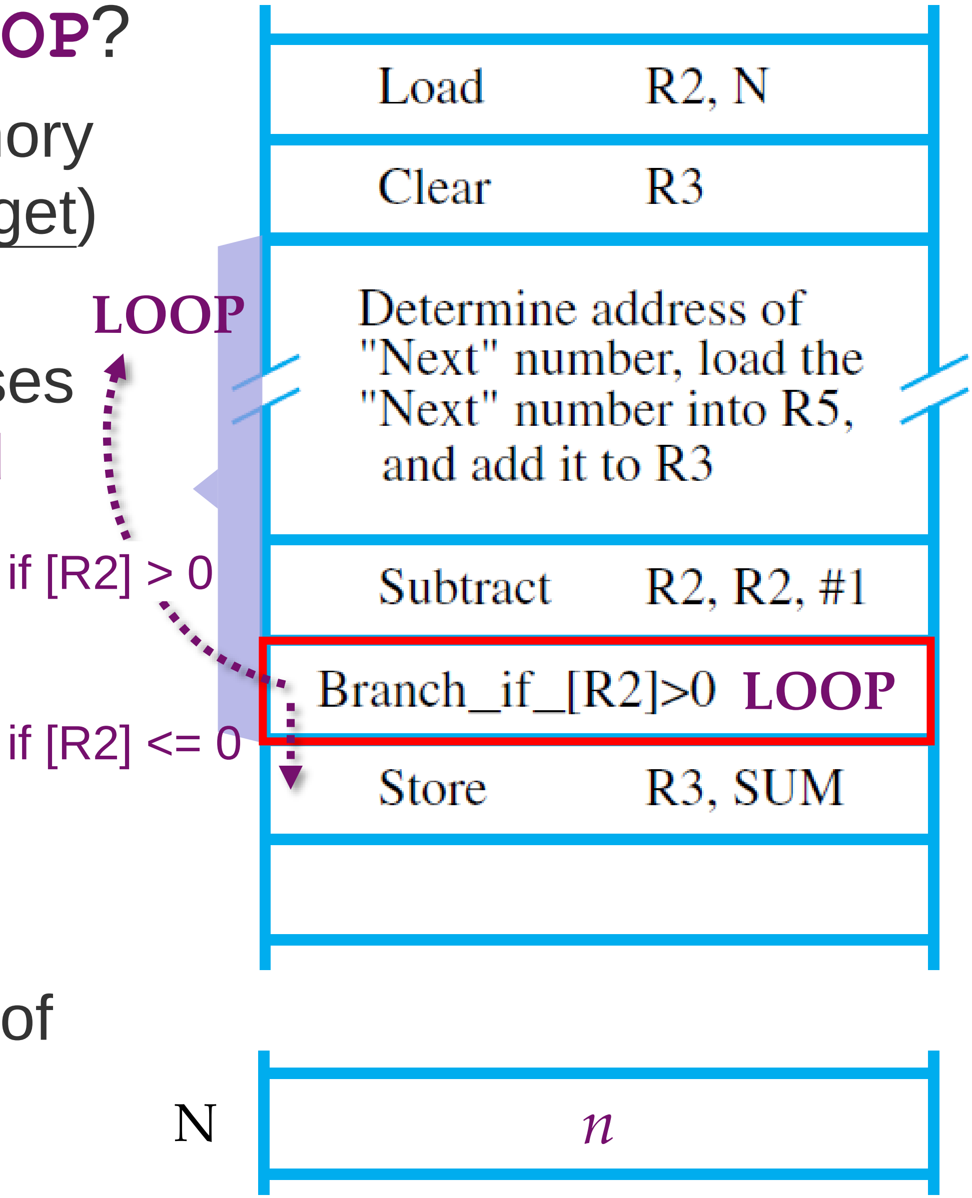
  `Subtract R2, R2, #1`

  - *Decreasing the contents of R2 by 1 each time through the loop.*



Branching: Implementing a Loop (2/2)

- How to "jump back" to **`LOOP`**?
  - **Branch**: loads a new memory address (called <u>branch target</u>) into the PC.
  - **Conditional Branch**: causes a branch only if a specified condition is satisfied.
- Branch_if_[R2]>0 **`LOOP`**
  - A **conditional branch** instruction that causes branch to location LOOP.
  - **Condition**: If the contents of R2 are <u>greater than zero</u>.



Class Exercise 5.2

- The program for adding a list of n numbers can be derived as follows. In which, the indirect addressing is used to access successive numbers in the list.
- Please fill in the blank comment fields below:

LABEL	OPCODE	OPERAND	COMMENT
	`Load`	`R2, N`	
	`Clear`	`R3`	
	`Move`	`R4, addr NUM1`	
`LOOP:`	`Load`	`R5, (R4)`	
	`Add`	`R3, R3, R5`	
	`Add`	`R4, R4, #4`	
	`Subtract`	`R2, R2, #1`	
	`Branch_if_[R2]>0`	`LOOP`	
	`Store`	`R3, SUM`	

Example of Nested Loops

	Move	R2, **addr T**	R2 points to string T.
	Move	R3, **addr P**	R3 points to string P.
	Load	R4, N	Get the value n.
	Load	R5, M	Get the value m.
	Subtract	R4, R4, R5	Compute $n - m$.
	Add	R4, R2, R4	The address of $T(n - m)$.
	Add	R5, R3, R5	The address of $P(m)$.
LOOP1:	Move	R6, R2	Use R6 to scan through string T.
	Move	R7, R3	Use R7 to scan through string P.
LOOP2:	LoadByte	R8, (R6)	Compare a pair of
	LoadByte	R9, (R7)	characters in
	Branch_if_[R8]≠[R9]	NOMATCH	strings T and P.
	Add	R6, R6, #1	Point to next character in T.
	Add	R7, R7, #1	Point to next character in P.
	Branch_if_[R5] > [R7]	**LOOP2**	Loop again if not done.
	Store	R2, RESULT	Store the address of $T(i)$.
	Branch	DONE	
NOMATCH:	Add	R2, R2, #1	Point to next character in T.
	Branch_if_[R4] ≥ [R2]	**LOOP1**	Loop again if not done.
	Move	R8, #−1	Write −1 to indicate that
	Store	R8, RESULT	no match was found.
DONE:	next instruction		

Chap. 2.12.2, Computer Organization and Embedded Systems (6th Ed.)

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Condition Codes (1/2)

- Operations performed by the processor typically generate number results of *positive*, *negative*, or *zero*.
  - E.g. `Subtract R2, R2, #1` (in the Loop program)
- **Condition Code Flags**: keep the information about the results for subsequent conditional branch (if any).
  - **Condition Code Register** (or **Status Register**): groups and stores these flags in a special register in the processor.
- Four common flags:

N (negative)	Set to 1 if the result is negative; otherwise, cleared to 0
Z (zero)	Set to 1 if the result is 0; otherwise; otherwise, cleared to 0
V (overflow)	Set to 1 if arithmetic overflow occurs; otherwise, cleared to 0
C (carry)	Set to 1 if a carry-out occurs; otherwise, cleared to 0

Condition Codes (2/2)

- Consider the Conditional Branch example:
  - If condition codes are used, the **`branch`** instruction (**`Branch_if_[R2]>0 LOOP`**) could be simplified as:

    `Branch>0 LOOP`

    without indicating the register involved in the test.
  - This new instruction causes a branch if neither N nor Z is 1.
    - The **`subtract`** instruction would cause both N and Z flags to be cleared to 0 if R2 is still greater than 0.

N (negative)	Set to 1 if the result is negative; otherwise, cleared to 0
Z (zero)	Set to 1 if the result is 0; otherwise; otherwise, cleared to 0
V (overflow)	Set to 1 if arithmetic overflow occurs; otherwise, cleared to 0
C (carry)	Set to 1 if a carry-out occurs; otherwise, cleared to 0

Class Exercise 5.3

- Given two 4-bit registers R1 and R2 storing signed integers in 2's-complement format. Please specify the condition flags that will be affected by **`Add R2, R1`**:

$if\ R1 = (2)_{10} = (0010)_2,\ \ R2 = (-5)_{10} = (1011)_2$

Answer: ____________________________

$if\ R1 = (2)_{10} = (0010)_2,\ \ R2 = (-2)_{10} = (1110)_2$

Answer: ____________________________

$if\ R1 = (7)_{10} = (0111)_2,\ R2 = (1)_{10} = (0001)_2$

Answer: ____________________________

$if\ R1 = (5)_{10} = (0101)_2,\ R2 = (-2)_{10} = (1110)_2$

Answer: ____________________________

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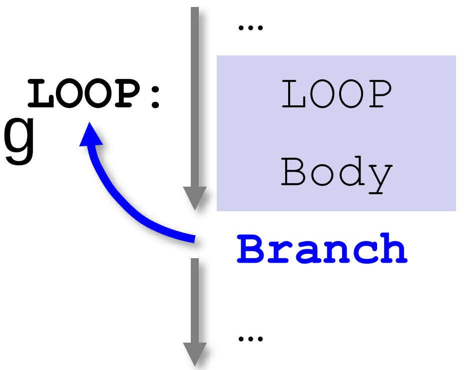
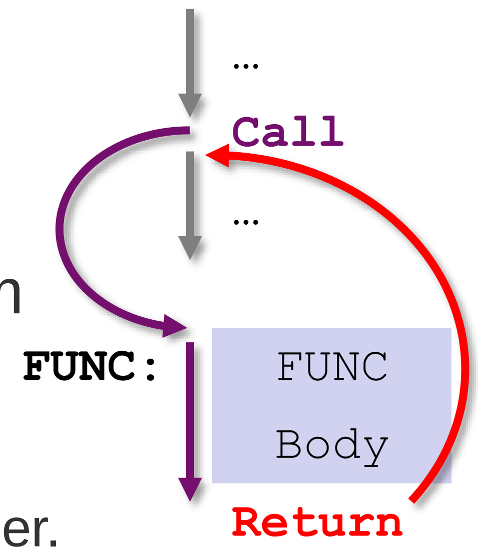
Branch vs. Subroutine

- **Branch**:
  - Jumping to a particular instruction by loading its memory address into PC.



- It's also common to perform a particular task many times on different values.
- **Subroutine/Function Call**
  - **Subroutine**: a block of instructions that will be executed each time when calling.
  - **Subroutine/Function Call**: when a program *branches* to and back from a subroutine.
    - **Call**: the instruction performing the branch.
    - **Return**: the instruction branching back to the caller.
  - "**Stack**" is essential for subroutine calls.



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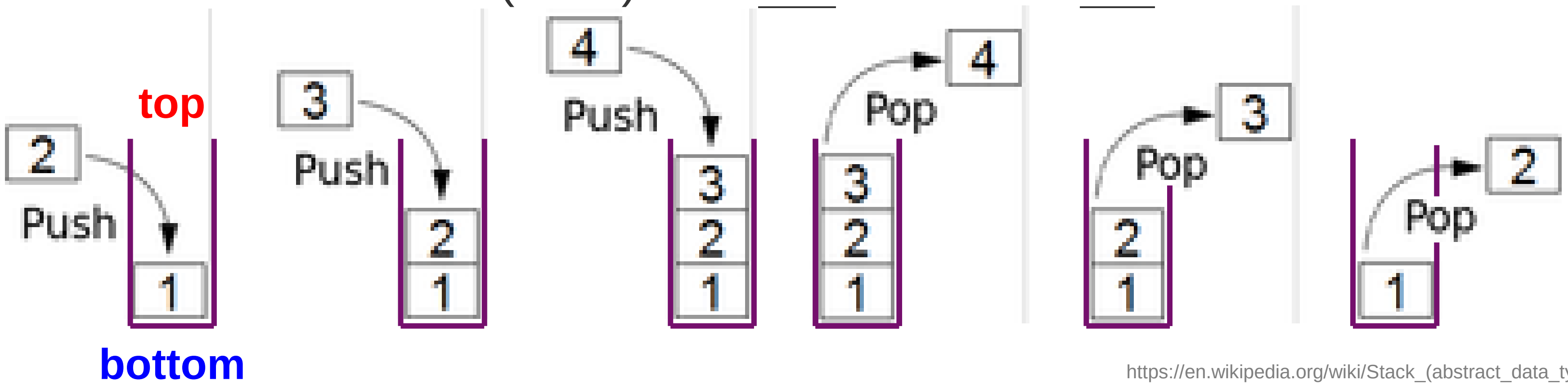
Stacks

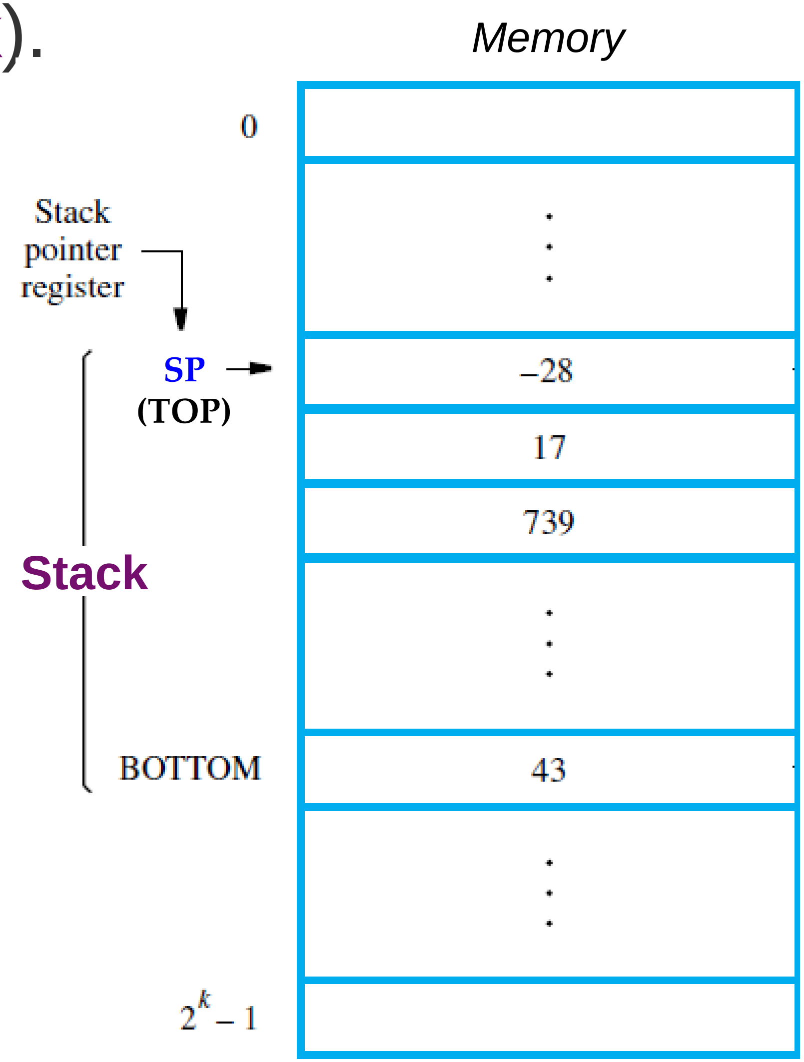
- **Stack** is a list of data elements (usually words):
  - *Elements can only be removed at one end of the list.*
    - This end is called the **top**, and the other end is called the **bottom**.
    - Examples: a stack of coins, plates on a tray, a pile of books, etc.
  - **Push**: Placing a new item at the top end of a stack
  - **Pop**: Removing the top item from a stack
  - Stack is often called LIFO or FILO stack:
    - *Last-In-First-Out* (LIFO): The last item is the first one to be removed.
    - *First-In-Last-Out* (FILO): The first item is the last one to be removed.



https://en.wikipedia.org/wiki/Stack_(abstract_data_type)

Processor Stacks (1/2)

- Modern processors usually provide native support to stacks (called processor stack).
  - A processor stack can be implemented by using a portion of the main memory.
    - Data elements of a stack occupy successive memory locations.
    - The first element is placed in location BOTTOM (*larger address*).
    - The new elements are pushed onto the TOP of the stack.
  - **Stack Pointer (SP)**: a special processor register to keep track of the address of the TOP item of processor stack.



Processor Stacks (2/2)

- Given a stack of word data items, and consider a byte-addressable memory with a 32-bit word:
  - **Push** an item in Rj onto the stack:

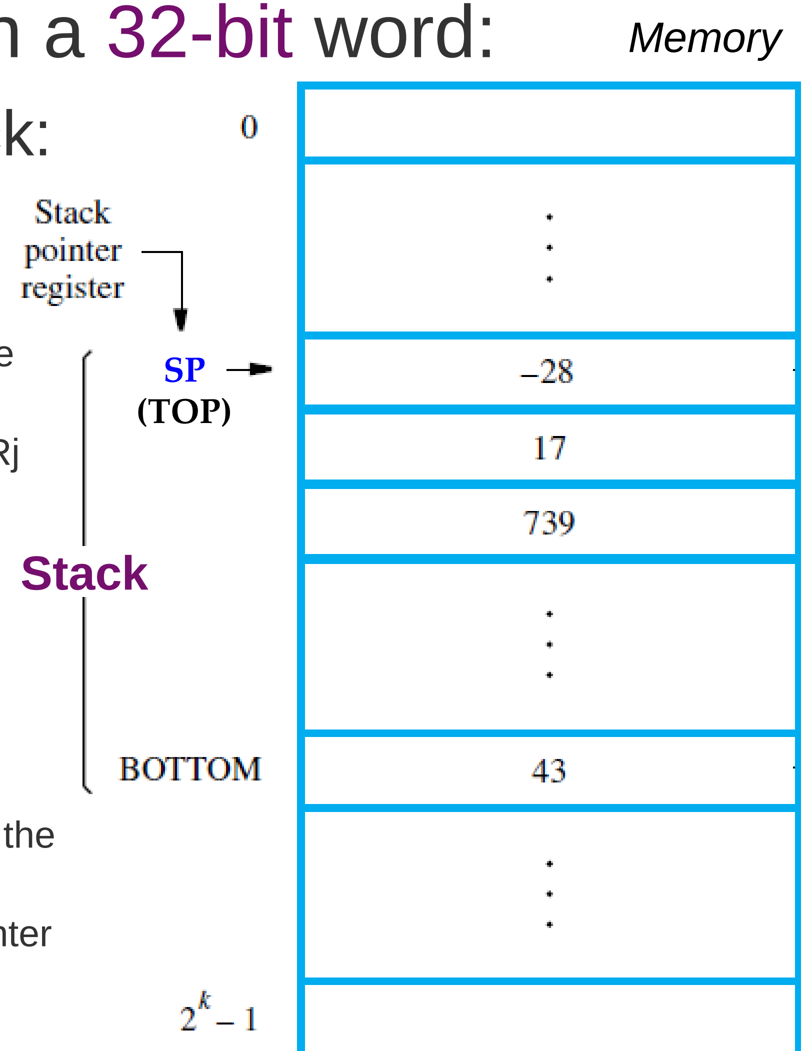
```
Subtract    SP, SP, #4
Store       Rj, (SP)
```

    - The `Subtract` instruction first subtracts 4 from the contents of SP and places the result in SP.
    - The `Store` instruction then places the content of Rj onto the stack.

  - **Pop** the top item into Rj

```
Load        Rj, (SP)
Add         SP, SP, #4
```

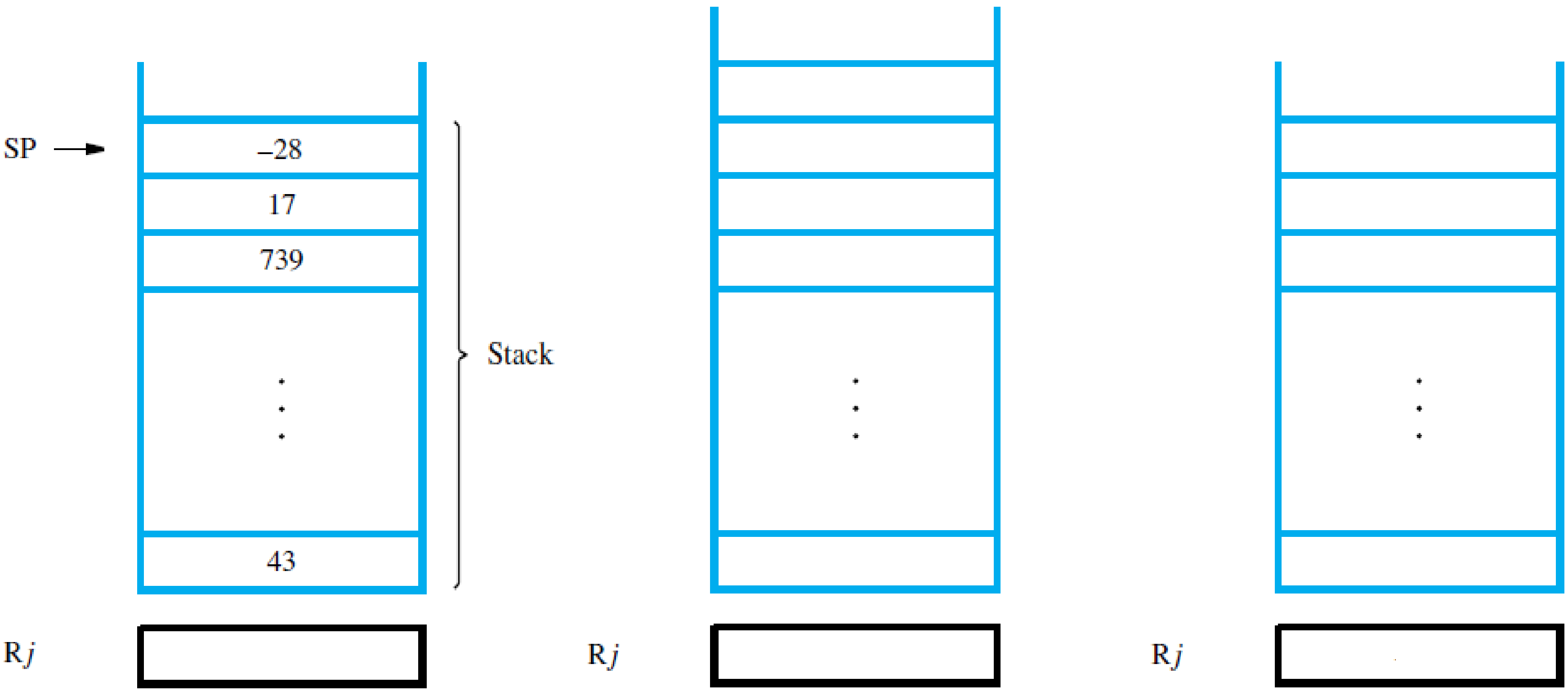
    - The `Load` instruction first loads the top value from the stack into register Rj
    - The `Add` instruction then increments the stack pointer by 4.



How to use Autoincrement/Autodecrement addressing modes to simplify?

Class Exercise 5.4

1) Fill in the contents of the stack and the register Rj, 2) denote the location of SP, and 3) specify the range of the stack, after ***push*** or ***pop*** operation is performed:



(a) Before **Push/Pop** (b) After **Push** (c) After **Pop**

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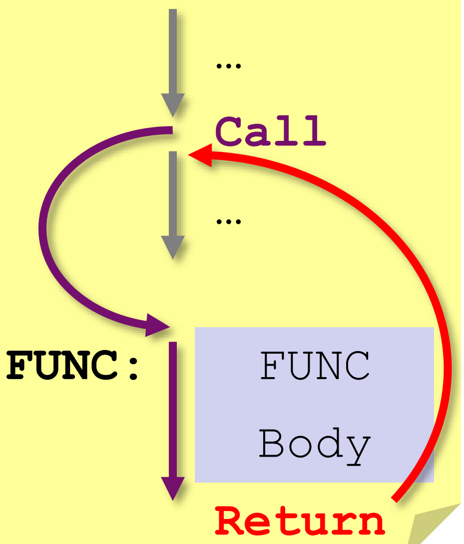
Revisit: Subroutine

- Recall:
  - When a program branches to a subroutine we say that it is **calling** the subroutine.
  - After a subroutine calling, the subroutine is said to **return** to the program that called it.
    - Continuing immediately after the instruction that called the subroutine.

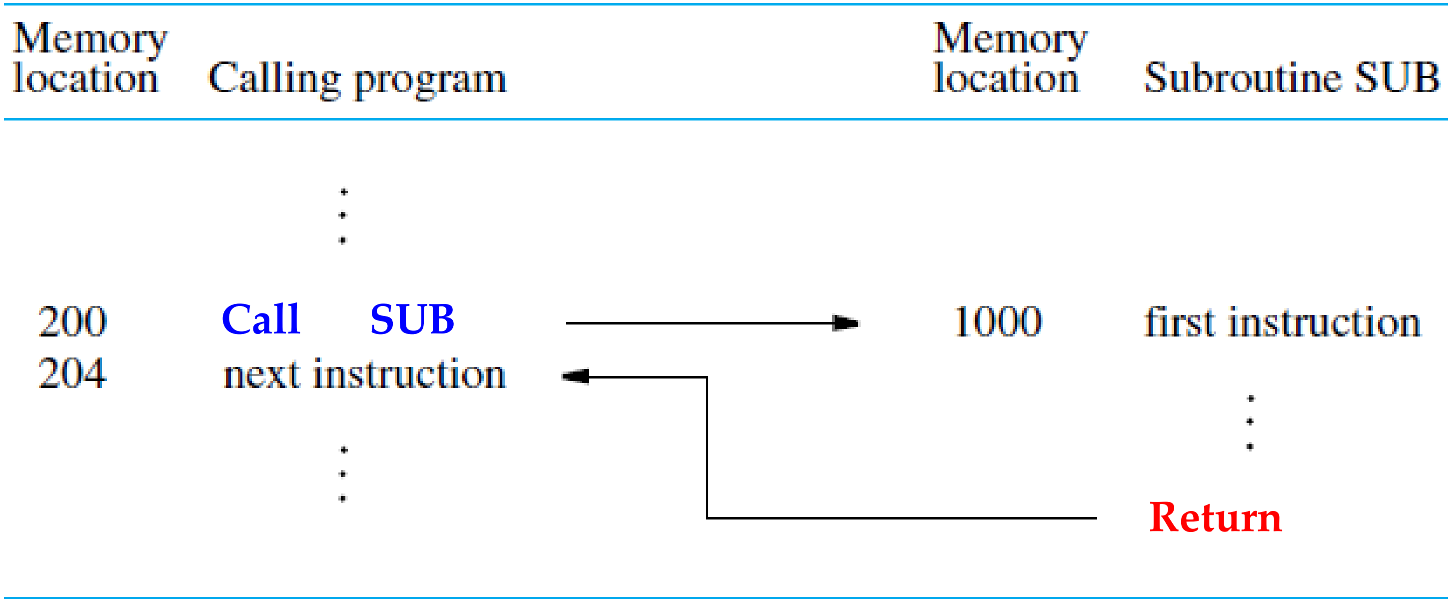


- However, the subroutine may be called from different places in a calling program.
- Thus, provision must be made for **returning** to the appropriate location.
  - That is, the contents of the PC must be saved by the Call instruction to enable correct return to the calling program.

Subroutine Linkage

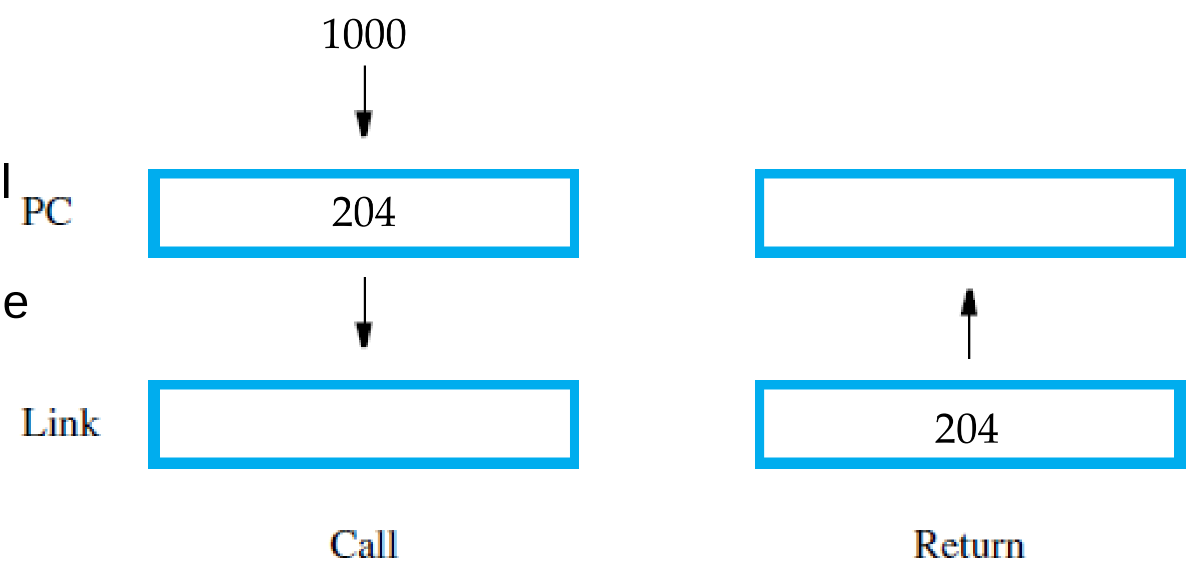
- **Subroutine Linkage** method: the way makes it possible to call and return from subroutines.
  - The simplest method: saving the return address in a special processor register called the link register.
- With the help of link register,
  - The **Call** instruction can be implemented as a special *branch* instruction:
    - Store the contents of the PC in the link register.
    - Branch to the target address specified by the Call instruction.
  - The **Return** instruction can be implemented as a special *branch* instruction as well:
    - Branch to the address contained in the link register.

Example of Subroutine Linkage



Branch to the target address specified by Call

Store PC into the link register.



Branch back to the address contained in the link register.

Question: Is one link register enough for all cases?

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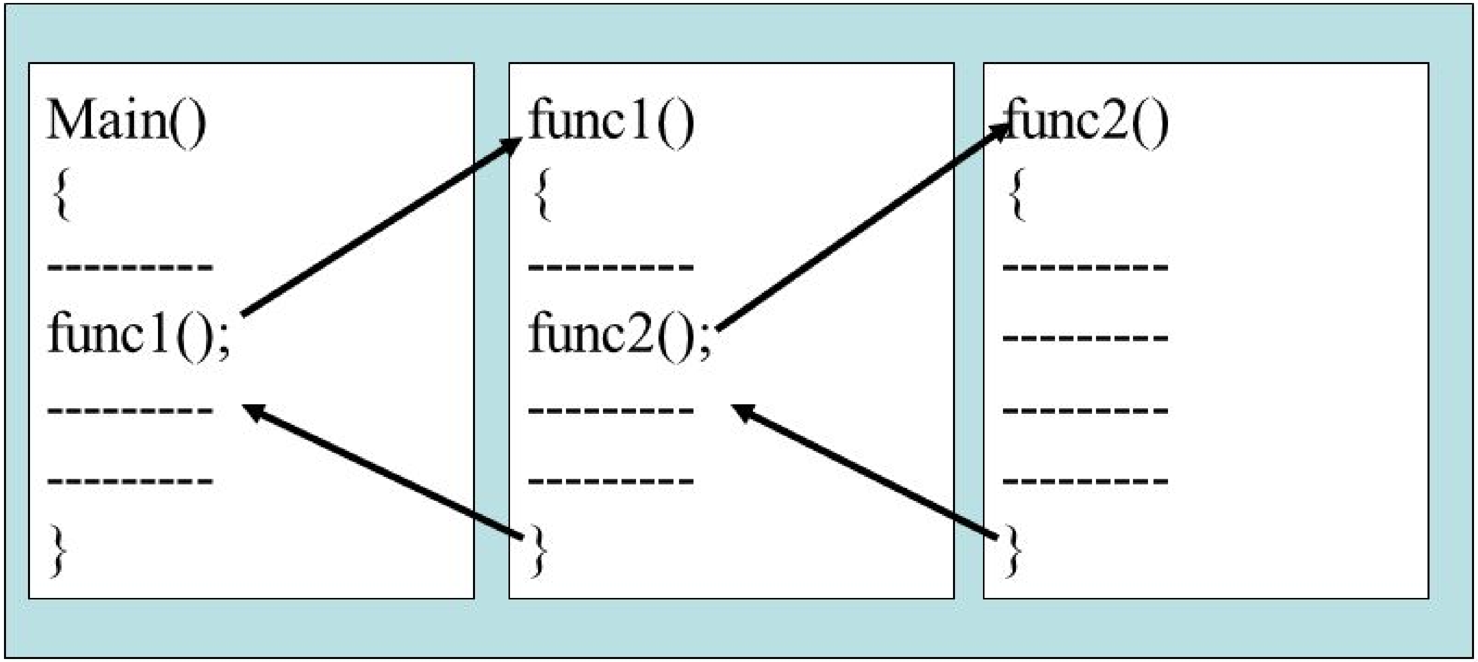
Subroutine Nesting (1/3)

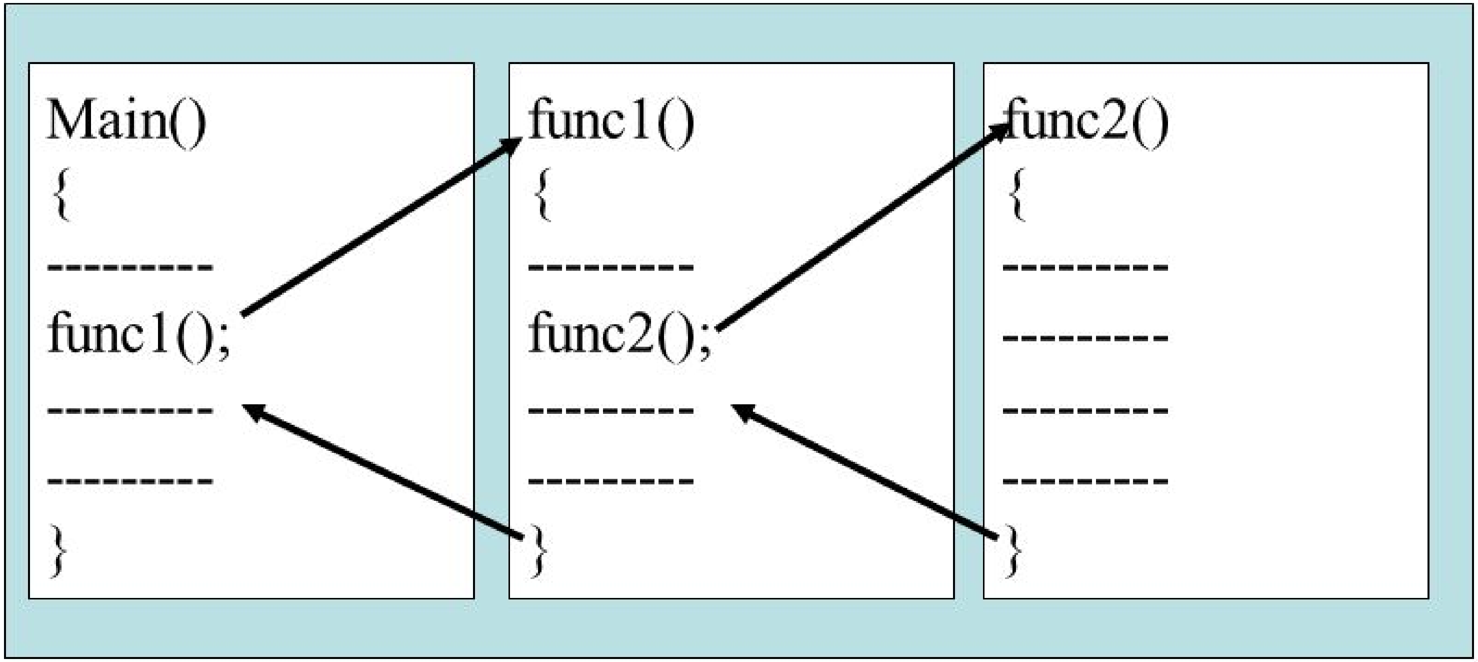
- **Subroutine Nesting**: One subroutine calls another subroutine or itself (i.e. recursion).
  - If the return address of the second call is also stored in the link register, the first return address will be lost … ERROR!
  - Subroutine nesting can be carried out to any depth …



https://slideplayer.com/slide/7603076/

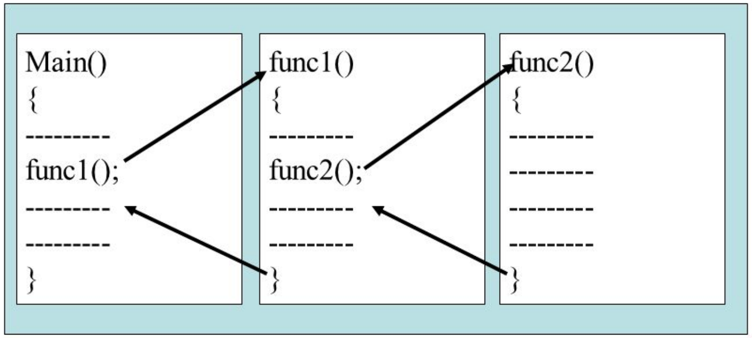
Subroutine Nesting (2/3)

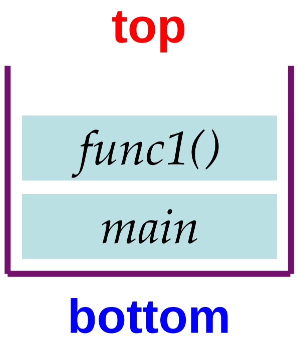
- *Observation*: The return address needed for the first return is the last one generated in the nested calls.
  - That is, return addresses are generated and used in a last-in–first-out (LIFO) order.



Subroutine Nesting (3/3)

- **Processor stack** is useful to store subroutine linkage:
  - The **Call** instruction:
    - ~~Store the contents of the PC in the link register~~
    - → Push the contents of the PC to the processor stack
    - Branch to the target address specified by the Call instruction.
    - → (*Unchanged*)
  - The **Return** instruction:
    - ~~Branch to the address contained in the link register~~
    - → Branch to the address popped out from the processor stack





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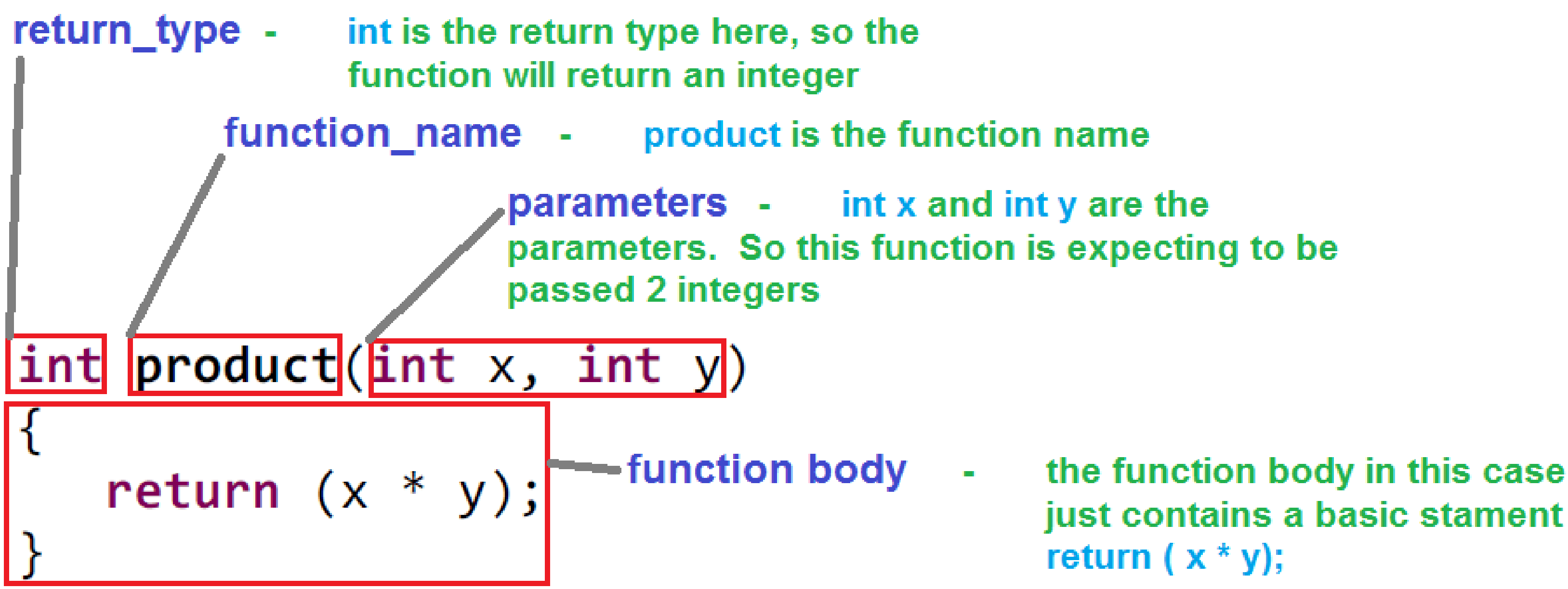
Parameter Passing

- **Parameter Passing**: The exchange of information between a calling program and a subroutine.
  - When calling a subroutine, a program must provide the parameters (i.e. operands or their addresses) to be used.
  - Later, the subroutine returns other parameters, which are the results of the computation.



http://coder-tronics.com/c-programming-functions-pt1/

Parameter Passing via Registers

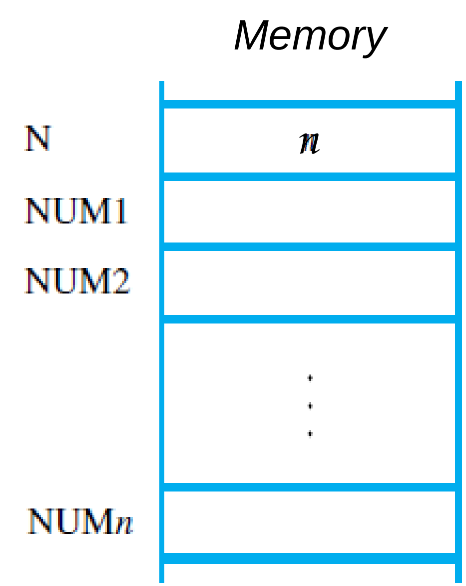
- The simplest way is placing parameters in registers.
- Recall the program for adding a list of numbers.
- The program can be implemented as a subroutine with
  - R2 & R4 are used to pass the size of list & the address of the first num,
  - R3 is used to pass back the sum computed by the subroutine.

Calling Program

```
            Load              R2, N          Parameter 1 is list size.
            Move              R4, addrNUM1   Parameter 2 is list location.
            Call              LISTADD        Call subroutine.
            Store             R3, SUM        Save result.
            :
```

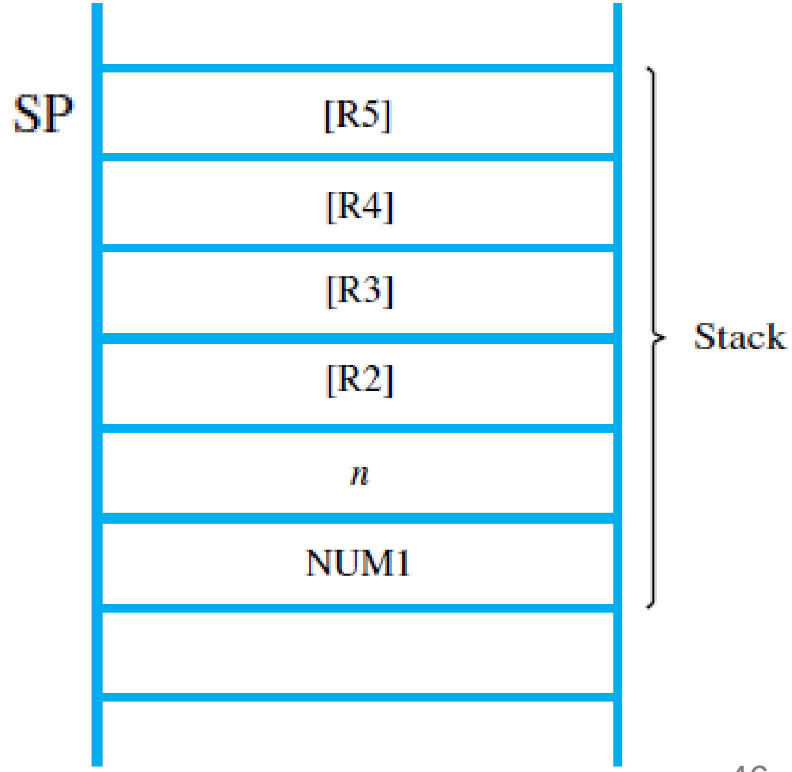
Subroutine

```
LISTADD:    Subtract          SP, SP, #4     Save the contents of
            Store             R5, (SP)         R5 on the stack.
            Clear             R3             Initialize sum to 0.
LOOP:       Load              R5, (R4)       Get the next number.
            Add               R3, R3, R5     Add this number to sum.
            Add               R4, R4, #4     Increment the pointer by 4.
            Subtract          R2, R2, #1     Decrement the counter.
            Branch_if_[R2]>0  LOOP
            Load              R5, (SP)       Restore the contents of R5.
            Add               SP, SP, #4
            Return                           Return to calling program.
```



Parameter Passing on Processor Stack

- What if there are more parameters than registers?
- What if the subroutine calls itself (recursion)?
- The processor stack, again, provides a good scheme to pass an arbitrary number of parameters.
- What we can pass via stack?
  1) We can push *all parameters to be computed* onto the stack.
  2) We can push *the contents of all "to-be-used" registers* onto the stack.
  3) We can also push *the computed result* before the return to the calling program.



Parameter Passing by Value / Reference

- What kind of parameters can we pass?
- **Passing by Value**
  - The actual number is passed by an immediate value.
- **Passing by Reference** (more powerful, be careful!)
  - Instead of passing the actual values in the list, the routine passes the starting address (i.e. reference) of the number.

https://www.mathwarehouse.com/programming/passing-by-value-vs-by-reference-visual-explanation.php

Class Exercise 5.5

- The below program adds a list of n numbers, in which
  - The size n is stored in memory location/address **N**, and
  - **NUM1** is the memory address for the first number.
- Are **N** and **NUM1** used as values or references?

LABEL	OPCODE	OPERAND	COMMENT
	`Load`	`R2, N`	*Load the size of the list.*
	`Clear`	`R3`	*Initialize sum to 0.*
	`Move`	`R4, addr NUM1`	*Get address of the first number.*
`LOOP:`	`Load`	`R5, (R4)`	*Get the next number.*
	`Add`	`R3, R3, R5`	*Add this number to sum.*
	`Add`	`R4, R4, #4`	*Increment the pointer to the list.*
	`Subtract`	`R2, R2, #1`	*Decrement the counter.*
	`Branch_if_[R2]>0`	`LOOP`	*Branch back if not finished.*
	`Store`	`R3, SUM`	*Store the final sum.*

Summary

- Revisit: Assembly Language Basics
- Program Execution
  - Flow for Generating/Executing an Program
  - Instruction Execution and Sequencing
  - Branching
    - Condition Codes
  - Subroutines
    - Stacks
    - Subroutine Linkage
    - Subroutine Nesting
    - Parameter Passing