Section 61. Operational Amplifier (Op Amp)

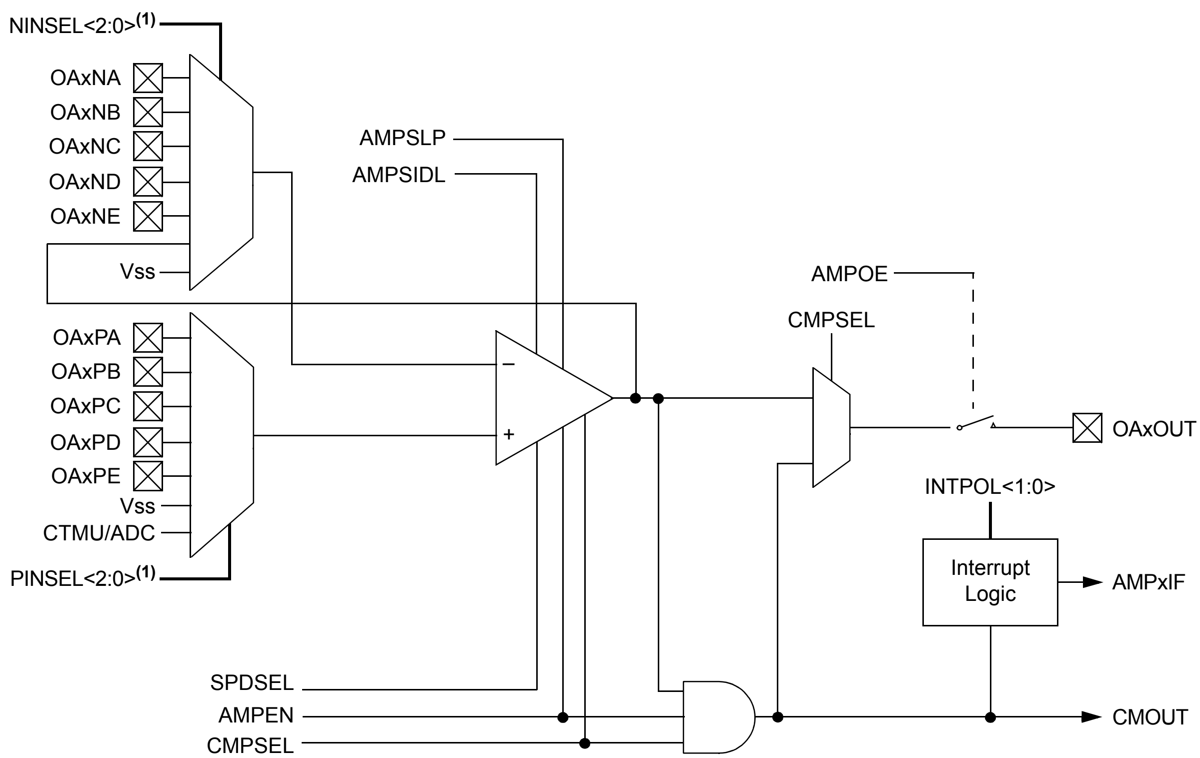
HIGHLIGHTS

This section of the manual contains the following major topics:

61.1 INTRODUCTION

The Operational Amplifier (Op Amp) module provides the ability to condition analog input signals, or it can be connected to work as a comparator. It can be configured to run in High or Low-Power mode, depending on the user specifications. The module also employs an interrupt to alert the core processor of a change in output. The inputs can be selected from I/O pins or several other modules on the PIC® MCU. The output can be present on an I/O pin, or only available to the internal chip, based on the settings of the control registers. A diagram further illustrates the module in Figure 61-1.

Figure 61-1: Operational Amplifier Module



Note 1: Input MUX selections are device-specific. Not all options shown may be implemented on all devices. Refer to the device-specific data sheet for actual MUX options.

61.2 Configuring the Operational Amplifier

The functionality of the Op Amp module is controlled by the AMPxCON register.

Register 61-1: AMPxCON: Op Amp Control Register

R/W-0	U-0	R/W-0	R/W-0	R/W-0	R/W-0	R-0	R/W-0
AMPEN	—	AMPSIDL	AMPSLP	INTPOL1[1,2]	INTPOL0[1,2]	CMOUT[1,2]	CMPSEL[1]
bit 15							bit 8

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0, HSC	R/C-0, HSC
SPDSEL	AMPOE[1]	NINSEL2	NINSEL1	NINSEL0	PINSEL2	PINSEL1	PINSEL0
bit 7							bit 0

Legend:	C = Clearable bit	U = Unimplemented bit, read as ‘0’	
R = Readable bit	W = Writable bit	HSC = Hardware Settable/Clearable bit	
-n = Value at POR	‘1’ = Bit is set	‘0’ = Bit is cleared	x = Bit is unknown

bit 15 **AMPEN:** Op Amp Control Module Enable bit
1 = Module is enabled
0 = Module is disabled

bit 14 **Unimplemented:** Read as ‘0’

bit 13 **AMPSIDL:** Peripheral Stop in Idle Mode bit
1 = Discontinue module operation when device enters Idle mode
0 = Continue module operation in Idle mode

bit 12 **AMPSLP:** Peripheral Enabled in Sleep Mode bit
1 = Continue module operation when device enters Sleep mode
0 = Discontinue module operation in Sleep mode

bit 11-10 **INTPOL<1:0>:** Interrupt Enable bits[1,2]
When CMPSEL = 1:
11 = Interrupt occurs on change
10 = Interrupt occurs on negative edge
01 = Interrupt occurs on positive edge
00 = Interrupts are disabled
When CMPSEL = 0:
Interrupts are not generated in Op Amp mode.

bit 9 **CMOUT:** Comparator Output Status bit[1,2]
1 = Comparator positive input is greater than the negative input
0 = Comparator positive input is less than the negative input

bit 8 **CMPSEL:** Comparator Mode Select bit[1]
1 = Configured as a comparator
0 = Configured as an Op Amp

bit 7 **SPDSEL:** Op Amp and Comparator Power/Speed Select bit
1 = Higher power, higher bandwidth/faster response speed
0 = Lower power, lower bandwidth/slower response speed

Note 1: These bits are implemented in select devices. Refer to the specific device data sheet for more information.
2: This bit is only available in Comparator mode; it is forced to ‘0’ in Op Amp mode.

Register 61-1: AMPxCON: Op Amp Control Register (Continued)

bit 6	**AMPOE:** Amplifier Output Enable bit[1] `1` = Amplifier output is sent to a pin (amplifier output is not enabled) `0` = Amplifier output is not sent to a pin (amplifier output is enabled)
bit 5-3	**NINSEL<2:0>:** Inverting Op Amp Input Channel Select bits `xxx` = Device-specific; refer to device data sheet for channel select mapping
bit 2-0	**PINSEL<2:0>:** Non-Inverting Op Amp Input Channel Select bits `xxx` = Device-specific; refer to device data sheet for channel select mapping

Note 1: These bits are implemented in select devices. Refer to the specific device data sheet for more information.
2: This bit is only available in Comparator mode; it is forced to '`0`' in Op Amp mode.

61.3 OPERATION

61.3.1 Enabling the Op Amp

The Operational Amplifier is enabled when the AMPEN bit is set (AMPxCON<15>). When the Op Amp module is disabled, current consumption is minimized and outputs are driven to their inactive state. Additionally, if the module is being used in Operational Amplifier mode, the comparator output, CMOUT, (AMPxCON<9> = `0`) is cleared and the analog output of the Op Amp is driven to a high-impedance state.

61.3.2 Modes of Operation

In select devices, the Op Amp has two modes of operation, as determined by the CMOUT bit (AMPxCON<9>). When CMOUT is set, the module operates in Comparator mode. In this mode, the analog output of the module is active and the Comparator Output (CMOUT) bit is '`1`' when the positive input (selected by PINSEL<2:0>) is greater than the negative input (selected by NINSEL<2:0>). When CMOUT is cleared, the comparator output is forced to '`0`' and the module behaves as an Operational Amplifier.

In addition to choosing between Comparator and Op Amp modes, the module also has the ability to choose between High-Power and Low-Power Consumption modes with the SPDSEL bit (AMPxCON<7>). When the bit is set, the amplifier is in High-Power/High-Speed mode, resulting in significant gains in gain bandwidth, slew rate and a decrease in voltage noise. This is accompanied by a higher current budget. Low-Power/Low-Speed mode enables the Op Amp with a significantly lower current draw, at the cost of the performance specifications. Refer to the specific device family data sheet for the individual electrical characteristics.

61.3.3 Input Selection

The inputs to the amplifier or comparator are chosen by the NINSEL and PINSEL bits (AMPxCON<5:3> and AMPxCON<2:0>, respectively). The NINSEL bits connect to the negative input and the PINSEL bits connect to the positive input. The inputs can be external pins or other modules internal to the device. Refer to the family device data sheet to see the specific connections and **Section 12. I/O Ports with Peripheral Pin Select (PPS)** (DS39711) for more information on input pin selection.

61.3.4 Output Selection

The output of the Op Amp is controlled by the AMPOE bit (AMPxCON<6>), when implemented (refer to the family device data sheet for clarification). When this bit is set, the output of the amplifier or comparator is routed to an external pin. Refer to **Section 12. I/O Ports with Peripheral Pin Select (PPS)** for more information on output pin selection.

When the bit is cleared, the output of the amplifier is available internal to the device. Refer to the device data sheet for modules implemented on the device that use the Op Amp output as an input.

In Comparator mode, when the voltage source on PINSELx is greater than NINSELx, the output is set to one. When PINSELx are less than NINSELx, the comparator output is cleared to zero. This is signified by the CMOUT bit being set or cleared, respectively.

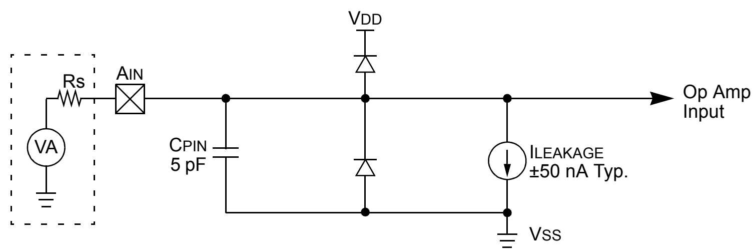
In devices where AMPOE is not implemented, the output of the amplifier is always routed to the OAxOUT pin. The signal can still be used internally (sampled by the A/D, sent to a comparator, etc.) by selecting the appropriate analog selection bits in the configuration of the desired module.

61.4 ANALOG INPUT CONNECTION CONSIDERATIONS

A simplified circuit for an analog input is shown in Figure 61-2. Any external component connected to an analog input pin, such as a capacitor or a Zener diode, should have very little leakage current.

Refer to the specific device data sheet for input voltage limits.

Figure 61-2: Operational Amplifier Analog Input Model



Legend:
CPIN = Input Capacitance
ILEAKAGE = Leakage Current at the Pin Due to Various Junctions
RS = Sampling Switch Resistance
VA = Sample/Hold Capacitance (from DAC)

61.5 INTERRUPTS

In devices where Comparator mode is implemented and the comparator is enabled (CMPSEL = `1`), interrupts are controlled by the INTPOL<1:0> bits (AMPxCON<11:10>). In devices where Comparator mode is not implemented, the Op Amp will not generate interrupts and there are no corresponding interrupt flags, interrupt enable or interrupt priority bits.

These bits allow the disabling of interrupts or enabling them in certain conditions. Specifically, interrupts can occur on a low-to-high transition (INTPOL<1:0> = `01`), a high-to-low transition (INTPOL<1:0> = `10`) or on both transition edges (INTPOL<1:0> = `11`).

If the Op Amp Interrupt Enable bit (AMPxIE) is cleared, an interrupt will not be generated. However, the AMPxIF bit will be set if an interrupt condition, as defined by the INTPOL bits, occurs. The user can clear the Interrupt Service Routine (ISR) by clearing AMPxIF. See **Section 8. Interrupts** in the *"PIC24F Family Reference Manual"* for more information.

61.6 EXAMPLE APPLICATIONS

The following code examples show a typical sequence for initializing and configuring a detection event for an analog comparator or Operational Amplifier. While these examples only discuss a single comparator, operations for several comparators are very similar.

61.6.1 Comparator Initialization and Operation

The initialization sequence in Example 61-1 configures one amplifier in Comparator mode. The example code also includes an example application, wherein the output transitions are counted; it counts positive and negative transitions. By modifying the INTPOL bits, only the positive or negative edges would be counted, depending on the end use application.

Example 61-1: Initialization Sequence

```
AMP1CONbits.AMPSIDL = 0;             //Continue operation in Idle mode
AMP1CONbits.AMPSLP = 0;              //Discontinue operation in Sleep mode
AMP1CONbits.INTPOL = 0b11;           //Interrupt on change
AMP1CONbits.CMPSEL = 1;              //Comparator mode
AMP1CONbits.SPDSEL = 1;              //High power/high speed operation
AMP1CONbits.AMPOUTEN = 1;            //output is sent to external pin
AMP1CONbits.NINSEL = 5;              //Input selection is device-specific; refer to the
AMP1CONbits.PINSEL = 5;              //family datasheet for specific options.
AMP1CONbits.AMPEN = 1;               //enabler operation.

unsigned int event Count = 0;

_AMP1IF = 0;

while (1) // Loop forever
{
    if (_AMP1IF) // Check Amplifier Interrupt Flag
    {
            eventCount++; // Count transition edges
            _AMP1IF = 0;
    }
}
```

61.6.2 Op Amp Initialization and Operation

Example 61-2 configures the module to operate as an Op Amp. Notice that the primary difference is that the CMPSEL bit has been cleared. The example is set as a voltage follower, which can be used to boost the current output of a low-strength signal. It can also better match loads (i.e., connecting a device with high source impedance to a device with low input impedance).

Refer to *AN682, "Using Single Supply Operational Amplifiers in Embedded Systems"* for more examples of applications of Op Amps for embedded systems.

Example 61-2: Op Amp Module Configuration Code

```
AMP1CONbits.AMPSIDL = 0;          //Continue operation in Idle mode
AMP1CONbits.AMPSLP = 0;           //Discontinue operation in Sleep mode
AMP1CONbits.CMPSEL = 0;           //Op Amp mode
AMP1CONbits.SPDSEL = 1;           //High power/high speed operation
AMP1CONbits.AMPOE = 1;
AMP1CONbits.NINSEL = 5;           //Input selection is device-specific; refer to the
AMP1CONbits.PINSEL = 5;           //family datasheet for specific options.
AMP1CONbits.AMPEN = 1;            //enabler amplifiter operation.
asm volatile("repeat #40");       //Delay 10us
Nop();
```

61.6.3 Input Offset Voltage Calculations

For high-precision applications, the user may want to calibrate for any possible input offset voltage in the Op Amp circuit. The input offset voltage is the difference in voltage between the positive and negative input terminals of the amplifier. The input offset voltage causes a small DC error at the output of the Op Amp. When the Op Amp output is sampled with the A/D, it is possible to measure the Op Amp offset voltage and use firmware to correct for the offset.

In order to find the offset bias voltage:

1. Configure a known input voltage.
2. Configure the A/D to select the input voltage for conversion (refer to **Section 51. 12-Bit A/D Converter with Threshold Detect** for information on configuring the A/D).
3. Store the output of the calculation, either in an A/D buffer that won't be overwritten, or at an appropriate location in memory.
4. Configure the Op Amp with the positive input as the selected voltage and the negative input as the output of the amplifier (voltage follower configuration).
5. Configure the A/D to select the output of the Op Amp for conversion.
6. Subtract the results of the second conversion from the results of the first conversion.

The result of the subtraction is the input offset. By using the Op Amp as a unity-gain buffer, the output should theoretically be identical to the input. If it is not, there is some offset between the amplifier inputs. This value will now allow the user to calculate out any error induced from this value or account for the offset in hardware.

61.6.4 Active Guarding

In capacitive touch applications, the Operational Amplifier can be implemented to increase noise immunity and improve robustness of the touch sense algorithm.

Capacitive touch applications operate by sensing the additional capacitance added to the circuit when a touch occurs. For a more complete explanation of how capacitive touch applications work, refer to *AN1250, "Microchip CTMU for Capacitive Touch Applications"* (DS01250).

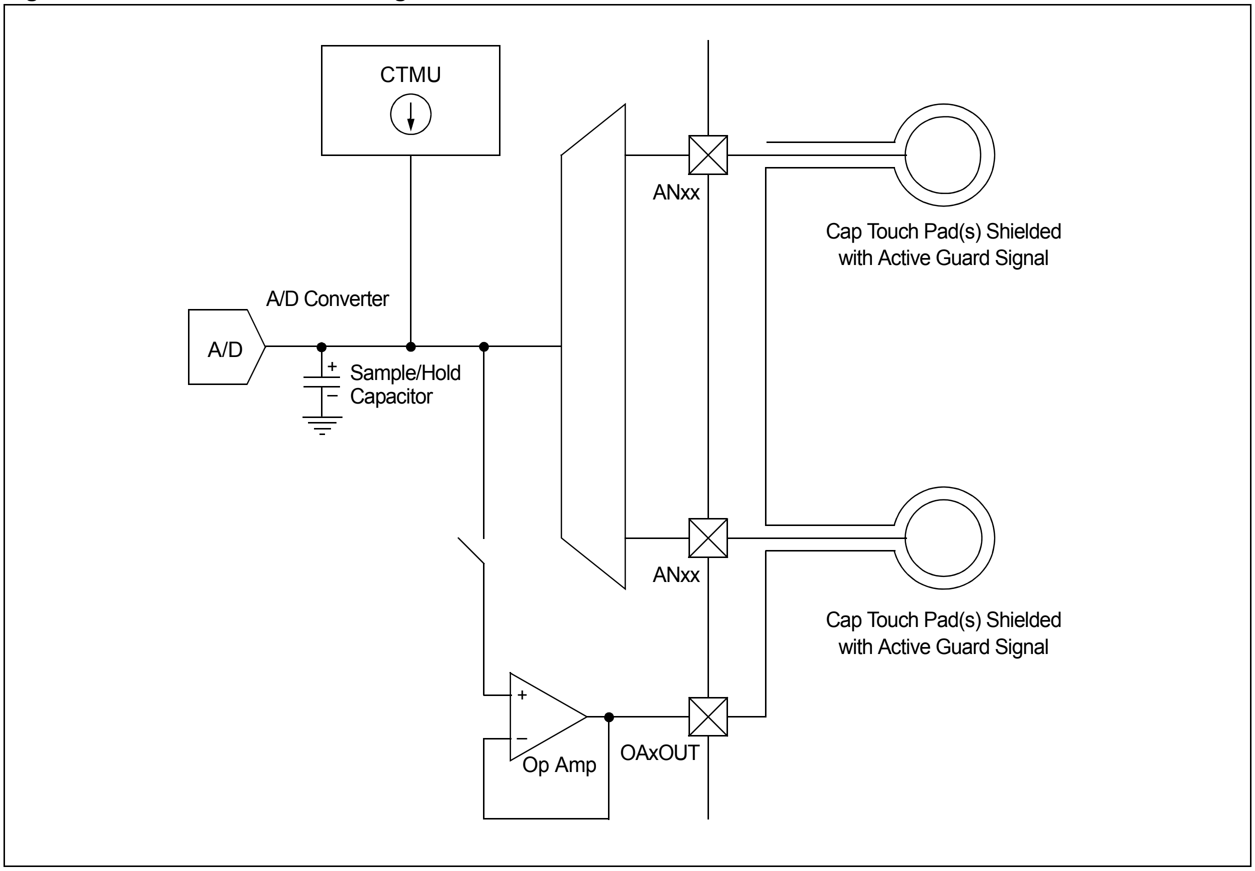
Noise is a prevalent concern in capacitive touch applications. In order to diminish the corruption of measurements by noise, the cap touch pad is shielded, leaving only the pad exposed. In a typical application, this shield is connected to the circuit ground, having the unintended consequence of increasing the capacitance of the pad. In a capacitive touch environment, the determination of when a touch occurs is made by evaluating the difference between the capacitance of the pad when it is touched versus untouched. Increasing the capacitance of the sensor implies that the change in capacitance, caused by a touch, will be proportionally smaller. This means that a touch will be harder to detect, and in an especially noisy environment, some touches may be missed entirely.

Active guarding provides a solution to missed touches. Instead of shielding the cap touch pads at ground potential, the shielding is connected to the output of the Operational Amplifier. The amplifier is configured as a unity-gain buffer, with the positive input connected to the A/D Sample-and-Hold (S/H) capacitor. In this configuration, the voltage of the shielding is the same as the voltage on the touch pad being sampled. This similarly protects the device from external noise, but setting the shielding and the pad at the same potential, significantly diminishes parasitic capacitance. In some situations, this can improve the sensitivity of the measurement by 75% to 80%.

To get the most benefit from active guarding, the shielding must surround the touch pads as completely as possible. In configuring the application, the Op Amp should be configured as a unity-gain buffer, with the positive input to the capacitor connected to the A/D Sample-and-Hold cap. Only one Op Amp needs to be employed for all the capacitive touch pads in the application.

Figure 61-3 provides a visual representation of this technique.

Figure 61-3: Active Guard Configuration



61.6.5 Signal Condition for A/D Conversion

The Operational Amplifier can be implemented to significantly improve the functionality of the Analog-to-Digital Converter. It can be used to allow for the conversion of higher impedance sources than are specified for the A/D. Using the Op Amp as a unity-gain buffer (in voltage follower configuration), the desired source can be selected as the positive input to the Op Amp. The input to the A/D will be the output of the Op Amp, which satisfies the loading conditions of the amplifier. The gating factor will now be the input impedance specification of the Op Amp, typically a few mega Ohms. Refer to your device data sheet for specific input characteristics.

The Op Amp can also be used to prevent aliasing of the input signal. Aliasing occurs when the frequency of the sampled signal is greater than the Nyquist frequency, or half the sampling rate of the A/D. This results in the sampled waveform being a corrupted copy of the input signal and it makes reconstructing the original signal impossible.

This can be avoided by using the Operational Amplifier to implement a low-pass filter. The filter can be implemented such that its cutoff frequency will attenuate frequencies above the Nyquist frequency, allowing for accurate sampling. Also, as a filter with an Op Amp is an active filter, gain can be applied to amplify the desired frequency range. The signal can be amplified to encompass the input range, increasing the Signal-to-Noise Ratio (SNR) and improving the accuracy of the samples.

Figure 61-4 shows a first-order low-pass filter. The DC gain is determined by:

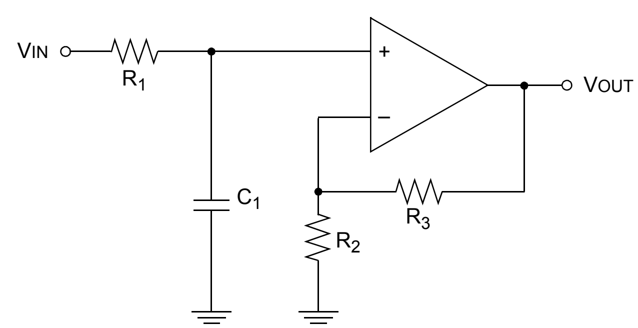
$$1 + \frac{R_3}{R_2}$$

and the cutoff frequency is calculated as (measured in Hertz):

$$\frac{1}{2\pi R_1 C_1}$$

This means that voltage amplitude at low frequencies (from 0 Hz approaching the cutoff frequency) is multiplied by the DC gain at the output. Unity DC gain can be achieved by connecting the Op Amp in a voltage follower configuration, omitting R2 and R3. At the cutoff frequency, the output has been attenuated by 3 dB. The output will continue to be attenuated as the frequency increases at a slope of 20 dB/decade.

Figure 61-4: Low-Pass Filter



The filter design can be modified to accommodate a sharper cutoff slope, the amount of ripple in the pass band or stop band and the settling time of the output waveform. Guidance for these design choices can be found in *AN699, "Anti-Aliasing, Analog Filters for Data Acquisition Systems"* (DS00699).

As an additional flexibility, the negative input can have up to seven external inputs (eight selections with one for the voltage follower), allowing the application to choose between different feedback networks as the application requires.

61.7 OPERATIONS DURING SLEEP AND IDLE MODES

61.7.1 Op Amp Operation During Sleep

When an Op Amp is active and the device is placed in Sleep mode, the Op Amp remains active, and the interrupt is functional, available and enabled. This interrupt will wake-up the device from Sleep mode, when enabled. Each enabled Op Amp will consume additional current, as shown in the electrical characteristics of the device-specific family.

To minimize power consumption while in Sleep mode, turn off all Op Amps/comparators by clearing the AMPEN bit (AMPxCON<15> = `0`) before entering Sleep. Alternatively, clearing the AMPSLP bit (AMPxCON<12> = `0`) will disable the device in Sleep mode. If AMPEN is set and AMPSLP is cleared, when the device wakes from Sleep, normal Op Amp operation will continue. The contents of AMPxCON are not affected when the device wakes up from Sleep. See **Section 10. Power-Saving Features** (DS39698) in the *"PIC24F Family Reference Manual"* for additional information on Sleep.

61.7.2 Comparator Operation During Idle

When an Op Amp is active and the device is placed in Idle mode, the Op Amp remains active and interrupts are generated, if enabled, and AMPSIDL = `0` (AMPxCON<13>). If it is desired for the Op Amp to discontinue operation in Idle mode, configure AMPSIDL = `1` (AMPxCON<13>). See **Section 10. Power-Saving Features** in the *"PIC24F Family Reference Manual"* for more information on Idle.

61.8 EFFECTS OF A RESET

A device Reset forces the AMPxCON register to its Reset state, causing the Op Amp module to be turned off (AMPEN = `0`). However, the input pins, multiplexed with analog input sources, are configured as analog inputs, by default, on device Reset. The I/O configuration for these pins is determined by the setting of the ADxPCFG or ANSx registers, depending on the device. Therefore, device current is minimized when analog inputs are present at Reset time.

61.9 RELATED APPLICATION NOTES

This section lists application notes that are related to this section of the manual. These application notes may not be written specifically for the PIC24F device family, but the concepts are pertinent and could be used with modification and possible limitations. The current application notes related to the programming and diagnostics are:

Title	Application Note #
Using Single Supply Operational Amplifiers in Embedded Systems	AN682
Anti-Aliasing, Analog Filters for Data Acquisition Systems	AN699
Operational Amplifier Topologies and DC Specifications	AN722
Amplifying High-Impedance Sensors – Photodiode Example	AN951
Microchip CTMU for Capacitive Touch Applications	AN1250

Note:	Please visit the Microchip web site (www.microchip.com) for additional application notes and code examples for the PIC24F family of devices.

61.10 REVISION HISTORY

Revision A (September 2012)

This is the initial released revision of this document.

NOTES:

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
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