

Analog-to-Digital Conversion Using a PIC16C5X/PIC16F5X

Author: Mark Pallones
 Author: Kristine Angelica Sumague
 Author: Mike Gomez
 Microchip Technology Inc.

- Available off-the-shelf from distributors
- Calibration in software for improved measurement accuracy
- Power savings using Sleep mode
- Output pins have large, current source/sink capability to drive LEDs directly

INTRODUCTION

There are various ways on how to implement the Analog-to-Digital (A/D) conversion in a circuit. For a simple and low bandwidth analog application such as DC voltmeter, it is desirable to have a low cost yet high resolution A/D converter.

This application note describes a method to implement A/D conversion on the PIC16C5X and PIC16F5X series of microcontrollers. The converter requires only five external components and is software and hardware configurable for conversion resolutions from six bits up to ten bits, and conversion times of 250 us or longer. The method is usable for both voltage and current conversion and uses a software calibration technique that compensates for time and temperature drift, as well as component errors. Following are reasons why PIC16C5X and PIC16F5X microcontroller families are ideal for simple analog applications:

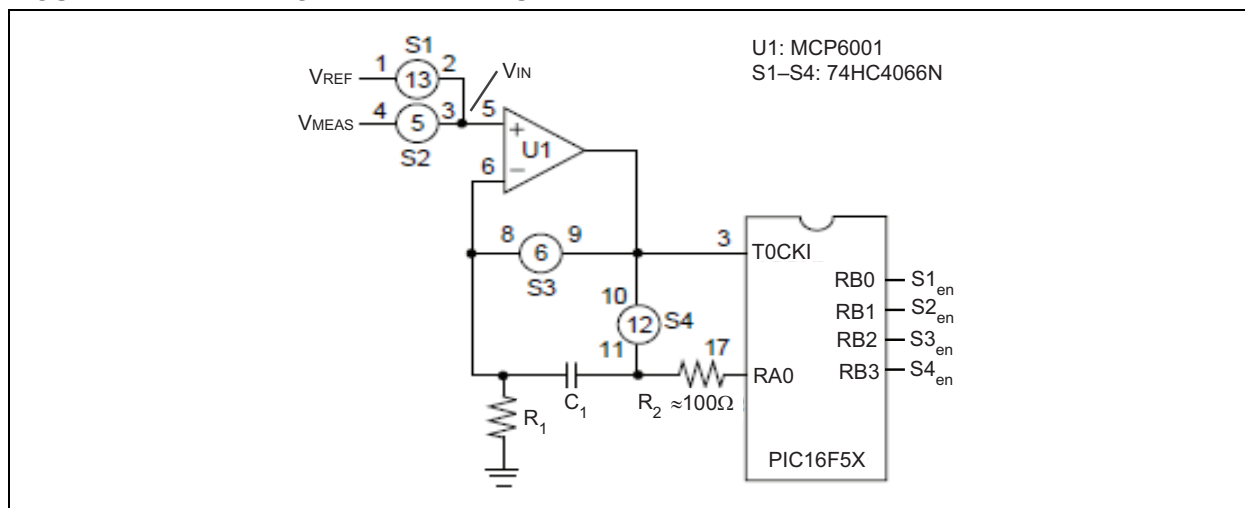
- Very low cost
- Few external components required
- Fully programmable; PIC16C5X microcontrollers for One-Time-Programmable (OTP) EEPROM devices and PIC16F5X for Flash devices

THEORY OF OPERATION

Figure 1 shows a simplified schematic of the A/D converter circuit. There are two input voltages connected one at a time to op amp U1. VREF is the fixed reference voltage used in calibration and VMEAS is the unknown voltage to be converted. Resistor R1 and Capacitor C1 form a charging circuit used to convert input voltage to time. The existence of U1 in the circuit removes the logarithmic characteristic that would occur if the input voltage is directly applied to R1 and C1. The microcontroller controls the U1 operation by turning ON/OFF the four switches, S1-S4 of Analog Switch IC, at different conversion stages. Additionally, the microcontroller measures the time and calculates the digital representation of the unknown input voltage.

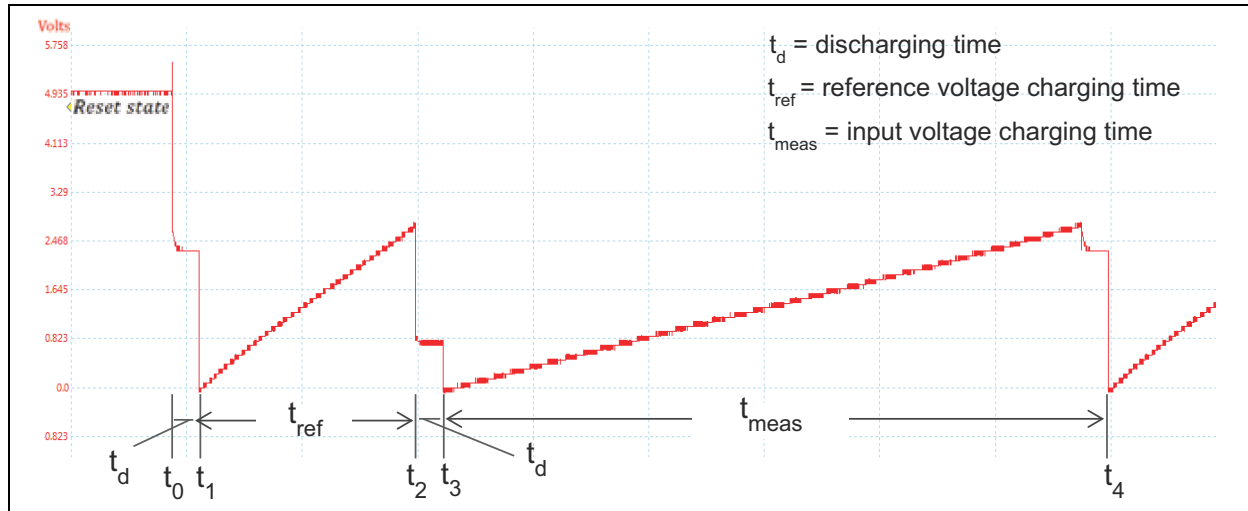
The circuit can also be used as a Current mode A/D converter. In this case, the input voltage to the current converter is not needed and the reference current and input current are both routed via analog switches directly into the capacitor.

FIGURE 1: A/D CONVERTER CIRCUIT



In order to visualize the different stages of conversion, let us refer to U1 output voltage V_O waveform shown in Figure 2.

FIGURE 2: OPERATIONAL AMPLIFIER OUTPUT VOLTAGE WAVEFORM



At t_0 - t_1 , S1 and S3 are ON, S2 and S4 are OFF and RA0 is pulled to ground by the software. This yields the equivalent circuit in Figure 3. V_O is equal to V_{REF} since V_{IN} is equal to V_{REF} and S3 force unity gain feedback. C1 is discharging or is initially discharged after the Reset state. In any case, this stage ensures that C1 is fully discharged before going to the next stage. At the end of t_1 , S1 remains ON, S2 remains OFF, S3 is OFF, S4 is ON and RA0 is configured as an input pin. This yields the equivalent circuit in Figure 4. As a function of V_{REF} , V_O is started to ramp-up linearly while C1 is charging. The V_O ramp-up continues until the threshold voltage input V_{th} of the microcontroller trips. This generates a software calibration value equal to t_{ref} . This calibration value is measured and used to calibrate out most circuit errors, including inaccuracies in the resistor and capacitor, changes in the V_{th} , and temperature variation.

FIGURE 3: EQUIVALENT CIRCUIT DURING DISCHARGING

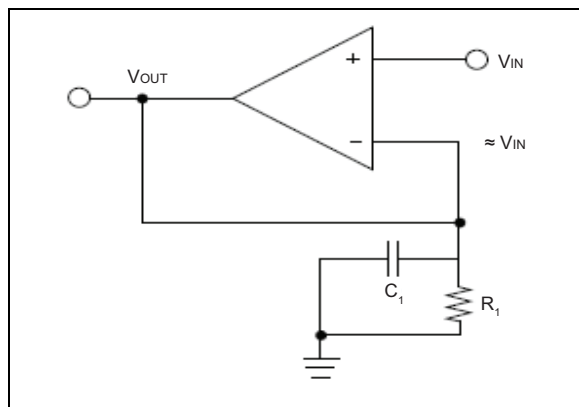
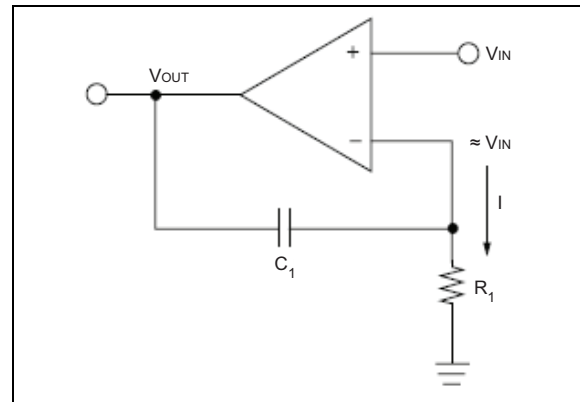


FIGURE 4: EQUIVALENT CIRCUIT DURING MEASUREMENT



After the software calibration value is measured at t_2 , S2 and S3 are ON, S1 and S4 are OFF and RA0 is pulled to ground again by the software. This yields the same equivalent circuit in Figure 3. However, V_O is equal to V_{MEAS} since V_{IN} is equal to V_{MEAS} and S3 force unity feedback. C1 is discharging from t_2 to t_3 . At the end of t_3 , S2 remains ON, S1 remains OFF, S3 is OFF, S4 is ON and RA0 is configured as an input pin. This yields the same equivalent circuit in Figure 4. As a function of V_{MEAS} , V_O is started to ramp-up linearly while C1 is charging. The V_O ramp-up continues until the V_{th} of the microcontroller trips. This generates a software V_{MEAS} value equal to t_{meas} . This value is compared to the software calibration value to determine the actual digital representation of V_{MEAS} .

A/D CONVERTER EQUATIONS

Based on the circuit operation, equation is used by the microcontroller in order to calculate the final conversion result.

In [Figure 4](#), current through R1 is equal to the current through C1.

When input voltage V_{IN} is equal to V_{REF} , the relation between the two currents are represented as (see [Equation 1](#)):

EQUATION 1: R1 AND C1 CURRENT EQUATION WHEN INPUT VOLTAGE IS V_{REF}

$$\frac{V_{ref}}{R1} = C1 \frac{dV_0}{dt}$$

and when V_{IN} is equal to V_{MEAS} , the relation between the two currents are represented as (see [Equation 2](#)):

EQUATION 2: R1 AND C1 CURRENT EQUATION WHEN INPUT VOLTAGE IS V_{MEAS}

$$\frac{V_{meas}}{R1} = C1 \frac{dV_0}{dt}$$

Integrating Equation 1 and 2 results (see [Equation 3](#) and [Equation 4](#)):

EQUATION 3: INTEGRATION RESULT OF EQUATION 1

$$V_0 = \frac{1}{R1C1} \int_0^{t_{ref}} V_{ref} dt$$

and

EQUATION 4: INTEGRATION RESULT OF EQUATION 2

$$V_0 = \frac{1}{R1C1} \int_0^{t_{meas}} V_{meas} dt$$

Since V_{REF} and V_{MEAS} is constant input, [Equation 3](#) and [Equation 4](#) can be reduced further to:

EQUATION 5: U1 VOLTAGE OUTPUT EQUATION AS A FUNCTION OF V_{REF}

$$V_0 = \frac{V_{ref} t_{ref}}{R1C1}$$

and

EQUATION 6: U1 VOLTAGE OUTPUT EQUATION AS A FUNCTION OF V_{MEAS}

$$V_0 = \frac{V_{meas} t_{meas}}{R1C1}$$

At the end of each measurement, V_0 of [Equation 5](#) and [Equation 6](#) are both equal to V_{th} , therefore, equating both equations yields:

EQUATION 7: RESULT OF EQUATIONS 5 AND 6

$$\frac{V_{ref} t_{ref}}{R1C1} = \frac{V_{meas} t_{meas}}{R1C1}$$

In [Equation 7](#), R1 and C1 can be eliminated and solved for V_{MEAS} , the unknown input voltage.

EQUATION 8: FINAL CONVERSION

$$V_{meas} = \frac{V_{ref} t_{ref}}{t_{meas}}$$

In [Equation 8](#), it is apparent that the measurement is independent of the value of circuit elements R1 and C1. This makes the conversion insensitive to errors in R1 and C1 value, due to the inaccuracy or temperature variation. However, this does not mean that the value of R1 and C1 is unimportant in the design of the A/D converter. The values of R1 and C1 should be selected based upon the number of bits of resolution. Looking back at [Equation 6](#) and solving R1C1 (see [Equation 9](#)):

EQUATION 9: CALCULATION OF R1C1 VALUE

$$R1C1 = \frac{V_{meas} t_{meas}}{V_0}$$

where

V_{meas} = Lowest voltage to be measured(at least ten LSBs)

t_{meas} = Time to do the number of bits of resolution desired
($2^N \times 1/f_{osc} \times 4 \text{ clock/cycle} \times \text{instruction cycles per count}$. Where N is number of bit resolution)

$V_0 = V_{th}$ Threshold Voltage input of the PIC16C5x/PIC16F5x being used (3V estimated)

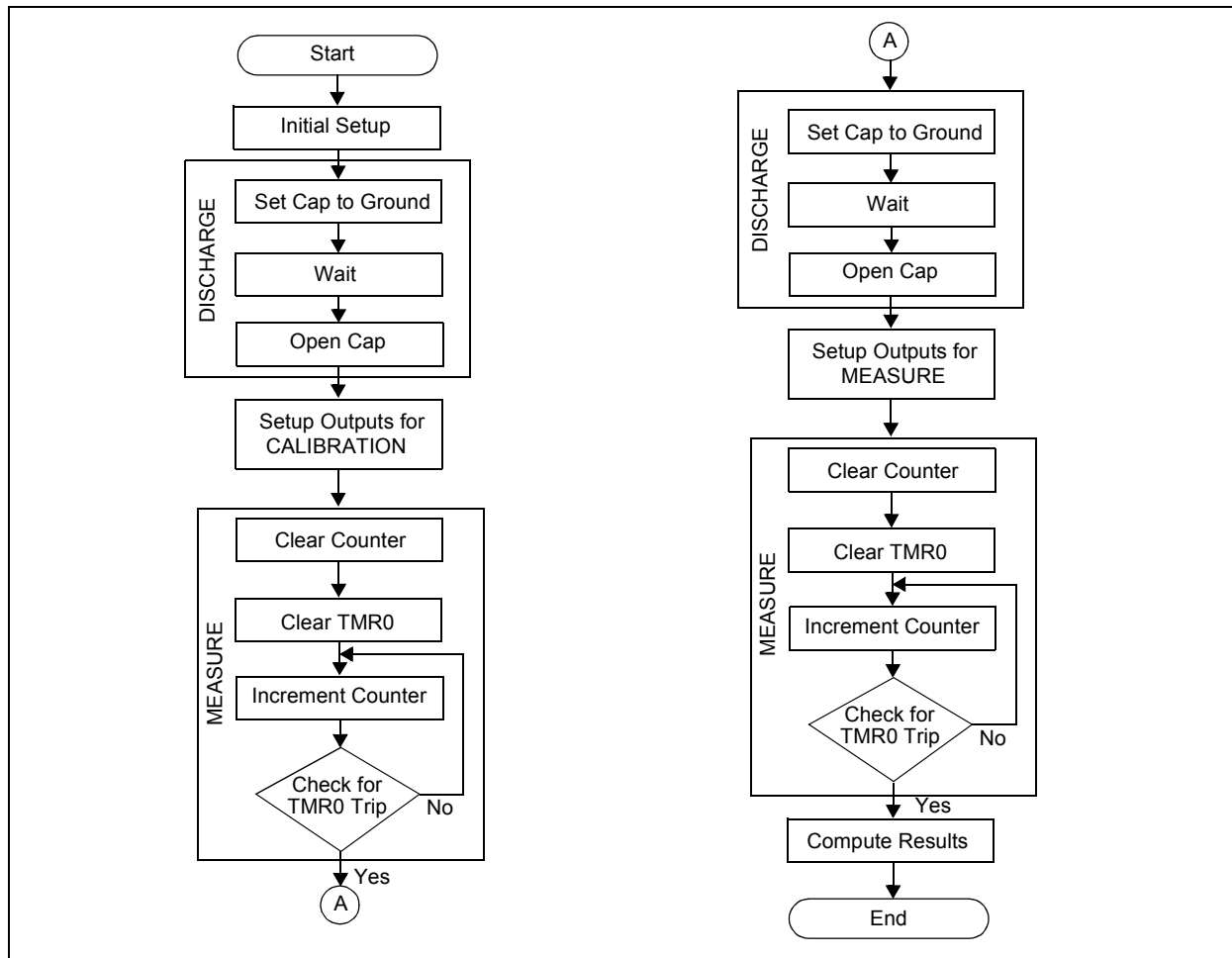
The actual value for R1C1 should be slightly smaller than calculated, to ensure that the PIC16C5X or PIC16F5X does not over count during the measurement.

CIRCUIT CONFIGURATIONS

C and Assembly code implementing the circuit of Figure 1 is listed in [Appendix A: "Source Code in C"](#) and [Appendix B: "Source Code in Assembly"](#).

These codes measure the time up to 16 bits. The full implementation of algorithm can be seen in the flowchart shown in [Figure 5](#).

FIGURE 5: A/D CONVERSION FLOWCHART



There is a difference between the R1C1 value when implementing in Assembly and C. This is because the instruction cycles per count, when using C, is greater than the Assembly.

Using the 4 MHz external RC clock oscillator, the value of R1C1 can be calculated as follows (see [Equation 10](#)):

For the C code:

EQUATION 10: R1C1 CALCULATION IN C

$$R1C1 = \frac{100mV \times 2^{16} \times \frac{1}{4MHz} \times 4 \frac{clocks}{cycle} \times 16 \text{ cycles per count}}{3V}$$

For the Assembly code (see [Equation 11](#)):

EQUATION 11: R1C1 CALCULATION IN ASSEMBLY

$$R1C1 = \frac{100mV \times 2^{16} \times \frac{1}{4MHz} \times 4 \frac{clocks}{cycle} \times 6 \text{ cycles per count}}{3V}$$

In actual applications, if measurement accuracy permits, it may be advantageous to use lower resolution bits and higher clock source. The math code can be substantially reduced and the measure time is reduced by the simpler code and shorter count.

CIRCUIT PERFORMANCE

The calibration value removes all first order errors (offset, gain, R and C inaccuracy, power supply voltage and temperature) except the reference voltage drift. Any change in the reference voltage, including noise, may result in measurement errors. Other error sources may be analog switch leakage, resistor and capacitor non-linearities, input threshold uncertainty and time measurement uncertainty (\pm one instruction cycle time). Measured performance shows the converter to be accurate within $\pm 1\%$ of full scale.

FIGURE 6: PERCENT ERROR AT FULL-SCALE CONVERSION

$V_{REF} = 2.5V$; $R1 = 33K\text{ ohm}$; $C1 = 1\mu F$					
V_{IN}	Computed		Actual		%ERROR
	HEX	DEC	HEX	DEC	
2.5	9A3	2467	9A1	2465	0.081%

CONCLUSION

For a simple and low bandwidth analog application, it usually requires a low cost yet high resolution A/D converter. By using the PIC16C5X and PIC16F5X baseline family of microcontrollers, this application note demonstrates how to meet such requirements. The A/D converter does not only use fewer components but also has a capability to calibrate out most circuit errors.

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EXAMPLE A-1: A/D CONVERTER PROGRAM IN C

```
/*
File Name:
  PIC16F5xADC.c

Summary:
  This is the main file used for the Application Note AN00513

Hardware implementation requires:
  R1 = 33K ohm
  C1 = 1uF
  RC oscillator value are 4.7K ohm and 22pF, respectively.
  Vref = 2.5V

Generation Information :
  Device      : PIC16F57
  Compiler    : XC8 v1.21
  MPLAB      : MPLAB X 1.90
*/

/*****
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*****/

#include <xc.h>

// CONFIG
#pragma config OSC = RC          // Oscillator selection bits (RC oscillator)
#pragma config WDT = OFF        // Watchdog timer enable bit (WDT disabled)
#pragma config CP = OFF         // Code protection bit (Code protection off)

void initPORTS()
{
    PORTA = 0x00; //set RA0 low (on when activated)
    TRISB = 0x00; //set all pins in PORTB as output
    OPTION = 0x28; //select positive edge for TMR0
}
```

EXAMPLE A-2: A/D CONVERTER PROGRAM IN C

```
}  
  
void DSCHRG_CAP()  
{  
    TRISA = 0x00;    //RA0 on  
    _delay(5000);    //RC discharging time  
    TRISA = 0x01;    //set RA0 to have high impedance  
}  
  
void main()  
{  
    unsigned int Tcount, Tmeas, Tref, Vref, Vmeas;  
    unsigned long mpy;  
  
    Vref = 0x09A3;    //Digital Equivalent of Vref voltage  
    Vmeas = 0;        // Initiate Vmeas to 0  
    initPORTS();     //Initialize I/O pin  
    while(1)  
    {  
  
        PORTB = 0x05; //S1 and S3 activated (Vref)  
        DSCHRG_CAP(); //discharge capacitor charge  
        PORTB = 0x09; //S1 and S4 activated  
  
        TMR0 = 0x00; //reset counter and TMR0  
        Tcount = 0;  
  
        while(!TMR0) //increment Tcount until TMR0 trips  
        {  
            Tcount++;  
        }  
        Tref = Tcount;  
  
        PORTB = 0x06; //S2 and S3 activated (Vmeas)  
        DSCHRG_CAP(); //discharge capacitor charge  
        PORTB = 0x0A; //S2 and S4 activated  
  
        TMR0 = 0x00; //reset counter and TMR0  
        Tcount = 0;  
  
        while(!TMR0) //increment Tcount until TMR0 trips  
        {  
            Tcount++;  
        }  
        Tmeas = Tcount;  
  
        mpy = (long) Tref*Vref; //perform mathematical operation to get Vin  
        Vmeas = mpy / Tmeas; //result  
  
    }  
}
```

APPENDIX B: SOURCE CODE IN ASSEMBLY

EXAMPLE B-1: A/D CONVERTER PROGRAM IN ASSEMBLY

```

*****
; Revision Date:
;   12-10-2013
;
; File Name:
;   PIC16F5xADCasm.asm
;
; Summary:
;   This is the main file used for the Application Note AN00513
;
; Hardware implementation requires:
;   R1 = 13K ohm
;   C1 = 1uF
;   RC oscillator value are 4.7K ohm and 22pF, respectively.
;
; Generation Information :
;   Device       : PIC16F54
;   Compiler     : MPASM v5.52
;   MPLAB       : MPLAB X 1.90
*****

*****
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*****
#include <P16F54.INC>

__config 0xFFFB                ;configuration setting:
                                ; OSC_RC, WDT_OFF, CP_OFF

                                ;Digital Equivalent of Vref voltage
#define VCALMS      009        ;VCAL MSB VALUE IN HEX
#define VCALLS     02E        ;VCAL LSB VALUE IN HEX

```

EXAMPLE B-2: A/D CONVERTER PROGRAM IN ASSEMBLY

```

ACCA    EQU    8
ACCB    EQU    0A
ACCC    EQU    0C
ACCD    EQU    0E
ACCE    EQU    10
TMEAS   EQU    12
TEMP    EQU    14

TEMP1   EQU    16
TEMP2   EQU    17
TEMP3   EQU    18

        ORG    0
        GOTO   VOLTS           ;PROGRAM CODE

MADD    MOVF   ACCA+1,W
        ADDWF  ACCB+1, F       ;ADD LSB
        BTFSC  3,0             ;ADD IN CARRY
        INCF  ACCB, F
        MOVF  ACCA,W
        ADDWF  ACCB, F         ;ADD MSB
        RETLW  0
        NOP

MPY     CALL   SETUP           ;RESULTS IN B(16 MSB'S) AND C(16 LSB'S)
MLOOP   RRF    ACCD, F         ;ROTATE D RIGHT
        RRF    ACCD+1, F
        SKPNC                ;NEED TO ADD?
        CALL   MADD
        RRF    ACCB, F
        RRF    ACCB+1, F
        RRF    ACCC, F
        RRF    ACCC+1, F
        DECSZ  TEMP, F        ;LOOP UNTIL ALL BITS CHECKED
        GOTO   MLOOP
        RETLW  0

        NOP
SETUP   MOVLW  10
        MOVWF  TEMP
        MOVF  ACCB,W           ;MOVE B TO D
        MOVWF  ACCD
        MOVF  ACCB+1,W
        MOVWF  ACCD+1
        MOVF  ACCC,W
        MOVWF  ACCE
        MOVF  ACCC+1,W
        MOVWF  ACCE+1

        CLRF  ACCB
        CLRF  ACCB+1
        RETLW  0

```

EXAMPLE B-3: A/D CONVERTER PROGRAM IN ASSEMBLY

```

NOP
DIV    CALL    SETUP
      MOVLW   20
      MOVWF  TEMP
      CLRF   ACC
      CLRF   ACC+1
DLOOP  CLRC
      RLF   ACCE+1, F
      RLF   ACCE, F
      RLF   ACCD+1, F
      RLF   ACCD, F
      RLF   ACCC+1, F
      RLF   ACCC, F
      MOVF  ACCA,W
      SUBWF ACCC,W           ;CHECK IF A>C
      SKPZ
      GOTO  NOCHK
      MOVF  ACCA+1,W
      SUBWF ACCC+1,W       ;IF MSB EQUAL THEN CHECK LSB
NOCHK  SKPC           ;CARRY SET IF C>A
      GOTO  NOGO
      MOVF  ACCA+1,W       ;C-A INTO C
      SUBWF ACCC+1, F
      BTFSS 3,0
      DECF  ACCC, F
      MOVF  ACCA,W
      SUBWF ACCC, F
      SETC           ;SHIFT A 1 INTO B (RESULT)
NOGO   RLF   ACCB+1, F
      RLF   ACCB, F
      DECFSZ TEMP, F       ;LOOP UNTILL ALL BITS CHECKED
      GOTO  DLOOP
      RETLW 0

DSCHRG MOVLW  B'00001110'   ;DISCHARGE C (RA0 ON)
      TRIS  5
      MOVLW 0FF
      MOVWF TEMP1
      MOVWF TEMP2
      MOVWF TEMP3
LOOP1  DECFSZ TEMP1, F       ;WAIT
      GOTO  LOOP1
LOOP2  DECFSZ TEMP2, F       ;WAIT
      GOTO  LOOP2
LOOP3  DECFSZ TEMP3, F       ;WAIT
      GOTO  LOOP3
      MOVLW  B'00001111'   ;ALL RA HIGH Z
      TRIS  5
      RETLW 0

M_TIME CLRF  1           ;CLEAR RTCC REGISTER
      CLRF  ACCA+1       ;CLEAR 16 BIT COUNTER
      CLRF  ACCA

```

EXAMPLE B-4: A/D CONVERTER PROGRAM IN ASSEMBLY

```

TLOOP   INCFSZ  ACCA+1, F
        GOTO    ENDCHK
        INCFSZ  ACCA, F
        GOTO    ENDCHK
        GOTO    END_M
ENDCHK  BTFSS   1,0           ;CHECK FOR RTCC TRIP
        GOTO    TLOOP
END_M   MOVF    1,W
        RETLW   0

VOLTS   MOVLW   B'00000110'   ;SET S2 AND S3 HIGH(ON WHEN ACTIVATED)
        MOVWF   6
        MOVLW   B'00000000'   ;ACTIVATE SWITCHES S1-S4
        TRIS    6
        MOVLW   B'00101000'   ;SELECT POSITIVE EDGE FOR RTCC
        OPTION
        MOVLW   B'00000000'
        MOVWF   5           ;SET RA0 LOW (ON WHEN ACTIVATED)

MEAS    CALL    DSCHRG        ;CHARGE CAPACITOR TO VIN
        MOVLW   B'00001010'   ;S2 AND S4 ON
        MOVWF   6
        CALL    M_TIME        ;MEASURE TIME
        MOVF    ACCA+1,W
        MOVWF   TMEAS+1      ;STORE LSB
        MOVF    ACCA,W
        MOVWF   TMEAS        ;STORE MSB

CAL     MOVLW   B'00000101'   ;S1 AND S3 ON
        MOVWF   6
        CALL    DSCHRG        ;CHARGE CAPACITOR TO VREF
        MOVLW   B'00001001'   ;S1 AND S4 ON
        MOVWF   6
        CALL    M_TIME        ;MEASURE TIME

        MOVLW   VCALLS
        MOVWF   ACCB+1
        MOVLW   VCALMS
        MOVWF   ACCB

        CALL    MPY           ;MULTIPLY ACCA(TCAL) * ACCB(VREF)

        MOVF    TMEAS+1,W
        MOVWF   ACCA+1
        MOVF    TMEAS,W
        MOVWF   ACCA

        CALL    DIV           ;DIVIDE ACCB(TCAL * V) BY ACCA(TMEAS)

        GOTO    VOLTS

END

```

NOTES:

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