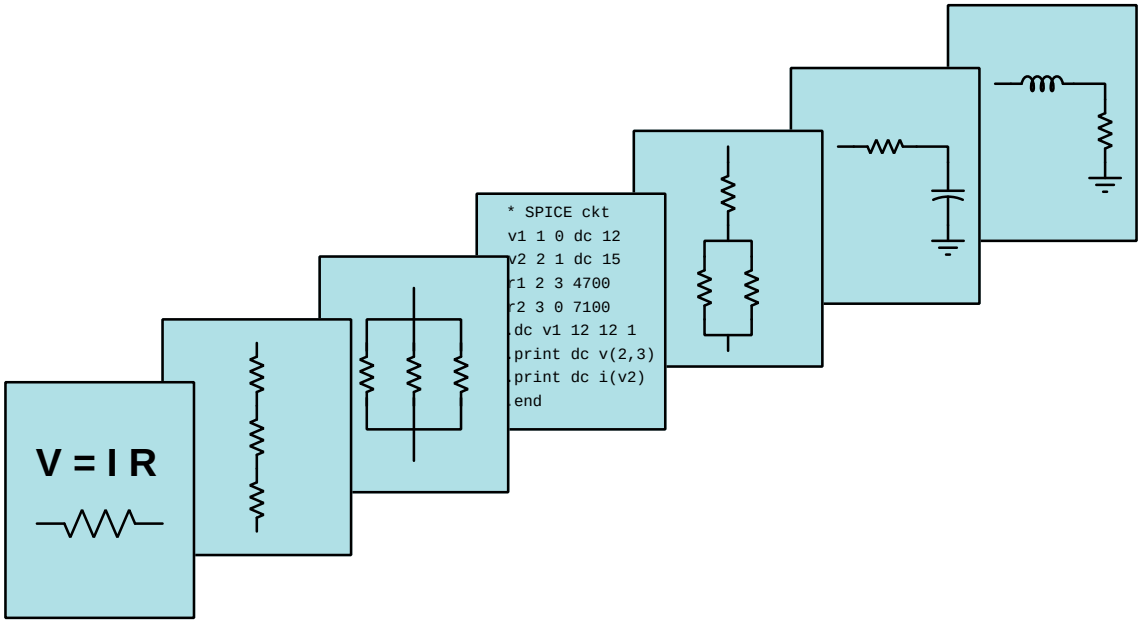
Modular Electronics Learning (ModEL) project



Introduction to Assembly Language Programming

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Chapter 1

Introduction

Digital processors follow instructions consisting of binary codes – strings of "high" and "low" states – called *opcodes*, and these opcodes are typically written in hexadecimal for the sake of human readability. However, most human beings find this *machine code* difficult to follow because the reader must know all the opcodes in detail, or at least be able to quickly and efficiently reference them when necessary. Additionally, each microprocessor or microcontroller "family" has its own arbitrary set of opcodes, even for similar functions. For example, the simple "No Operation" opcode is `0xEA` for the MOS 6502 microprocessor; `0x00` for the Intel 8051 microcontroller; `0x90` for the Intel x86 series of microprocessors; `0x0000`, `0x0020`, `0x0040`, or `0x0050` for the Microchip PIC 16F84A microcontroller; and `0xFD******` for Donald Knuth's hypothetical MMIX processor.

Chapter 2

Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: Motorola 68HC11 adding two numbers

The following program was written in Motorola 68HC11 machine language and viewed using the BUFFALO monitor program[1] running on a Fox11 trainer board. The code is shown here is "hand-assembled" machine code, with the hexadecimal codes arranged in the same format one would expect to see in an assembly-language program. I have inserted comments for each line to help explain the program:

```
B6 C1 00 ; Load Accumulator A (opcode 0xB6) from address 0xC100
BB C1 01 ; Add Accumulator A (opcode 0xBB) from address 0xC101
B7 C1 10 ; Store Accumulator A (opcode 0xB7) to address 0xC110
7E E0 00 ; Jump (opcode 0x7E) to address 0xE000 (start of Buffalo monitor)
```

Next, the "display memory" command was issued to the BUFFALO monitor program to show a memory map beginning at address `0x0020`. Our short program fits within the first line:

```
>md 0020

0020 B6 C1 00 BB C1 01 B7 C1  10 7E E0 00 FF FF FF FF
0030 FF FF FF FF FF FF FF FF  FF FF FF FF FF FF FF FF
0040 FF FF FF FF FF FF FF FF  FF FF E4 E4 E4 E4 64 E3                d
0050 F3 00 E4 64 E3 F3 00 57  00 20 E4 B6 E7 BA E1 FA     d d   X
0060 FF FF FF FF FF FF FF FF  D0 00 41 6D 64 20 30 30            Amd 00
0070 32 30 0D 20 63 31 30 30  0D FF FF FF FF FF FF FF  20  c100
0080 FF FF FF FF FF FF FF FF  FF FF FF FF FF FF 4D 44                MD
0090 20 1B 5B 42 4D 4D 00 20  B6 00 B7 FF 00 00 00 00    [BMM
00A0 00 00 00 00 01 01 01 00  04 21 00 20 00 00 00 72           @     r
```

Next, we instruct the BUFFALO monitor to execute this program starting at address `0x0020`:

```
>go 0020
```

[1] A "monitor" program may be thought of as a very crude operating system for the microprocessor. It provides a simple interface environment to allow the user to program the memory, execute the program, and perform simple debugging of any problems. *BUFFALO* is an acronym, standing for Bit User Fast Friendly Aid to Logical Operation.

Lastly, we view memory starting at address `0xC100` to see the numerical values:

```
>md c100

C100 44 55 6F A1 39 3D A0 D4  24 64 00 B3 9E 06 C9 98  DUo 9=  $d
C110 99 06 08 00 63 40 9C 18  B4 00 F0 00 30 D3 09 DC      c@      0
C120 6A 04 57 8E 19 27 D1 88  49 10 04 B5 88 06 16 2A  j W  ’  I      *
C130 05 65 A9 04 15 72 47 7C  4A 44 0D B4 20 49 38 0D   e   rG JD   I8
C140 7D 38 A5 93 30 B4 24 C0  43 08 25 D4 50 91 42 58   8  0 $ C % P BX
C150 9E D0 C0 C1 54 01 88 0C  10 70 55 23 CC 40 01 76      T    pU# @ v
C160 2C C5 43 AC F8 1D A1 30  ED 71 AA 18 16 20 2E 1C  , C    0 q    .
C170 15 6D 25 C5 6E 07 02 72  38 FD 21 2D D5 67 93 24   m% n  r8 !- g $
C180 92 43 12 30 0A 89 2C 4F  80 95 79 B6 A4 3C 2C 10   C 0  ,O  y  <,
```

Note the values stored in `0xC100` (44) and `C101` (55), and in `0xC110` (99) which of course is the sum of 44 and 55. All the other memory addresses contain random numbers from the last power-up.

2.2 Example: Motorola 68HC11 blinking an LED

The following assembly-language program was assembled using the `as11` assembler and run on an Axiom CME11E9-EVBU evaluation board in "single-chip" mode. All text to the right of a semicolon (;) are comments ignored by the assembler.

```
; ================================================
; Blinking LED program
;
; LED cathode connected through 1k Ohm resistor to ground
; LED anode connected to PB0 terminal (port B, bit 0)
; ================================================

; "Equates" (similar to "DEFINE" directives in C programming)
PORTB   equ $1004       ; Port B at memory address 0x1004
LED1    equ %00000001   ; Bit 0 select

    org $0100           ; program starts at address 0x0100
    ldx #PORTB          ; load x register with address of PortB

Main

; Turn LED on ("set" the bit)
    bset 0,x LED1       ; turn LED1 on
    bsr Delay           ; branch to subroutine

; Turn LED off ("clear" the bit)
    bclr 0,x LED1       ; turn LED1 off
    bsr Delay           ; branch to subroutine

    bra Main            ; "branch always" (loop forever)

; Delay subroutine
Delay
    ldy  #$ffff         ; load y register with 0xFFFF
Loop
    dey                 ; decrements Y register
    bne Loop            ; repeats "Loop" if Y != 0
    rts                 ; return
```

2.3 Example: Motorola 68HC11 blinking two LEDs

The following assembly-language program was assembled using the `as11` assembler and run on an Axiom CME11E9-EVBU evaluation board in "single-chip" mode. All text to the right of a semicolon (`;`) are comments ignored by the assembler.

```
; ================================================
; Blinking two LEDs
;
; LED cathode connected through 1k Ohm resistor to ground
; LED anode connected to PB0 terminal (port B, bit 0)
; LED anode connected to PB1 terminal (port B, bit 1)
; ================================================

; "Equates" (similar to "DEFINE" directives in C programming)
PORTB   equ $1004       ; Port B at memory address 0x1004
LED1    equ %00000001   ; Bit 0 select
LED2    equ %00000010   ; Bit 1 select

    org $0100           ; program starts at address 0x0100
    ldx #PORTB          ; load x with address of PortB

Main

; LED1 on and LED2 off
    bset 0,x LED1       ; turn LED1 on
    bclr 0,x LED2       ; turn LED2 off
    bsr Delay           ; branch to subroutine

; LED1 off and LED2 on
    bclr 0,x LED1       ; turn LED1 off
    bset 0,x LED2       ; turn LED2 on
    bsr Delay           ; branch to subroutine

    bra Main            ; "branch always" (loop forever)

; Delay subroutine
Delay
    ldy #$ffff          ; load y register with 0xFFFF
Loop
    dey                 ; decrements Y register
    bne Loop            ; repeats "Loop" if Y != 0
    rts                 ; return
```

2.4 Example: Motorola 68HC11 blinking eight LEDs

The following assembly-language program was assembled using the `as11` assembler and run on an Axiom CME11E9-EVBU evaluation board in "single-chip" mode. All text to the right of a semicolon (`;`) are comments ignored by the assembler.

```
; ================================================
; Blinking eight LEDs
;
; LED cathodes connected to ground
; LED anode connected to PB0 terminal (port B, bit 0) through 1k Ohm resistor
; LED anode connected to PB1 terminal (port B, bit 1) through 1k Ohm resistor
; LED anode connected to PB2 terminal (port B, bit 2) through 1k Ohm resistor
; LED anode connected to PB3 terminal (port B, bit 3) through 1k Ohm resistor
; LED anode connected to PB4 terminal (port B, bit 4) through 1k Ohm resistor
; LED anode connected to PB5 terminal (port B, bit 5) through 1k Ohm resistor
; LED anode connected to PB6 terminal (port B, bit 6) through 1k Ohm resistor
; LED anode connected to PB7 terminal (port B, bit 7) through 1k Ohm resistor
; ================================================

; "Equates" (similar to "DEFINE" directives in C programming)
PORTB   equ $1004       ; Port B at memory address $1004

        org $0100       ; program starts at address 0x0100

        ldaa #%10101010 ; initialize accumulator A with this bit pattern

Main
    staa PORTB          ; Store accumulator A to Port B
    bsr Delay           ; Wait
    coma                ; Invert all bits in accumulator A (complement A)
    bra Main            ; "branch always" (loop forever)

; Delay subroutine
Delay
    ldy #$ffff          ; load y register with 0xFFFF
Loop
    dey                 ; decrements Y register
    bne Loop            ; repeats "Loop" if Y != 0
    rts                 ; return
```

2.5 Example: Motorola 68HC11 counting in binary

The following assembly-language program was assembled using the `as11` assembler and run on an Axiom CME11E9-EVBU evaluation board in "single-chip" mode. All text to the right of a semicolon (`;`) are comments ignored by the assembler.

```
; ================================================
; Outputting decrementing register to four LED indicators
;
; LED cathodes connected to ground
; LED anode connected to PB0 terminal (port B, bit 0) through 1k Ohm resistor
; LED anode connected to PB1 terminal (port B, bit 1) through 1k Ohm resistor
; LED anode connected to PB2 terminal (port B, bit 2) through 1k Ohm resistor
; LED anode connected to PB3 terminal (port B, bit 3) through 1k Ohm resistor
; ================================================

; "Equates" (similar to "DEFINE" directives in C programming)
PORTB   equ $1004       ; Port B at memory address 0x1004

        org $0100       ; program starting address

        ldx PORTB       ; load x with address of PortB

        ldaa #%00001111 ; Loads register A with the binary value
                        ; 0b00001111 to light up first four LEDs

Outer_loop
    staa PORTB          ; writes contents of register A to port B,
                        ; where LEDs light up in response

    ldy #$6f4d          ; Loads register Y with the hex value
                        ; 0x6F4D (approx 0.1 second delay)

Inner_loop
    dey                 ; decrements Y register
    bne Inner_loop      ; repeats "Loop" if Y != 0

    deca                ; decrements A register
    bne Outer_loop      ; repeats Outer_loop if A != 0

    bra Outer_loop      ; return
```

2.6 Example: Motorola 68HC11 analog input

The following assembly-language program was assembled using the `as11` assembler and run on an Axiom CME11E9-EVBU evaluation board in "single-chip" mode. All text to the right of a semicolon (`;`) are comments ignored by the assembler.

```
; ================================================
; Analog input to binary LED display
; ================================================

; "Equates" (similar to "DEFINE" directives in C programming)
PORTB   equ $1004       ; Port B at memory address 0x1004
OPTION  equ $1039       ; "option" register (with ADPU bit 7)
ADCTL   equ $1030       ; ADC control register (selects modes and channels)
ADR1    equ $1031       ; ADC result register 1
ADR2    equ $1032       ; ADC result register 2
ADR3    equ $1033       ; ADC result register 3
ADR4    equ $1034       ; ADC result register 4

        org $0100       ; Starting address

; These lines configure the ADC channels the way we want them
    ldaa #%10000000     ; turns A/D on (bit 7 of "option" word powers up ADCs)
    staa OPTION
    ldaa #%00110100     ; continuous scan, multiple channel, scans Port E
                        ; channels 4 through 7
    staa ADCTL

Main
    ldaa ADR1           ; Choose ADC result register 1
    staa PORTB
    bra Main
```

2.7 Example: Microchip PIC 16F84A bitwise OR

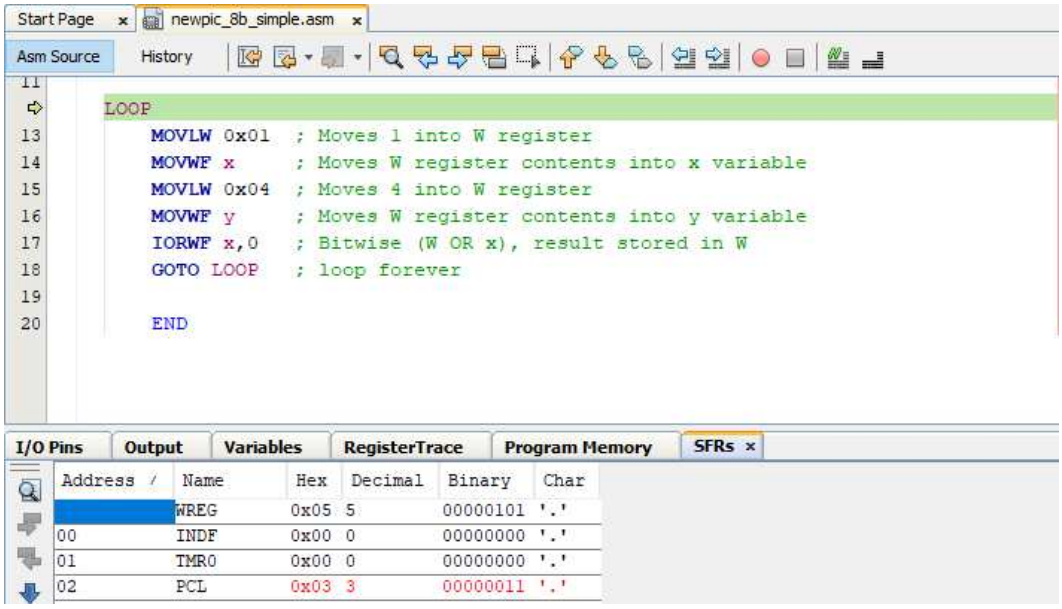
The following assembly-language program was assembled and simulated using the MPLABX Integrated Desktop Environment (version 5.35, using the MPASM assembler):

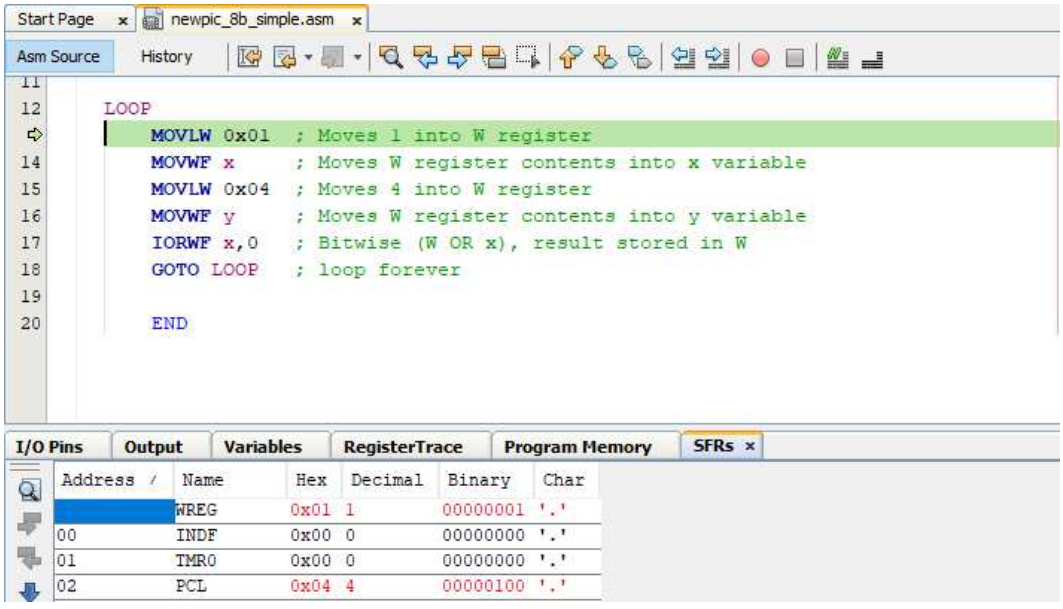
```
; Program for PIC 16F84A microcontroller
; Saves numbers into two memory locations, performs bitwise OR
;
    RES_VECT  CODE    0x0000        ; processor reset vector
    GOTO  LOOP                      ; go to beginning of program

x equ 0x0c   ; Variable "x" is equivalent to data memory address 0x0c
y equ 0x0d   ; Variable "y" is equivalent to data memory address 0x0d

MAIN_PROG CODE                      ; let linker place main program

LOOP
    MOVLW 0x01  ; Moves 1 into W register
    MOVWF x     ; Moves W register contents into x variable
    MOVLW 0x04  ; Moves 4 into W register
    MOVWF y     ; Moves W register contents into y variable
    IORWF x,0   ; Bitwise (W OR x), result stored in W
    GOTO LOOP   ; loop forever

    END
```

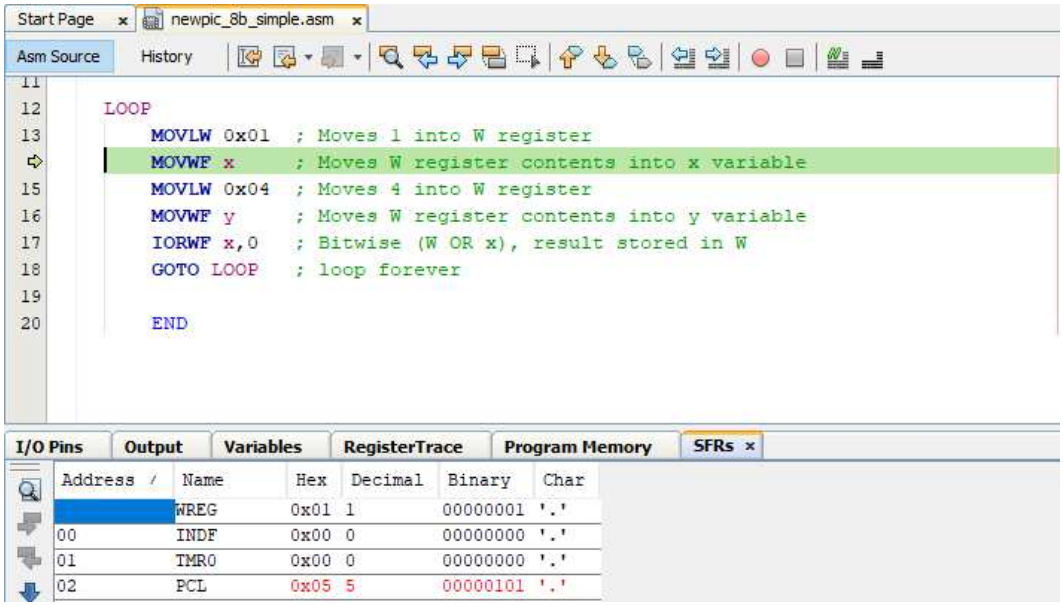
The following screenshot shows the microprocessor's program memory map, with memory addresses, 14-bit opcodes, and the disassembled instruction mnemonics and operands represented by those opcodes:

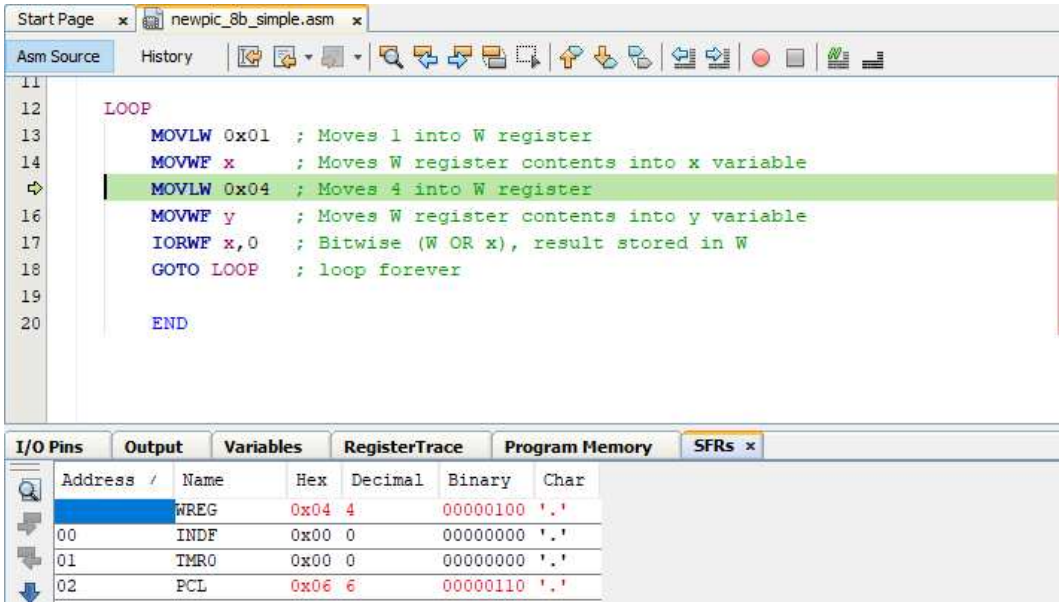
Line	Address	Opcode	Label	DisAssy
1	000	2803		GOTO 0x3
2	001	3400		RETLW 0x0
3	002	3400		RETLW 0x0
4	003	3001	LOOP	MOVLW 0x1
5	004	008C		MOVWF 0xC
6	005	3004		MOVLW 0x4
7	006	008D		MOVWF 0xD
8	007	040C		IORWF 0xC, W
9	008	2803		GOTO 0x3

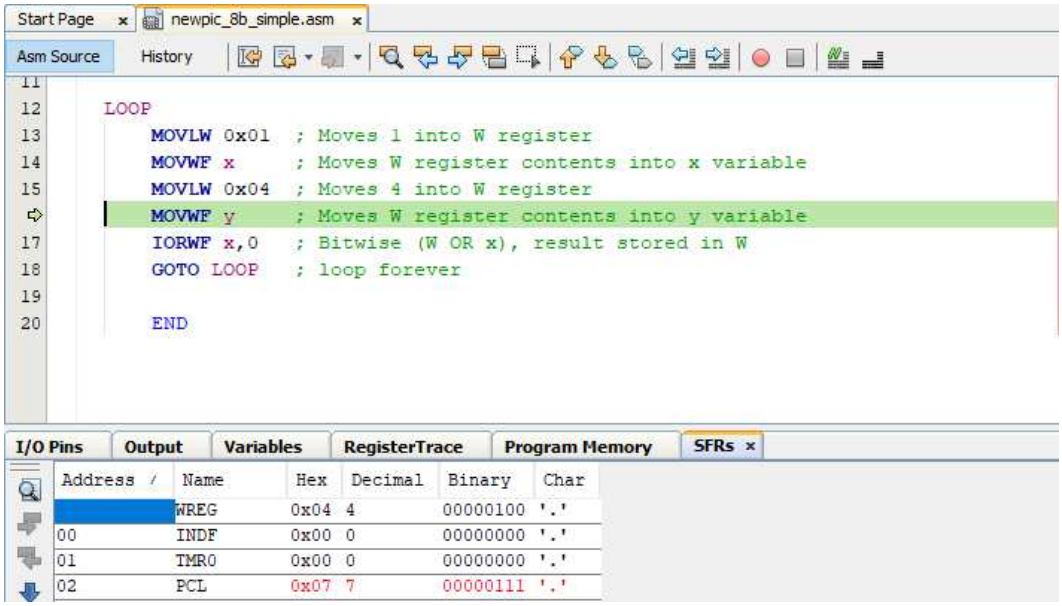
Using the debugging and simulation features of the IDE (Integrated Development Environment), we may step through the program one instruction at a time while monitoring some of the Special Function Registers:

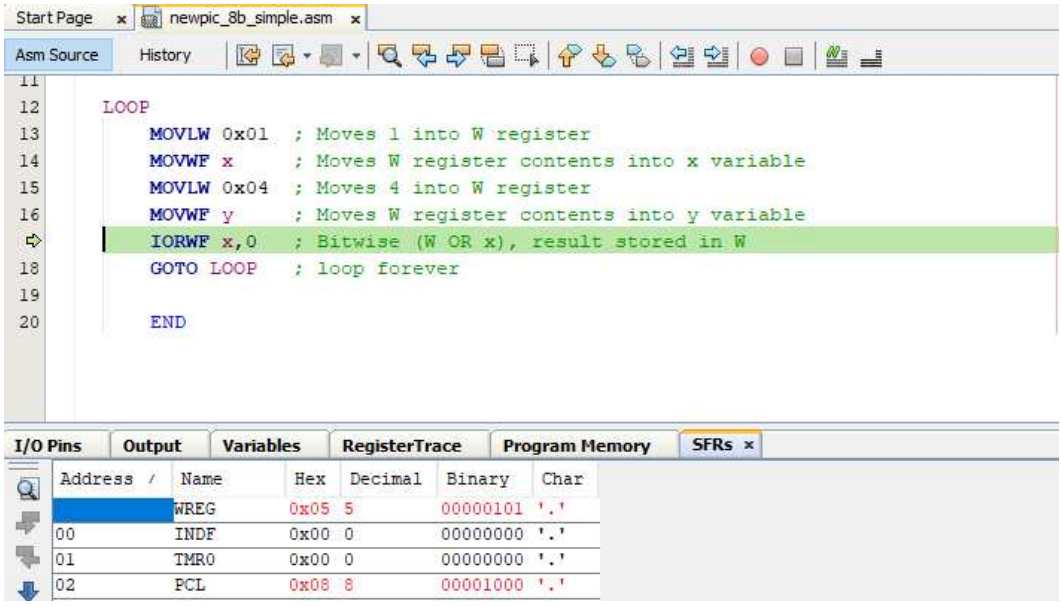





Start Page
newpic_8b_simple.asm
Asm Source
History
LOOP
MOVLW 0x01 ; Moves 1 into W register
MOVWF x ; Moves W register contents into x variable
MOVLW 0x04 ; Moves 4 into W register
MOVWF y ; Moves W register contents into y variable
IORWF x,0 ; Bitwise (W OR x), result stored in W
GOTO LOOP ; loop forever
END
I/O Pins
Output
Variables
RegisterTrace
Program Memory
SFRs
Address / Name Hex Decimal Binary Char
WREG 0x01 1 00000001 '.'
00 INDF 0x00 0 00000000 '.'
01 TMR0 0x00 0 00000000 '.'
02 PCL 0x05 5 00000101 '.'


Start Page
newpic_8b_simple.asm
Asm Source
History
LOOP
MOVLW 0x01 ; Moves 1 into W register
MOVWF x ; Moves W register contents into x variable
MOVLW 0x04 ; Moves 4 into W register
MOVWF y ; Moves W register contents into y variable
IORWF x,0 ; Bitwise (W OR x), result stored in W
GOTO LOOP ; loop forever
END
I/O Pins
Output
Variables
RegisterTrace
Program Memory
SFRs
Address / Name Hex Decimal Binary Char
WREG 0x04 4 00000100 '.'
00 INDF 0x00 0 00000000 '.'
01 TMR0 0x00 0 00000000 '.'
02 PCL 0x06 6 00000110 '.'


Start Page
newpic_8b_simple.asm
Asm Source
History
LOOP
MOVLW 0x01 ; Moves 1 into W register
MOVWF x ; Moves W register contents into x variable
MOVLW 0x04 ; Moves 4 into W register
MOVWF y ; Moves W register contents into y variable
IORWF x,0 ; Bitwise (W OR x), result stored in W
GOTO LOOP ; loop forever
END
I/O Pins
Output
Variables
RegisterTrace
Program Memory
SFRs
Address / Name Hex Decimal Binary Char
WREG 0x04 4 00000100 '.'
00 INDF 0x00 0 00000000 '.'
01 TMR0 0x00 0 00000000 '.'
02 PCL 0x07 7 00000111 '.'


Start Page
newpic_8b_simple.asm
Asm Source
History
LOOP
MOVLW 0x01 ; Moves 1 into W register
MOVWF x ; Moves W register contents into x variable
MOVLW 0x04 ; Moves 4 into W register
MOVWF y ; Moves W register contents into y variable
IORWF x,0 ; Bitwise (W OR x), result stored in W
GOTO LOOP ; loop forever
END
I/O Pins
Output
Variables
RegisterTrace
Program Memory
SFRs
Address / Name Hex Decimal Binary Char
WREG 0x05 5 00000101 '.'
00 INDF 0x00 0 00000000 '.'
01 TMR0 0x00 0 00000000 '.'
02 PCL 0x08 8 00001000 '.'

2.8 Example: Microchip PIC 16F84A conditional example

The following assembly-language program was assembled using the `gpasm` assembler[2] and simulated on the `simulpic` 16F84A simulator:

```
; Demonstration program for PIC 16F84A showing how to use btfss and btfsc
; instructions to make an output bit on Port A equal in state to an input
; bit on Port B.
;
; Equivalent to pseudocode:
;   if (PortBBit0 == 1)
;     then PortABit0 = 1
;   else PortABit0 = 0
;
; Assemble using the following command:
;   gpasm -p16F84A <filename>.asm
;

#include p16f84a.inc   ; This included file contains hexadecimal
                       ; register values for STATUS, TRISA, RP0,
                       ; etc. making programming easier.

    org 0x00           ; Program starts at address 0x00

    bsf STATUS, RP0    ; Switch to Bank 1 registers by setting RP0
    clrf TRISA         ; Clear all TRISA bits to declare Port A as output

    bcf STATUS, RP0    ; Switch to Bank 0 registers by clearing RP0
    clrf PORTA         ; Initialize PORTA by clearing output data latches

loop    btfss PORTB, 0 ; Skip next instruction if Port B bit 0 is set (=1)
        bcf PORTA, 0   ; Clear Port A bit 0 if the instruction is unskipped
        btfsc PORTB, 0 ; Skip next instruction if Port B bit 0 is cleared (=0)
        bsf PORTA, 0   ; Set Port A bit 0 if the instruction is unskipped
        goto loop

        end
```

[2] Command-line entry: `gpasm -p16F84A <filename>.asm`

```
; Demonstration program for PIC 16F84A showing how to use btfss and btfsc
; instructions to make an output bit on Port A opposite in state to an input
; bit on Port B.
;
; Equivalent to pseudocode:
;   if (PortBBit0 == 1)
;     then PortABit0 = 0
;   else PortABit0 = 1
;
; Assemble using the following command:
;   gpasm -p16F84A <filename>.asm
;

#include p16f84a.inc    ; This included file contains hexadecimal
                        ; register values for STATUS, TRISA, RP0,
                        ; etc. making programming easier.

        org 0x00        ; Program starts at address 0x00

        bsf STATUS, RP0 ; Switch to Bank 1 registers by setting RP0
        clrf TRISA      ; Clear all TRISA bits to declare Port A as output

        bcf STATUS, RP0 ; Switch to Bank 0 registers by clearing RP0
        clrf PORTA      ; Initialize PORTA by clearing output data latches

loop    btfss PORTB, 0  ; Skip next instruction if Port B bit 0 is set (=1)
        bsf PORTA, 0    ; Set Port A bit 0 if the instruction is unskipped
        btfsc PORTB, 0  ; Skip next instruction if Port B bit 0 is cleared (=0)
        bcf PORTA, 0    ; Clear Port A bit 0 if the instruction is unskipped
        goto loop

        end
```

2.9 Example: Microchip PIC 16F84A motor control

The following assembly-language program was assembled using the `gpasm` assembler[3] and simulated on the `simulpic` 16F84A simulator:

```
; Motor control program for PIC 16F84A
; Start PBNO to ground on pin 0 on Port B
; Stop PBNC to ground on pin 1 on Port B

outputs equ 0x05       ; Port A register (file 0x05) will be outputs
inputs equ 0x06        ; Port B register (file 0x06) will be inputs
                       ; Bit 0 is the Start signal (active-low)
                       ; Bit 1 is the Stop signal (active-high)
trisa equ 0x05         ; Port A data direction register (file 0x05,
                       ; actually 0x85 but the "8" is implied when RP0 is set)
status equ 0x03        ; Status register (file 0x85)
rp0 equ 5              ; The RP0 bit of the Status register is bit 5

      org 0x00         ; Program starts at address 0x00

      bsf status, rp0  ; Switch to Bank 1 registers by setting rp0
      clrf trisa       ; Clear all TRISA bits to declare Port A as output

      bcf status, rp0  ; Switch to Bank 0 registers by clearing rp0
      clrf outputs     ; Initialize PORTA by clearing output data latches

loop    btfss inputs, 0 ; Skip next instruction if input bit 0 is set (=1)
                        ; (i.e. Start pushbutton switch unpressed)
        bsf outputs, 0  ; Set output bit 0 if the instruction is unskipped
        btfsc inputs, 1 ; Skip next instruction if input bit 1 is cleared (=0)
                        ; (i.e. Stop pushbutton switch unpressed)
        bcf outputs, 0  ; Clear output bit 0 if the instruction is unskipped
        goto loop

        end
```

[3] Command-line entry: `gpasm -p16F84A <filename>.asm`

2.10 Example: Microchip PIC 12F629 energizing a LED

The following assembly-language program was assembled using the MPLABX Integrated Development Environment assembler (called MPASM) and run on a 12F629 microcontroller IC plugged into a breadboard, interfaced using a PICkit4 in-circuit programmer/debugger tool connected to pins 6 and 7 (ICSPCLK and ICSPDAT, respectively). General-purpose I/O GP4 is pin 3 on the IC:

```
list     p=12F629
radix    dec  ; Allows numerical entry in decimal rather than (default) hex
#include "p12f629.inc"

; CONFIG
; __config 0x3FDD __CONFIG _FOSC_INTRCCLK & _WDTE_ON & _PWRTE_OFF &
_MCLRE_OFF & _BOREN_ON & _CP_OFF & _CPD_OFF


; Beginning of program

org     0x00
bsf     131, 5          ; Selecting bank 1 (STATUS 83h, bit 5 = rp0)
bcf     133, 4          ; Setting GP4 as an output (TRISIO 85h)
movlw   b'00001111'     ; bit 3 = 1 = WDT 011=/8 WDT= 18 ms x 8 = 0.144 seconds
movwf   129             ; must be in bank 1 (OPTION_REG 81h)
bcf     131, 5          ; Selecting bank 0 (STATUS 83h, bit 5 = rp0)
movlw   b'00010000'     ; to set GP4 high and energize the LED
xorwf   GPIO,f
sleep

END
```

2.11 Example: Microchip PIC 16F18346 blinking an LED

The following assembly-language program was assembled using the MPLABX Integrated Development Environment assembler (called MPASM) and run on a 16F18346 microcontroller IC plugged into a "Curiosity" development board:

```
; Blinking LED program with nested delays

#include "p16f18346.inc"

; CONFIG1
; __config 0x3FCF
 __CONFIG _CONFIG1, _FEXTOSC_ECH & _RSTOSC_LFINT & _CLKOUTEN_OFF & _CSWEN_ON &
 _FCMEN_ON
; CONFIG2
; __config 0x3FF3
 __CONFIG _CONFIG2, _MCLRE_ON & _PWRTE_OFF & _WDTE_OFF & _LPBOREN_OFF &
 _BOREN_ON & _BORV_LOW & _PPS1WAY_ON & _STVREN_ON & _DEBUG_OFF
; CONFIG3
; __config 0x3FFF
 __CONFIG _CONFIG3, _WRT_OFF & _LVP_ON
; CONFIG4
; __config 0x3FFF
 __CONFIG _CONFIG4, _CP_OFF & _CPD_OFF

RES_VECT  CODE    0x0000            ; processor reset vector
    GOTO    START                   ; go to beginning of program

MAIN_PROG CODE                      ; let linker place main program

START

    BANKSEL PORTA
    CLRF PORTA                      ; Init PORTA
    BANKSEL LATA                    ; Data Latch
    CLRF LATA
    BANKSEL ANSELA
    CLRF ANSELA                     ; digital I/O
    BANKSEL TRISA
    MOVLW B'00000000'               ; Set all bits as outputs
    MOVWF TRISA

BANKSEL LATA
```

```
LOOP
    CALL DELAY1
    BSF LATA,2
    CALL DELAY1
    BCF LATA,2
    GOTO LOOP

DELAY1
    MOVLW 0x0A                      ; Delay time loaded into W
    MOVWF 0x20                      ; Move from W to an address in General RAM
INNERLOOP
    CALL DELAY2
    DECFSZ 0x20, 1
    GOTO INNERLOOP
    RETURN

DELAY2
    MOVLW 0xFF                      ; Delay time loaded into W
    MOVWF 0x21                      ; Move from W to an address in General RAM
INNERLOOP2
    DECFSZ 0x21, 1
    GOTO INNERLOOP2
    RETURN
    END
```

2.12 Example: Intel Xeon integer addition

The following program was written in the C language and compiled[4] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
void main (void)
{
  int x = 2, y = 5, sum;

  sum = x + y;
}
```

Next, the resulting executable file was "disassembled"[5] to show the machine-language and corresponding assembly-language code. Only the portion of the disassembled code related to the `main` function is shown here:

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 fc 02 00 00 00  movl   $0x2,-0x4(%rbp)
  4005cb: c7 45 f8 05 00 00 00  movl   $0x5,-0x8(%rbp)
  4005d2: 8b 45 f8              mov    -0x8(%rbp),%eax
  4005d5: 8b 55 fc              mov    -0x4(%rbp),%edx
  4005d8: 01 d0                 add    %edx,%eax
  4005da: 89 45 f4              mov    %eax,-0xc(%rbp)
  4005dd: 5d                    pop    %rbp
  4005de: c3                    retq
  4005df: 90                    nop
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x4005c0` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[4] Command-line entry: `gcc -g -O0 -fno-builtin main.c`
[5] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

Next, a program adding four numbers together:

```
void main (void)
{
  int w = 0, x = -6, y = 9, z = 22, sum;

  sum = w + x + y + z;
}
```

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
  4005cb: c7 45 f8 fa ff ff ff  movl   $0xfffffffa,-0x8(%rbp)
  4005d2: c7 45 f4 09 00 00 00  movl   $0x9,-0xc(%rbp)
  4005d9: c7 45 f0 16 00 00 00  movl   $0x16,-0x10(%rbp)
  4005e0: 8b 45 f8              mov    -0x8(%rbp),%eax
  4005e3: 8b 55 fc              mov    -0x4(%rbp),%edx
  4005e6: 01 c2                 add    %eax,%edx
  4005e8: 8b 45 f4              mov    -0xc(%rbp),%eax
  4005eb: 01 c2                 add    %eax,%edx
  4005ed: 8b 45 f0              mov    -0x10(%rbp),%eax
  4005f0: 01 d0                 add    %edx,%eax
  4005f2: 89 45 ec              mov    %eax,-0x14(%rbp)
  4005f5: 5d                    pop    %rbp
  4005f6: c3                    retq
  4005f7: 66 0f 1f 84 00 00 00  nopw   0x0(%rax,%rax,1)
  4005fe: 00 00
```

2.13 Example: Intel Xeon integer subtraction

The following program was written in the C language and compiled[6] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
void main (void)
{
  int x = 2, y = 5, difference;

  difference = x - y;
}
```

Next, the resulting executable file was "disassembled"[7] to show the machine-language and corresponding assembly-language code. Only the portion of the disassembled code related to the `main` function is shown here:

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 fc 02 00 00 00  movl   $0x2,-0x4(%rbp)
  4005cb: c7 45 f8 05 00 00 00  movl   $0x5,-0x8(%rbp)
  4005d2: 8b 45 f8              mov    -0x8(%rbp),%eax
  4005d5: 8b 55 fc              mov    -0x4(%rbp),%edx
  4005d8: 89 d1                 mov    %edx,%ecx
  4005da: 29 c1                 sub    %eax,%ecx
  4005dc: 89 c8                 mov    %ecx,%eax
  4005de: 89 45 f4              mov    %eax,-0xc(%rbp)
  4005e1: 5d                    pop    %rbp
  4005e2: c3                    retq
  4005e3: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
  4005ea: 00 00 00
  4005ed: 0f 1f 00              nopl   (%rax)
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x4005c0` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[6] Command-line entry: `gcc -g -O0 -fno-builtin main.c`
[7] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

2.14 Example: Intel Xeon integer multiplication

The following program was written in the C language and compiled[8] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
void main (void)
{
  int x = 4, y = 7, z;

  z = x * y;
}
```

Next, the resulting executable file was "disassembled"[9] to show the machine-language and corresponding assembly-language code. Only the portion of the disassembled code related to the `main` function is shown here:

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 fc 04 00 00 00  movl   $0x4,-0x4(%rbp)
  4005cb: c7 45 f8 07 00 00 00  movl   $0x7,-0x8(%rbp)
  4005d2: 8b 45 fc              mov    -0x4(%rbp),%eax
  4005d5: 0f af 45 f8           imul   -0x8(%rbp),%eax
  4005d9: 89 45 f4              mov    %eax,-0xc(%rbp)
  4005dc: 5d                    pop    %rbp
  4005dd: c3                    retq
  4005de: 66 90                 xchg   %ax,%ax
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x4005c0` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[8] Command-line entry: `gcc -g -O0 -fno-builtin main.c`
[9] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

2.15 Example: Intel Xeon looping infinitely

The following program was written in the C language and compiled[10] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
void main (void)
{
  int x = 0;

  while(1)
    ++x;
}
```

Next, the resulting executable file was "disassembled"[11] to show the machine-language and corresponding assembly-language code. Only the portion of the disassembled code related to the `main` function is shown here:

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
  4005cb: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
  4005cf: eb fa                 jmp    4005cb <main+0xb>
  4005d1: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
  4005d8: 00 00 00
  4005db: 0f 1f 44 00 00        nopl   0x0(%rax,%rax,1)
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x4005c0` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[10] Command-line entry: `gcc -g -O0 -fno-builtin main.c`
[11] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

2.16 Example: Intel Xeon looping fifteen times

The following program was written in the C language and compiled[12] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
void main (void)
{
  int n, x = 0;

  for (n = 0 ; n < 15 ; ++n)
    --x;
}
```

Next, the resulting executable file was "disassembled"[13] to show the machine-language and corresponding assembly-language code. Only the portion of the disassembled code related to the `main` function is shown here:

```
00000000004005c0 <main>:
  4005c0: 55                    push   %rbp
  4005c1: 48 89 e5              mov    %rsp,%rbp
  4005c4: c7 45 f8 00 00 00 00  movl   $0x0,-0x8(%rbp)
  4005cb: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
  4005d2: eb 08                 jmp    4005dc <main+0x1c>
  4005d4: 83 6d f8 01           subl   $0x1,-0x8(%rbp)
  4005d8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
  4005dc: 83 7d fc 0e           cmpl   $0xe,-0x4(%rbp)
  4005e0: 7e f2                 jle    4005d4 <main+0x14>
  4005e2: 5d                    pop    %rbp
  4005e3: c3                    retq
  4005e4: 66 2e 0f 1f 84 00 00  nopw   %cs:0x0(%rax,%rax,1)
  4005eb: 00 00 00
  4005ee: 66 90                 xchg   %ax,%ax
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x4005c0` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[12] Command-line entry: `gcc -g -O0 -fno-builtin main.c`
[13] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

2.17 Example: Intel Xeon integer power

The following program was written in the C language and compiled[14] on a computer running the Linux operating system on an Intel 64-bit Xeon processor:

```
#include <math.h>

void main (void)
{
  int x = 3, y = 5, z;

  z = pow(x , y);
}
```

The power (`pow`) function is not part of the default C library, and so we need to include the header file `math.h` and also "link" the math library with our compiled object code (using the `-lm` option when invoking the `gcc` compiler software) to create an executable file for the computer to run.

[14] Command-line entry: `gcc -g -O0 -fno-builtin -lm main.c`

Next, the resulting executable file was "disassembled"[15] to show the machine-language and corresponding assembly-language code. Only the portions of the disassembled code related to the `main` function and the `pow` function call are shown here:

```
00000000004004a0 <pow@plt-0x10>:
  4004a0: ff 35 6a 05 20 00     pushq  0x20056a(%rip)
                                       # 600a10 <_GLOBAL_OFFSET_TABLE_+0x8>
  4004a6: ff 25 6c 05 20 00     jmpq   *0x20056c(%rip)
                                       # 600a18 <_GLOBAL_OFFSET_TABLE_+0x10>
  4004ac: 0f 1f 40 00           nopl   0x0(%rax)

00000000004004b0 <pow@plt>:
  4004b0: ff 25 6a 05 20 00     jmpq   *0x20056a(%rip)
                                       # 600a20 <_GLOBAL_OFFSET_TABLE_+0x18>
  4004b6: 68 00 00 00 00        pushq  $0x0
  4004bb: e9 e0 ff ff ff        jmpq   4004a0 <_init+0x18>

0000000000400630 <main>:
  400630: 55                    push   %rbp
  400631: 48 89 e5              mov    %rsp,%rbp
  400634: 48 83 ec 10           sub    $0x10,%rsp
  400638: c7 45 fc 03 00 00 00  movl   $0x3,-0x4(%rbp)
  40063f: c7 45 f8 05 00 00 00  movl   $0x5,-0x8(%rbp)
  400646: f2 0f 2a 4d f8        cvtsi2sdl -0x8(%rbp),%xmm1
  40064b: f2 0f 2a 45 fc        cvtsi2sdl -0x4(%rbp),%xmm0
  400650: e8 5b fe ff ff        callq  4004b0 <pow@plt>
  400655: f2 0f 2c c0           cvttsd2si %xmm0,%eax
  400659: 89 45 f4              mov    %eax,-0xc(%rbp)
  40065c: c9                    leaveq
  40065d: c3                    retq
  40065e: 66 90                 xchg   %ax,%ax
```

Memory addresses appear in the left-most column, followed by machine-language opcodes and operands in hexadecimal format. Assembly-language mnemonics and their operands appear on the farthest-right columns. For example, the first line of code for the `main` function shows it beginning at address `0x400630` with the opcode `55`, corresponding to the assembly-language mnemonic `push` with `%rbp` as its operand.

[15] Command-line entry: `objdump -d -s -f -m i386:x86-64 a.out`

Chapter 3

Simplified Tutorial

(Simplified tutorial text goes here)

Chapter 4

Full Tutorial

(Detailed tutorial text goes here)

Chapter 5

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

5.1 Big-endians and Little-endians

A fictional novel published in 1726 entitled *Gulliver's Travels Into Several Remote Nations of the World* contains a reference to a dispute between two nations, that of Lilliput and of Blefuscu. The dispute is over the most trivial of matters, namely which end of an egg should be broken prior to eating. Clearly a satire by Swift on the religious controversies of his day, the schism between the "Big-endians" and "Little-endians" served as a convenient reference for computer scientists to describe the differing ways in which digital data could be organized within a digital system.

Without further adieu, I present to you the passage from Swift's famous book introducing the term "Big-endian" into the English lexicon:

> . . . our histories of six thousand moons make no mention of any other regions than the two great empires of Lilliput and Blefuscu. Which two mighty powers have, as I was going to tell you, been engaged in a most obstinate war for six-and-thirty moons past. It began upon the following occasion. It is allowed on all hands, that the primitive way of breaking eggs, before we eat them, was upon the larger end; but his present majesty's grandfather, while he was a boy, going to eat an egg, and breaking it according to the ancient practice, happened to cut one of his fingers. Whereupon the emperor his father published an edict, commanding all his subjects, upon great penalties, to break the smaller end of their eggs. The people so highly resented this law, that our histories tell us, there have been six rebellions raised on that account; wherein one emperor lost his life, and another his crown. These civil commotions were constantly fomented by the monarchs of Blefuscu; and when they were quelled, the exiles always fled for refuge to that empire. It is computed that eleven thousand persons have at several times suffered death, rather than submit to break their eggs at the smaller end. Many hundred large volumes have been published upon this controversy: but the books of the Big-endians have been long forbidden, and the whole party rendered incapable by law of holding employments. During the course of these troubles, the emperors of Blefusca did frequently expostulate by their ambassadors, accusing us of making a schism in religion, by offending against a fundamental doctrine of our great prophet Lustrog, in the fifty-fourth chapter of the Blundecral (which is their Alcoran). This, however, is thought to be a mere strain upon the text; for the words are these: "that all true believers break their eggs at the convenient end." And which is the convenient end, seems, in my humble opinion to be left to every man's conscience, or at least in the power of the chief magistrate to determine. Now, the Big-endian exiles have found so much credit in the emperor of Blefuscu's court, and so much private assistance and encouragement from their party here at home, that a bloody war has been carried on between the two empires for six-and-thirty moons, with various success; during which time we have lost forty capital ships, and a much a greater number of smaller vessels, together with thirty thousand of our best seamen and soldiers; and the damage received by the enemy is reckoned to be somewhat greater than ours. However, they have now equipped a numerous fleet, and are just preparing to make a descent upon us; and his imperial majesty, placing great confidence in your valour and strength, has commanded me to lay this account of his affairs before you.

One of those computer scientists referencing Jonathan Swift's satirical novel was Danny Cohen, in a document appropriately dated on April Fool's Day (April 1), 1980. The tone of Cohen's document

is quite humorous, and definitely worth reading especially for those interested in the architectures of early computing hardware such as the Motorola 68000 microprocessor IC; Digital Equipment Corporation's PDP10, PDP11/45, VAX computers; and the IBM model 360 computer. He makes extensive reference of Swift's story while describing the fundamental decision of how to organize and communicate data words in a digital system.

Cohen's document concludes neatly with the following three sentences, which I include for your edification:

> It may be interesting to notice that the point which Jonathan Swift tried to convey in Gulliver's Travels in exactly the opposite of the point of this note.
>
> Swift's point is that the difference between breaking the egg at the little-end and breaking it at the big-end is trivial. Therefore, he suggests, that everyone does it in his own preferred way.
>
> We agree that the difference between sending eggs with the little- or the big-end first is trivial, but we insist that everyone must do it in the same way, to avoid anarchy. Since the difference is trivial we may choose either way, but a decision must be made.

At the time of this writing (2018), nearly four decades after Cohen's missive, the state of anarchy described by Cohen remains alive and well, with little-endian and big-endian formats commonly found among the various microprocessors and microcontrollers still in active use.

Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

6.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

6.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Conservation of Energy

Simplification as a problem-solving strategy

Thought experiments as a problem-solving strategy

Limiting cases as a problem-solving strategy

Annotating diagrams as a problem-solving strategy

Interpreting intermediate results as a problem-solving strategy

Graphing as a problem-solving strategy

Converting a qualitative problem into a quantitative problem

Converting a quantitative problem into a qualitative problem

Working "backwards" to validate calculated results

Reductio ad absurdum

Re-drawing schematics as a problem-solving strategy

Cut-and-try problem-solving strategy

Algebraic substitution

???

6.1.3 First conceptual question

Challenges

- ???.
- ???.
- ???.

6.1.4 Second conceptual question

Challenges

- ???.
- ???.
- ???.

6.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

6.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

6.2.3 First quantitative problem

Challenges

- ???.
- ???.
- ???.

6.2.4 Second quantitative problem

Challenges

- ???.
- ???.
- ???.

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

6.3.1 First diagnostic scenario

Challenges

- ???.
- ???.
- ???.

6.3.2 Second diagnostic scenario

Challenges

- ???.
- ???.
- ???.

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

2 June 2020 – minor edits to assembly language code in the Case Tutorial chapter (e.g. adding the `#` symbol before some of the `include` directives) and also mentioned the specific assembler I was using under *MPLABX*, called `MPASM`.

28-29 May 2020 – worked more on the Case Tutorial chapter content, adding examples of assembly language programming from my collection of past experiments.

27 May 2020 – document first created.

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