ENS1161 Computer Fundamentals

Module 5
Applications, programming languages and translation

Module Objectives

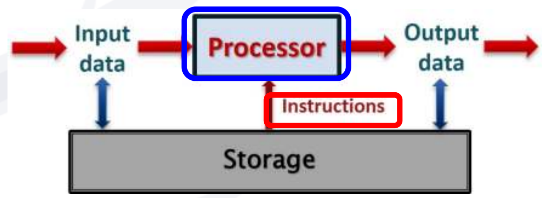
On completion of this module, students should be able to:

- Explain the differences between high-level languages (HLLs) and assembly language, and the advantages and disadvantages of writing programs in each of these.
- Describe the process of translating programs into executable binary code, including the translator tools used.
- Explain how HLL program control structures are implemented using conditional branch instructions.
- Explain what a stack is and how it functions.
- Explain how subroutine calls and returns work, including the role of the stack in these processes.

Moving forward..

- Last module:
  - How the ALU works
  - Flags (condition codes)
  - Arithmetic and Logic instructions
  - Some instructions that use condition codes

- Focus of this module: Programs
  - Programming languages
  - Programming 'tools' that convert programs to binary code



Introduction

- **Module Scope**
  - Levels of programming languages
  - Control structures in programming
  - Tools to convert program code to machine language
    - Roles, advantages and limitations

Using computing devices

- There are a wide variety of computing devices
  - From embedded systems in appliances, to mobile phones and laptops to desktop computers and servers.

- We use these devices though a wide variety of **applications** (*apps*)

Types of software *(recap Module 1)*

- 2 broad categories:
  - **Operating system**
    - Main function is to control the hardware and enable other software to interface with the hardware
    - Also acts as ‘control program’ for other applications
      - e.g. Windows, macOS, Android
  - **Application software**
    - Designed to perform a certain type of function
      - E.g. wordprocessor, browser, spreadsheet, etc.
  - *Operating systems covered in more detail in Module 9*

What is a program? *(recap Module 2)*

- A program is a series of instructions
  - stored in the memory sub-system
  - fetched and executed sequentially
- Each instruction consists of two parts
  - an *operation*
  - an *operand* or *operand address*
    - data / location of the data on which to perform the operation

Operand address

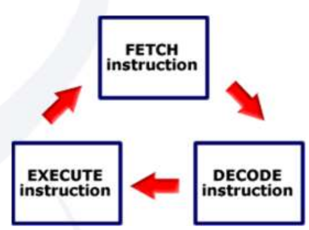
Operations

```
LDA  C100h    ; Load accumulator with data from memory location
              ; C100 hex (or 1100 0001 0000 0000 in binary)
ADDI 2        ; Add immediate value (2) to the number in the
              ; accumulator
```

Operand

How a Computer System Works *(recap)*

- A processor needs a set of instructions
  - tells it what operations to perform on what data
- Instructions (programs) are stored in memory
- The microprocessor:
  - *fetches* an instruction from memory
  - *decodes* it, and
  - *executes* the specified operation
- Sequence of *fetch*, *decode* and *execute* continues indefinitely
  - Until reach an instruction to stop or powered off



Instruction Set *(recap Module 2)*

- A processor can ONLY execute the set of instructions it was built to understand
  - *The set of operations a processor can perform*
  - Different for every processor family
- Each instruction (or variation of it) has a unique opcode
  - Also called object code or machine code
- Each instruction requires specific series of simple steps to complete the required operation
  - Normally done by a built-in *microprogram* (or *microcode*) in the Control Unit
    - Generates the controls signals for the instruction in the right order and at the right time
  - In the *Execution* phase, each opcode results in a separate microprogram being run

Instruction set and programs

- Instruction: binary code interpreted by the CPU to perform an action
- A program is a series of instructions in binary that the processor can read and interpret
- Difficult for humans to write programs in 1s and 0s, so programs are written in more 'human-like' programming languages
  - E.g. assembler, C, Java, Python
- These programs are translated to binary using other programs
  - Assemblers, compilers

Assembly language *(recap Module 2)*

- A program is a series of instructions in binary that the processor can read and interpret (*decode*)
- Difficult to write programs in *1*s and *0*s, so use *assembly language*
- **Assembly language**
  - programs use 3 or 4 character mnemonic English abbreviations
  - mnemonics correspond to the binary opcodes that the processor understands
    - E.g. **LDA** = 1011 0110 (*B6* in hexadecimal), **ADDI** = 1011 1010 (*BA*h)
  - translated to binary using an assembler program

```
LDA  C100h   ; Load accumulator with data from memory location        1011 0110
             ; C100 hex (or 1100 0001 0000 0000 in binary)      →     1100 0001
ADDI 2       ; Add immediate value (2) to the number in the           0000 0000
             ; accumulator                                            1011 1010
                                                                      0000 0010
```


Assembler

- An assembler is a program that converts assembly language programs to object code (binary code / machine language)
  - The process of conversion is called *assembly* or *assembling*
- Also allows programmers to use symbolic names
  - for data, functions and locations within programs
  - The assembler will work out (*resolve*) the actual memory addresses during assembly

```
MOV AL, first_val     ; 1st value into register AL   →   MOV AL, 100h    →   0100 1010
ADD AL, second_val    ; add the 2nd value to AL           ADD AL, 101h        0000 0001
MOV result, AL        ; store the answer in result        MOV 130h, AL        0000 0000
                                                                              0000 0010
                                                                              0000 0001
                                                                              0000 0001
                                                                              0100 1000
                                                                              ……
```

Addresses resolved by assembler

Advantages of programming in assembly

- There are some advantages of programming in assembly language over machine code:
  - Programmers can work with symbolic names
    - As opposed to just binary code or numeric addresses
  - Assemblers can detect certain errors
    - Syntax errors, invalid addressing modes, etc.
  - Programs can be optimised
    - Can be tailored to take full advantage of hardware features
    - However, requires understanding of processor architecture and operation
  - If done properly, code can be more compact

```
MOV AL, first_val
ADD AL, second_val
MOV result, AL
```


Limitations of assembly language

- Requires knowledge of the particular processor's instruction set
  - One-to-one between processor instruction and assembly code
- Requires understanding of the processor's architecture
  - Registers available, addressing modes
- The programs are not *portable*
  - Programs are tied to a particular processor or family of processors
  - Can't be run on other types of processors
- Quite cumbersome
  - Code / steps linked to the way the particular processor works
  - Does not reflect the way human's think or describe their processes
- Solution: High-level languages

```
MOV AL, first_val      ; 1st value into register AL
ADD AL, second_val     ; add the 2nd value to AL
MOV result, AL         ; store the answer in result
```

High-level languages

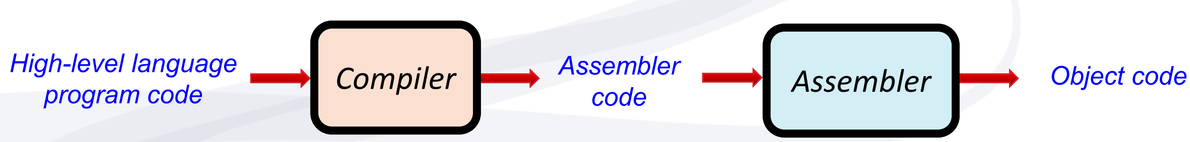
- Programming languages that are designed for human programmers
- Problem-oriented
  - Focuses on program logic

result := first_val + second_val ;

- Abstracts away the machine level details
  - Programmer does not need to know the underlying processor hardware architecture / components
- Makes code portable
  - Not tied to a particular processor / instruction set / architecture
- *Examples of HLL: C, Java, Python*

Compiler

- High-level programs will still need to be translated down to machine code before it can be executed on a processor
- Process is carried out by an application called a *compiler*
  - Compiler processes HLL program code and generates assembler code for the target processor
  - Assembler then processes that to generate object code *(executable binary code)*
  - ***Note:*** *The process consists of a number of stages – beyond the scope of this unit*

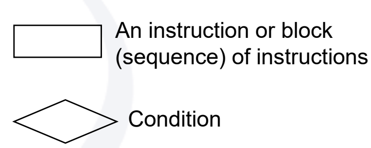


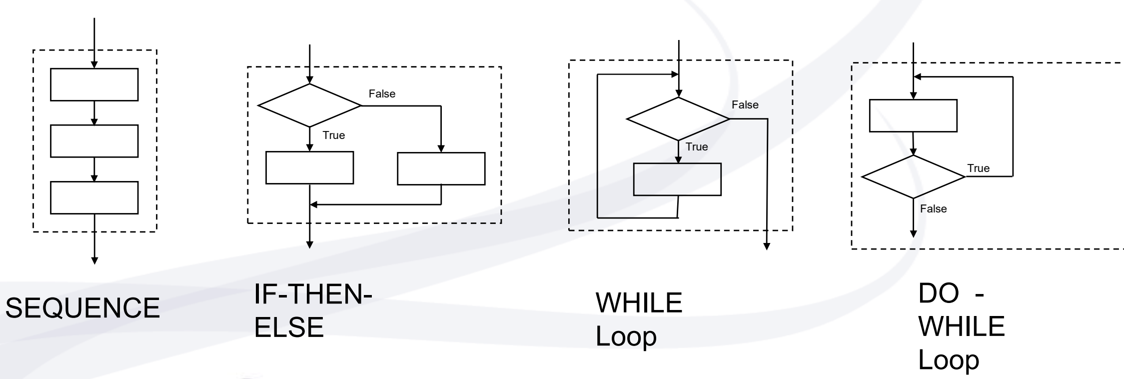
Program flow control

- Simplest program is a simple *straight-line* (sequential) program
- Execution is carried out on instructions stored sequentially in memory
  - limited to relatively simple programming tasks
- For more complex programs some form of *branching* (which includes looping) is usually required
- Branching allows the microprocessor to break out of the normal straight-line sequence
  - Jump or branch to a different section of code in program memory to continue executing instructions

Program flow control

- **High-level language constructs**





Jump and Branch Instructions

- ***Unconditional jump***
  - Processor will *always* jump to the new address given (e.g. **JMP**)
  - new address loaded into PC
    - *Refer addressing modes – Module 3*
- ***Conditional branch*** instructions
  - more flexibility in program flow control
  - will alter the sequence of execution only when specific conditions are met
    - E.g. JZ, JNZ, JG, etc. *(refer conditional branch instructions – Module 4)*

Conditional Branch Instructions *(recap)*

- Most conditional branch instructions are designed to be used after a CMP or arithmetic operation between two operands
  - e.g. A and B
  - Action whether to branch (jump) or not based on particular flags

Mnemonic	Condition	Mnemonic	Condition
JA	A > B (unsigned)	JC	C flag = 1
JAE	A ≥ B (unsigned)	JNC	C flag = 0
JB	A < B (unsigned)	JNO	O flag = 0
JBE	A ≤ B (unsigned)	JNP	P flag = 0
JE	A = B (Z = 1)	JNS	S flag = 0
JG	A > B (signed)	JNZ	Z flag = 0
JL	A < B (signed)	JO	O flag = 1
JNA	A ≯ B (unsigned)	JPE	P flag = 1
JNE	A ≠ B	JS	S flag = 1
JNL	A ≮ B	JZ	Z flag = 1

Absolute program addressing *(recap Module 3)*

- Also known as *direct* mode
- The instruction specifies a value that is written directly to the PC register

  - *Intel 8086* example
    - JMP 02A3H ; Program to **Jump** to location 02A3h

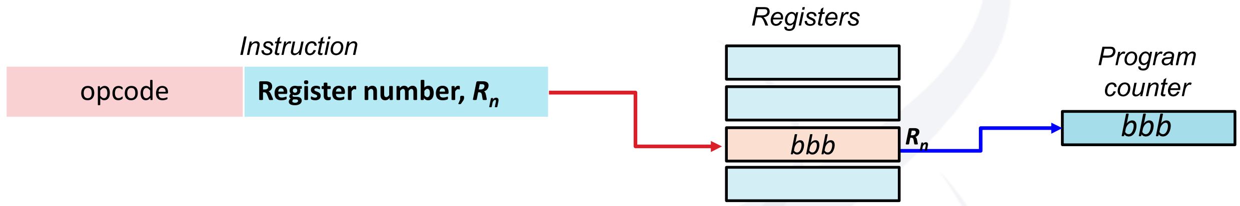
Relative program addressing *(recap Module 3)*

- The instruction specifies a value (positive or negative) that is added to the PC register
  - Causes the program to move forward or backward a certain number of bytes

  - *Intel 8086* example
    - JNZ 08 ; **Jump if** previous result is **Not Zero** forward 8 bytes

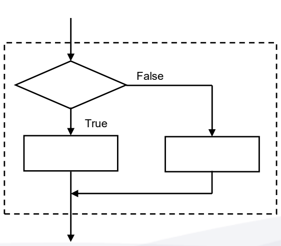
Indirect program addressing *(recap Module 3)*

- The program counter is loaded with the value from the register specified in the instruction

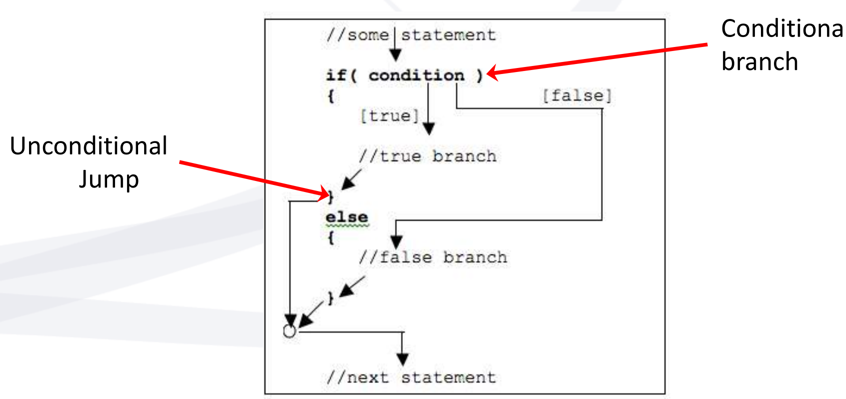


IF .. THEN .. ELSE

- IF condition = TRUE : THEN branch executed
- IF condition = FALSE : ELSE branch executed
- One conditional branch and one unconditional jump instruction required

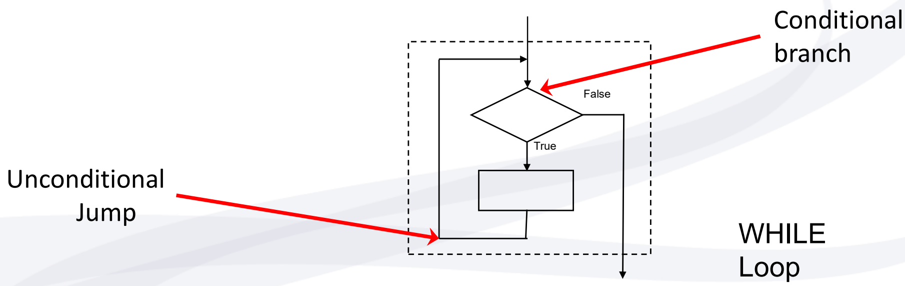


IF-THEN-ELSE



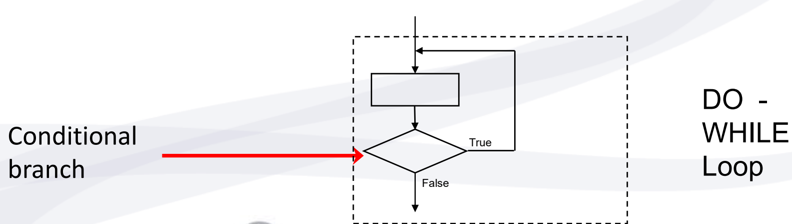
WHILE Loop

- Condition tested at the start of the loop
- IF condition = True THEN execute the loop code ELSE exit the loop
  - Similar to IF statement except that unconditional jump is back to the condition check
- Code in the loop is never run if condition is false the first time checked



DO – WHILE Loop

- Condition tested at the end of the loop
- IF condition = True THEN loop back to start (*DO*)
  ELSE continue next instruction (*exit the loop*)
  - Only requires 1 conditional branch instruction
  - Condition at the end of the loop
- The loop code will run at least once
  - even if condition is false the first time checked



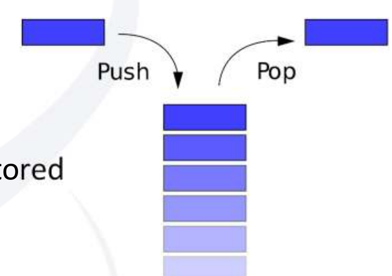
Assembler features for flow control

- **Symbolic Addresses (Labels)**
  - One of the most useful features of assembly language programming:
    - symbolic addresses may be used
    - instead of physical RAM addresses

Address	Label	Mnemonic	Comments
0100	**Start:**	CMP AX, BX	; Compare registers AX and BX
0101		JNE *Here*	; Jump to label 'Here' if not equal ; (difference not 0)
0102		JMP *FarAway*	; Otherwise jump to label 'Faraway'
0103	**Here:**	……	; Code to be done if not equal
…	…	…	…
0200	**Faraway:**		; Some code fragment elsewhere for 'ELSE'

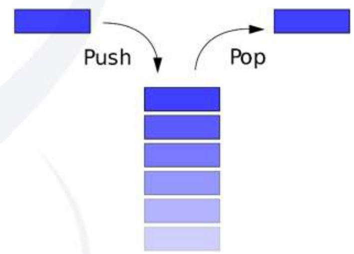
Stack

- A data structure (memory locations)
  - Primarily for temporary storage of information
- Storing ('pushing') a word
  - puts it at "top" of stack
  - location address is one word less than the previous word stored
- Words must be read ('popped') from the top of stack
  - in the opposite order from that in which they were placed
- The stack is referred to as being *last in, first out* or LIFO
- The address of the top of the stack is stored in the Stack Pointer register (SP)



Stack

- An important concept in programming
- Used by programmers :
  - Temporary storage of register contents etc.
- Used by the processor :
  - Storage of return addresses and other critical information
  - During subroutine calls *(covered next)*
  - Also for interrupt service routines *(covered in Module 8)*

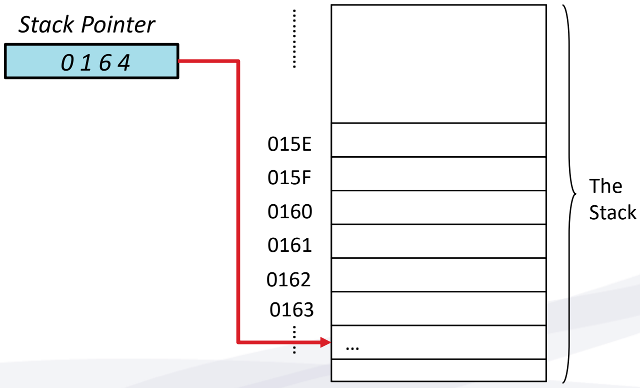


Stack Instructions

- **8086 Stack Instructions**
  - The processor controls the stack pointer (SP) during these operations
- **PUSH** *Reg / Mem*
  - Decrements SP by 2 *(stores 16-bit values, 2 bytes)*
    - Moves pointer up to new 'top of stack'
  - Copies contents of the specified register or memory location onto the stack
- **POP** *Reg / Mem*
  - Copies data from the top of the stack (pointed to by SP)
  - Then loads the data into the specified register or memory location
  - Increments SP by 2
    - Moves pointer down to new 'top of stack'

Pushing onto the stack

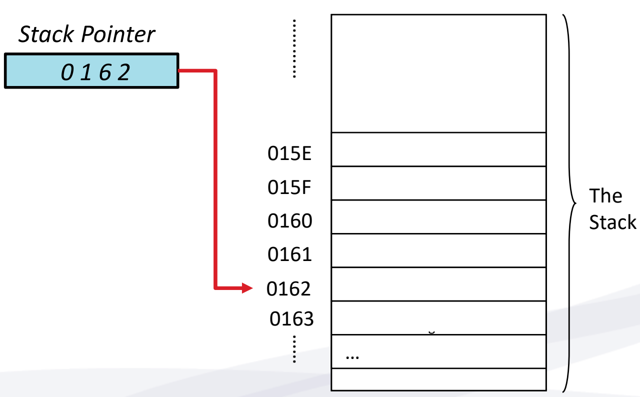
- Example



- 3 words stored onto the stack:
  - Word A
  - then B
  - finally Word C
- Initially SP = address 0164h

Pushing onto the stack

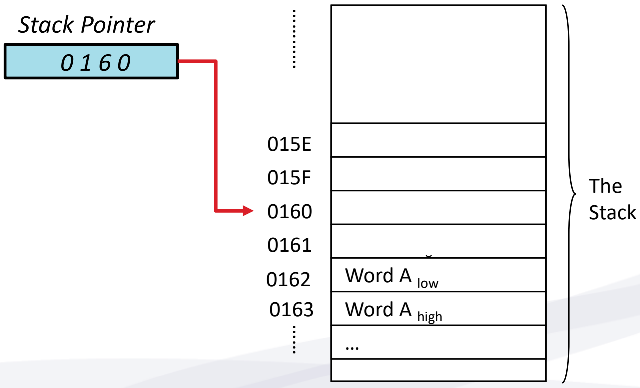
- Example



- 3 words stored onto the stack:
  - Word A
  - then B
  - finally Word C
- Initially SP = address 0164h
- When Word A pushed:
  - SP automatically decremented to point to 0162h
  - Then Word A stored (*little endian*)

Pushing onto the stack

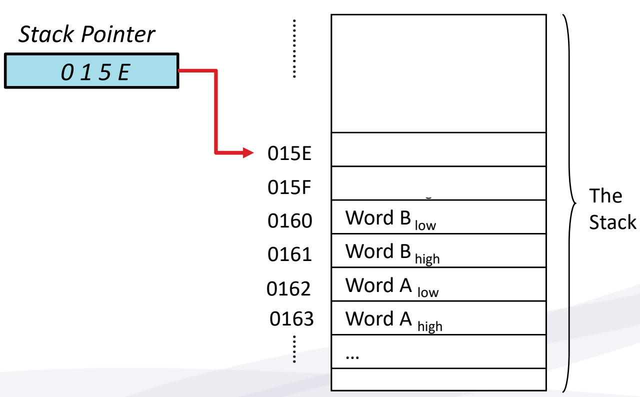
- **Example**



- 3 words stored onto the stack:
  - Word A
  - then B
  - finally Word C
- Initially SP = address 0164h
- When Word A pushed:
  - SP automatically decremented to point to 0162h
  - Then Word A stored (*little endian*)
- Then Word B

Pushing onto the stack

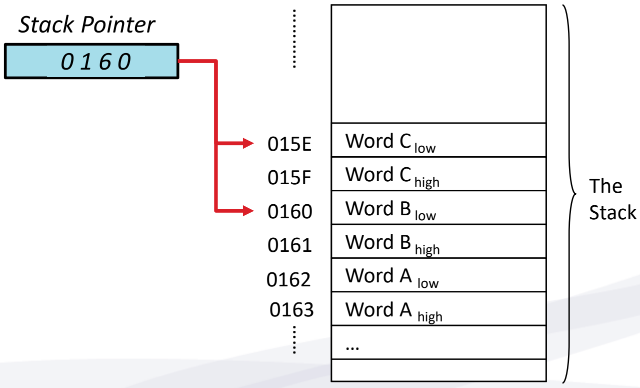
- **Example**



- 3 words stored onto the stack:
  - Word A
  - then B
  - finally Word C
- Initially SP = address 0164h
- When Word A pushed:
  - SP automatically decremented to point to 0162h
  - Then Word A stored (*little endian*)
- Then Word B
- After Word C pushed:
  - SP will contain the address 015Eh
  - the new "top" of the stack
- Reverse process happens when 'popping off' data from stack.

Popping off the stack

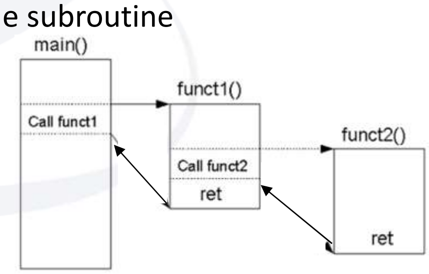
- **Example**



- Reverse process happens when ‘popping off’ data from stack.
  - E.g POP *AX*
    - Top of stack data copied to register AX
      - Then SP automatically incremented to point to 0160h
      - the new “top” of the stack

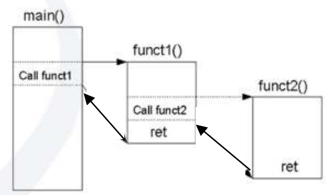
Subroutines

- **What is a Subroutine?**
  - A subroutine:
    - is a sequence of instructions that perform a specific task
    - it is written once and stored in a specific area of memory
  - When main program needs to perform that task:
    - the processor simply jumps to the address for the subroutine (*call*)
    - executes the code there
    - returns to original program when done



Calling a subroutine

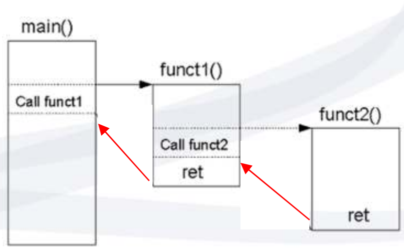
- Most processors have a **CALL** Instruction
  - Used to direct the processor to jump to a subroutine
  - Name may vary, but function is essentially the same
    - Operand provided gives the subroutine address to go to
    - The subroutine address is loaded into the program counter (PC)
    - Execution of subroutine continues as normal till the end of the routine
    - Program execution returns to calling routine (*next instruction*)



- How does processor now how to go back to *calling* routine?
  - The **PC** register contents are pushed onto the stack before new subroutine address is loaded

Returning from a subroutine

- Most processors have a Return (**RET**) instruction
  - Used to direct the processor to return to the calling process
    - The RET instruction pops the return address back from the top of the stack into the PC register
    - Continues with next instruction after the initial CALL



Subroutines

- **Example using assembly language**

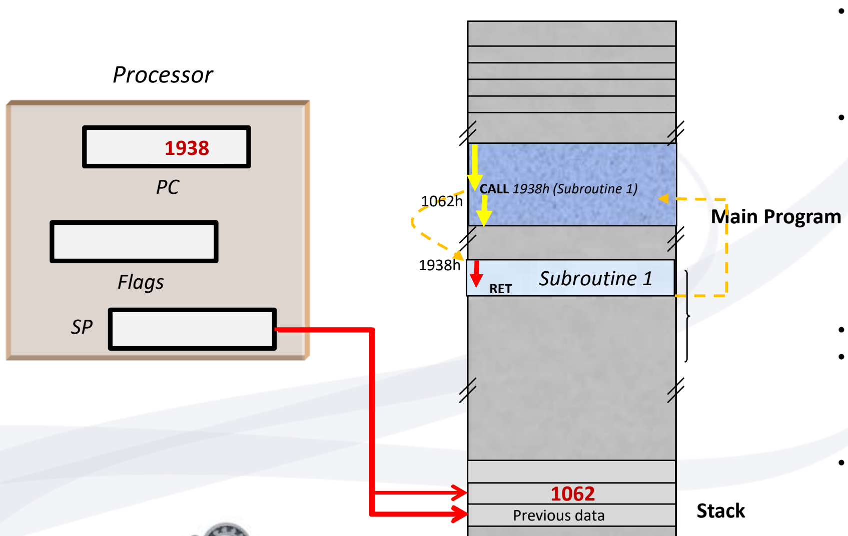
```
...
CALL NewProcedure          ; call procedure
 xxx                       ; next instruction
....
 ....

NewProcedure PROC NEAR     ; Subroutine to do something
      xxxx
      ...
      RET                  ; Return to location called from (next inst)
NewProcedure ENDP
```

Push PC (address of instruction *xxx*) on stack, load PC with *NewProcedure* address

Pop PC from stack (address of instruction *xxx* pushed previously)

Subroutine Calls



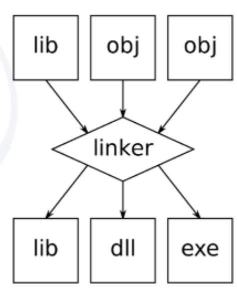
- User program runs
- Fetches 'CALL *Subroutine 1'*
  - PC is incremented to 0162h (ready for next instruction
- Executes the CALL instruction
  - PC contents pushed to stack
  - Address of Subroutine 1 loaded from program memory into PC
- Subroutine runs
- *Return* instruction reached and executed
  - Saved PC value popped from stack
- Main program continues from after subroutine call

Why use subroutines?

- Allows for efficient and logical coding
  - Commonly used functions can be embedded in subroutines and called repeatedly as needed
  - Do need to repeat the code for a function over and over in the main program
  - Once tested, can be sure the routine works – less errors
- Allows for previously developed code to be used
  - E.g. library functions
- Allows code written in a different platform / language to be linked
  - Provided interface / parameter passing is correct
  - E.g. calling an assembly routine from a C program

Linker

- A linker is a program that combines various object files into a single executable file
  - A program may call many subroutines that sit in various libraries
  - The linker pulls in the required (called) library functions and creates a single executable (machine code) file that has all the required code.
- Linkers may also relocate code
  - Change the addresses of absolute jumps, load and stores
  - Based on where a program is loaded in memory



Assemblers, Compilers and Linkers

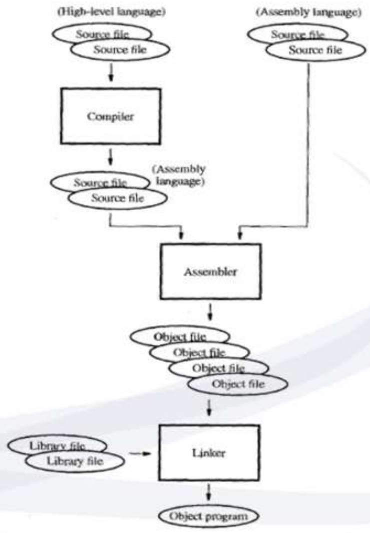


Figure 4.1 Overall flow for generating an object program.

(Hamacher, 2016)

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