

ECE 2049 LECTURE 13

OFFICE HRS

- TUES: SEE CALENDAR
- WED: 4-6PM (NICK)
- THU: 2-6PM (NICK)
- FRI: YES (TIME TBA)

ADMINISTRIVIA

- HW6: DUE TODAY BY 11:59PM EDT

- HW7: OUT WITH THIS VIDEO, DUE THURSDAY BY START OF CLASS

⇒ ACTUALLY A PRACTICE EXAM, YOU MUST DO 2 PROBLEMS FOR HW CREDIT

- LAB2: NOW DUE NEXT THU, 6/30 BY END OF OFFICE HOURS

IF YOU HAVE OTHER OUTSTANDING

LABS (LAB0, LAB1) YOU SHOULD CONTACT ME ASAP TO LET ME KNOW YOUR STATUS (IF YOU HAVE NOT DONE SO ALREADY)

I CAN BE FLEXIBLE, BUT YOU MUST ATTEMPT ALL REQUIRED LABS (LAB0, LAB1, LAB2) TO RECEIVE A PASSING GRADE!

- LAB3: EXTRA BONUS LAB, OUT NEXT WEEK, DUE BY WED, 7/5

ECE2049: Homework 6

Content: Lectures 11-12

Submission notes:

- For full credit, please show your work and denote your answers with a circle or a box.
- Always write and draw your diagrams neatly! We cannot be expected to GUESS what you meant to write! Some problems (such as those involving code) must be typed to be graded—the others may be handwritten (neatly!) or typed.
- Points for each problem are as indicated. Some problems are marked as “BONUS,” which count as extra credit.

1. (Lecture 12, 10 pts) An MSP430 is being used to monitor the temperature in an experimental chamber. The temperature sensor used in the chamber outputs a voltage that is linear across the temperature ranges used in the experiment, -60 to 90° C, based on the following formula:

$$V_{Temp} = 0.00475 * (Temp \text{ } ^\circ C) + 1.29V$$

- a. What are the output voltages (V_{Temp}) that correspond to the minimum and maximum temperatures?
- b. Assuming that you are using the MSP430's ADC12, which of the standard reference voltages (V_{CC} , 1.5V, or 2.5V) would you choose for the reference voltage V_{Ref+} to achieve the finest resolution? Explain your reasoning.
You can assume that $V_{Ref-} = 0V$.
- c. Assuming that you are using the reference voltages configured in part (b), what is the smallest change in *temperature* that you can measure?
- d. What is the output voltage of the sensor *and* the ADC code output if the temperature inside the chamber is 24.8° C?
- e. What is the temperature if the output code of the ADC is equal to the decimal value 2415?
- f. (BONUS, 3pts) Write a C function to convert an output code from the ADC for this sensor into temperature in degrees Celsius. Your function should take one argument (the ADC code), and return the temperature as a single-precision floating point value (ie, type `float`).

(continued on the next page)

ECE2049: Homework 6

4. (Lecture 11, 5 pts) **Using a global time count:** The program listed below is an incomplete main() for a system using a timer that triggers interrupts every 25ms. Complete the main() function such that the function do_thing() is called once every 500ms. You may declare additional variables as necessary, but your code must not change the value of time_count. Assume the timer configuration (not shown) is correct—there is no need to change it.

Hint: you do not need a lot of code for this, keep it simple!

```
volatile unsigned long time_count = 0;
```

```
// This ISR runs every 25ms  
#pragma vector=TIMER2_A0_VECTOR  
__interrupt void Timer_ISR(void) {  
    time_count++;  
}
```

```
void main(void)
```

```
{  
    UNSIGNED LONG LAST_UPDATE = 0  
    configure_everything();  
    start_25ms_timer();  
    _enable_interrupt();
```

```
while(1) {
```

```
    IF((TIME_COUNT - LAST_UPDATE) ≥ 20) {  
        do_thing();
```

```
        LAST_UPDATE = TIME_COUNT
```

```
    }
```

```
}
```

RUNS EVERY 25MS

1 COUNT EVERY 25MS

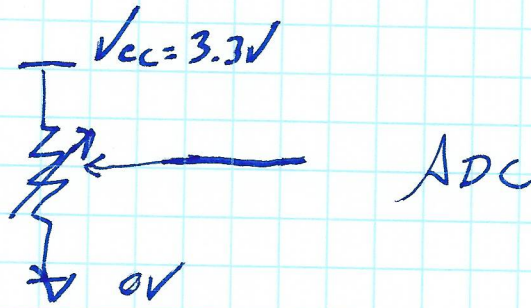
*RUN WHEN
DIFF ≥ 20
TICKS*

$$\frac{500\text{ms}}{25\text{ms TICK}} = 20 \text{ TICKS}$$

*SAVE TIME OF
LAST UPDATE.*

ADC EXAMPLE: POTENTIOMETER (VARIABLE RESISTOR)

04



WHAT DO WE NEED?

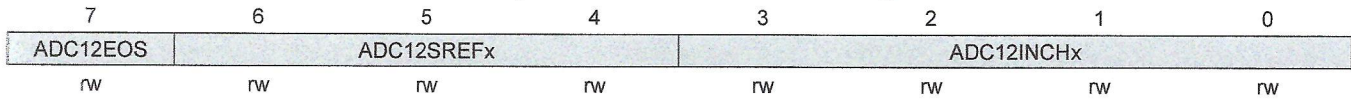
- REFERENCE VOLTAGES: 1.5V, 2.5V, 3.3V
- INPUT CHANNELS:
 - ANALOG INPUT ON MSP430
 - PICK A1 (PG.1) - SET FOR FUNCTION MODE.

THIS IS GOOD, BUT...

28.3.5 ADC12MCTLx Register

ADC12_A Conversion Memory Control Register

Figure 28-17. ADC12MCTLx Register



Can be modified only when ADC12ENC = 0

Table 28-8. ADC12MCTLx Register Description

Bit	Field	Type	Reset	Description
7	ADC12EOS	RW	0h	End of sequence. Indicates the last conversion in a sequence. 0b = Not end of sequence 1b = End of sequence
6-4	ADC12SREFx <i>SREF = 0</i>	RW	0h	Select reference $000b = V(R+) = AVCC$ and $V(R-) = AVSS$ $001b = V(R+) = VREF+$ and $V(R-) = AVSS$ $010b = V(R+) = VeREF+$ and $V(R-) = AVSS$ $011b = V(R+) = VeREF+$ and $V(R-) = AVSS$ $100b = V(R+) = AVCC$ and $V(R-) = VREF-/VeREF-$ $101b = V(R+) = VREF+$ and $V(R-) = VREF-/VeREF-$ $110b = V(R+) = VeREF+$ and $V(R-) = VREF-/VeREF-$ $111b = V(R+) = VeREF+$ and $V(R-) = VREF-/VeREF-$
3-0	ADC12INCHx <i>INCH = 1</i>	RW	0h	Input channel select $0000b = A0$ $0001b = A1$ $0010b = A2$ $0011b = A3$ $0100b = A4$ $0101b = A5$ $0110b = A6$ $0111b = A7$ $1000b = VeREF+$ $1001b = VREF-/VeREF-$ $1010b =$ Temperature diode $1011b = (AVCC - AVSS) / 2$ $1100b = A12$. On devices with the Battery Backup System, VBAT can be measured internally by the ADC. $1101b = A13$ $1110b = A14$ $1111b = A15$

Module 10. Operating Modes and More

Topics

- Revisiting interrupts
- Operating modes

ADC12 Interrupts

Our examples so far have used the ADC12SC bit to start conversions, and then we poll the ADC12BUSY bit to see when a conversion is complete:

```

LED_ON() ← DEMO: USE I/O PIN (LED) TO MEASURE TIME
ADC12CTL0 |= ADC12SC;           WE WANT FOR ADC

LED_OFF()
while (ADC12CTL1 & ADC12BUSY) {
  __no_operation();             // Could just leave body of loop empty
}
LED_ON()                         CONVERSION TAKES ≈ 200µs

in_value = ADC12MEM0 & 0x0FFF;

```

This is another form of *busy-waiting*, which is like `swDelay`:

- The CPU isn't doing any useful work—it's just sitting in a loop!
- While ADC conversions happen very quickly ($\ll 1$ ms), the CPU executes faster, so we do need to wait for a result

The main purpose of on-chip peripherals like the Timer and ADC is to remove burdens from or provide services to the CPU.

→ TIMERS, ADC, ETC OPERATE INDEPENDENTLY
FROM THE CPU!
 ↑
 (ASYNCHRONOUSLY)

IN THIS LECTURE WE
 WILL SEE WHY THIS IS IMPORTANT.

The solution to this is to use an **Interrupt**, an external signal sent by a peripheral requesting that the CPU do something. Interrupts are hard-wired into certain peripherals. Fortunately for us, the ADC12 can trigger interrupts.

On the ADC12, an interrupt can signal the end of a conversion, **meaning that it is ready for the CPU to read data from its memory registers.**

Here is an example configuration with two channels:

```

ADC12CTL0 = ADC12SHT0_9 | ADC12REFON | ADC12ON | ADC12MSC;
ADC12CTL1 = ADC12SHP | ADC12CONSEQ_1;

// Here, we are performing conversions for two channels
ADC12MCTL0 = ADC12SREF_0 + ADC12INCH_5;
ADC12MCTL1 = ADC12SREF_1 + ADC12INCH_6 + ADC12EOS;

// Because we are converting for two channels, we want the interrupt
// to occur after BOTH conversions are complete, so we enable the
// interrupt for MEM1.
ADC12IE = BIT1;
__enable_interrupt(); // Globally enable interrupts

ADC12CTL0 |= ADC12SC + ADC12ENC; // Enable ADC and start conversion

```

Handwritten notes: An arrow points from the comment above to the line `ADC12IE = BIT1;`. Another arrow points from the text "TRIGGER INT AFTER CH. 1" to the same line.

What should the ISR do? It's triggered when a conversion is finished, so it just needs to read the memory registers!

```

// Global variables for storing data
// (could also store into an array!)
volatile unsigned int in_value1, in_value2;

#pragma vector=ADC12_VECTOR
__interrupt void ADC12_ISR(void)
{
    // Move the results for both channels into global variables
    in_value1 = ADC12MEM0 & 0xFFFF;
    in_value2 = ADC12MEM1 & 0xFFFF;
}

```

Handwritten note: An arrow points from the text "CONVERSION IS DONE HERE" to the opening curly brace of the interrupt service routine.

“Scheduling” ADC measurements

It's also possible to have the ADC perform conversions automatically. An easier option is to trigger ADC conversions from a timer and use ADC interrupts to read the results.

```
// NOTE: this example assumes the timer and ADC have already been configured.

volatile unsigned int in_value1, in_value2;

// Timer A2 ISR
#pragma vector=TIMER2_A0_VECTOR
__interrupt void Timer_A2_ISR(void)
{
    timer++; // KEEP TIME AS USUAL

    ADC12CTL0 |= ADC12SC; ← START CONVERSION
}

// ADC 12 ISR
#pragma vector=ADC12_VECTOR
__interrupt void ADC12_ISR(void)
{
    in_value1 = ADC12MEM0 & 0x0FFF;
    // . . .
}

void main(void)
{
    setup_everything();
    _enable_interrupt();

    while(1){
        display_adc_values(in_value1, in_value2);
    }
}
```

Here, we now have two ISRs, one for the ADC, and one for the timer. Thus, our main program can simply use `in_value1` and `in_value2` without needing to explicitly start conversions.

↳ REMOVES SOME BURDEN FROM MAIN().

BUT CAN WE DO BETTER?

Polling versus Interrupts Revisited

So far most of our code has relied heavily on Polling.

-- We've been using Timer A2 as a time base, but our main functions are still does busy-waiting in some form of loop:

```
while (1)
{
  if (global_time_cnt > last_time)
  {
    take_ADC_meas();
    last_time = global_time_count;
  }
  button = checkButtons();
  . . .

  // Other task(s) can occur at different intervals
  if ((global_time_cnt % cnt_per_second) == 0)
  {
    toggleLED(LED2)
    displayHHMMSS(global_time_cnt);
  }
  . . .
}
```

TASK:
TASK: READ ADC

TASK:
UPDATE
DISPLAY

As an alternative, we can organize our code to *schedule* tasks to occur at specific “real” times, and even assign priorities to tasks.

--> We do this by implementing the Scheduler INSIDE Timer ISR!

```
// A simple task scheduler for the MSP430F5529
#pragma vector=TIMER2_A0_VECTOR
__interrupt void Timer_A2(void)
{
    // First priority: maintain time base
    global_time_cnt++;

    // Some of the app task(s) may execute every time slice
    take_ADC_meas();
    button = checkButtons();
    . . .

    // Other application task(s) at different intervals
    if ((global_time_cnt % cnt_per_second) == 0)
    {
        toggleLED(LED2)
        displayHHMMSS(global_time_cnt);
    }
    . . . . .
}
```

DIFFERENT TASKS "SCHEDULED" REGULARLY BY TIMER

THESE ~~ARE~~ TASKS ONLY RUN WHEN ISR FIRES. NO BUSY WAITING!

Here, main() would consist of initialization followed by an “empty” loop:

```
void main()
{
    WDTCTL = WDTPW + WDTHOLD; // Stop watchdog timer
    init_sys(); // Initialize the MSP430
    setupButton(); // configure buttons
    setupADC(); // configure ADC

    . . .

    _enable_interrupt(); // Global Interrupt enable
    runTimerA2(); // Start scheduler

    // An empty forever loop!
    // All application tasks are scheduled and dispatched
    // from within TimerA2 ISR
    while(1)
    {
        __no_operation();
    }
}
```

MAIN() DOES NOTHING!! ALL WORK HANDLED BY ISR.

GOAL: REPLACE THIS WITH SLEEP(). SAVE ENERGY!

What are we assuming by organizing or scheduling our application's tasks like this?

There some very important assumptions here:

- ISR MUST BE DONE BEFORE
NEXT X_{INT}

- ALL ~~TASKS~~ TASKS MUST BE DONE WITHIN ONE X_{INT} .

- CODE IN ISR MUST NOT "BLOCK" (WAIT)
FOR LONGER THAN X_{INT}

Remember the rule of interrupts!

- We can have multiple interrupt sources for different peripherals—we want to maintain this behavior when scheduling tasks.
- By default, interrupts are disabled inside an ISR. Therefore, one interrupt cannot normally interrupt another one, but we can change this behavior when we need it.

- CAN STILL HAVE MULTIPLE INTERRUPT
SOURCES

- NORMALLY CAN'T HAVE ONE INTERRUPT
INTERRUPT ANOTHER, BUT CAN CHANGE THIS.

- THIS CAN GET COMPLEX - CAN USE TO
IMPLEMENT MULTITASKING.

- WANT TO KNOW MORE? TRY ECE 3849

"REAL-TIME OS"

INTERRUPTS HAVE FIXED PRIORITIES AND MAY PRE-EMPT ONE ANOTHER.

Interrupt Priorities

Interrupt Vector Addresses

The interrupt vectors and the power-up start address are located in the address range 0FFFh to 0FF80h. The vector contains the 16-bit address of the appropriate interrupt-handler instruction sequence.

FIXED PRIORITIES

UNINTERRUPTIBLE

Table 4. Interrupt Sources, Flags, and Vectors

INTERRUPT SOURCE	INTERRUPT FLAG	SYSTEM INTERRUPT	WORD ADDRESS	PRIORITY
System Reset Power-Up External Reset Watchdog Timeout, Password Violation Flash Memory Password Violation	WDTIFG, KEYV (SYSRSTIV) ⁽¹⁾⁽²⁾	Reset	0FFFEh	63, highest
System NMI PMM Vacant Memory Access JTAG Mailbox	SVMLIFG, SVMHIFG, DLYLIFG, DLYHIFG, VLRIFG, VLRHIFG, VMAIFG, JMBNIFG, JMBOUTIFG (SYSSNIV) ⁽¹⁾	(Non)maskable	0FFFCh	62
User NMI NMI Oscillator Fault Flash Memory Access Violation	NMIIFG, OFIFG, ACCVIFG, BUSIFG (SYSUNIV) ⁽¹⁾⁽²⁾	(Non)maskable	0FFFAh	61
Comp_B	Comparator B interrupt flags (CBIV) ⁽¹⁾⁽³⁾	Maskable	0FFF8h	60
TB0	TB0CCR0 CCIFG0 ⁽³⁾	Maskable	0FFF6h	59
TB0	TB0CCR1 CCIFG1 to TB0CCR6 CCIFG6, TB0IFG (TB0IV) ⁽¹⁾⁽³⁾	Maskable	0FFF4h	58
Watchdog Timer_A Interval Timer Mode	WDTIFG	Maskable	0FFF2h	57
USCI_A0 Receive or Transmit	UCA0RXIFG, UCA0TXIFG (UCA0IV) ⁽¹⁾⁽³⁾	Maskable	0FFF0h	56
USCI_B0 Receive or Transmit	UCB0RXIFG, UCB0TXIFG (UCB0IV) ⁽¹⁾⁽³⁾	Maskable	0FFEEh	55
ADC12_A TA0	ADC12IFG0 to ADC12IFG15 (ADC12IV) ⁽¹⁾⁽³⁾⁽⁴⁾ TA0CCR0 CCIFG0 ⁽³⁾	Maskable	0FFEC h	54
TA0	TA0CCR1 CCIFG1 to TA0CCR4 CCIFG4, TA0IFG (TA0IV) ⁽¹⁾⁽³⁾	Maskable	0FFE8h	52
USB_UBM	USB interrupts (USBIV) ⁽¹⁾⁽³⁾	Maskable	0FFE6h	51
DMA TA1	DMA0IFG, DMA1IFG, DMA2IFG (DMAIV) ⁽¹⁾⁽³⁾ TA1CCR0 CCIFG0 ⁽³⁾	Maskable	0FFE4h	50
TA1	TA1CCR1 CCIFG1 to TA1CCR2 CCIFG2, TA1IFG (TA1IV) ⁽¹⁾⁽³⁾	Maskable	0FFE2h	49
I/O Port P1	P1IFG.0 to P1IFG.7 (P1IV) ⁽¹⁾⁽³⁾	Maskable	0FFDEh	47
USCI_A1 Receive or Transmit	UCA1RXIFG, UCA1TXIFG (UCA1IV) ⁽¹⁾⁽³⁾	Maskable	0FFDC h	46
USCI_B1 Receive or Transmit TA2	UCB1RXIFG, UCB1TXIFG (UCB1IV) ⁽¹⁾⁽³⁾ TA2CCR0 CCIFG0 ⁽³⁾	Maskable	0FFDAh	45
TA2	TA2CCR1 CCIFG1 to TA2CCR2 CCIFG2, TA2IFG (TA2IV) ⁽¹⁾⁽³⁾	Maskable	0FFD8h	44
I/O Port P2	P2IFG.0 to P2IFG.7 (P2IV) ⁽¹⁾⁽³⁾	Maskable	0FFD6h	43
RTC_A	RTCRDYIFG, RTCTEVIFG, RTCAIFG, RT0PSIFG, RT1PSIFG (RTCIV) ⁽¹⁾⁽³⁾	Maskable	0FFD4h	42
Reserved	Reserved ⁽⁵⁾		0FFD0h	40
			⋮	⋮
			0FF80h	0, lowest

HIGHER PRIORITY

AVE 12

TIMER A2

(1) Multiple source flags
 (2) A reset is generated if the CPU tries to fetch instructions from within peripheral space or vacant memory space.
 (Non)maskable: the individual interrupt-enable bit can disable an interrupt event, but the general-interrupt enable cannot disable it.
 (3) Interrupt flags are located in the module.
 (4) Only on devices with ADC, otherwise reserved.
 (5) Reserved interrupt vectors at addresses are not used in this device and can be used for regular program code if necessary. To maintain compatibility with other devices, it is recommended to reserve these locations.

Operating Modes

What's the advantage of scheduling tasks?

>>Our CPU doesn't need to be running all the time!!

This means we can use the MSP430's operating modes to save energy when not performing tasks.

The MSP430F5529 has 6 Operating Modes:

WE ARE HERE!

Active Mode => "Normally Active" = CPU is active, all enabled clocks are active

Low Power Mode 0 => CPU, MCLK are disabled, SMCLK, ACLK are active

MORE FUNCTIONS DISABLED

↳ LPM0

Low Power Mode 1 => CPU, MCLK, DCO osc. are disabled, DC generator is disabled if the DCO is not used for MCLK or SMCLK in active mode, SMCLK, ACLK are active

POWER USAGE DECREASES

Low Power Mode 2 => CPU, MCLK, SMCLK, DCO osc. are disabled, DC generator remains enabled, ACLK is active

WAKE TIME INCREASES

Low Power Mode 3 => CPU, MCLK, SMCLK, DCO osc. are disabled, DC generator disabled, ACLK is active

Low Power Mode 4 => CPU and all clocks disabled (RAM retention mode)

Low Power Mode 4.5 => CPU and all clocks disabled (no RAM retention), PWR management off, Digital IO pin configuration retained

LPM4.5

RAM RETENTION: RAM IS VOLATILE, SO CAN POWER OFF RAM, BUT WILL LOSE ALL DATA STORED THERE. SHOULD !!

Operating Mode Basics

AAA BATTERY IS RATED
W/ CAPACITY OF 1100mA·h

>> Most embedded systems run on batteries

-- Enter Low Power Mode to conserve batteries

ACTIVE MODE: @ 1MHz, 3V

I_{AM, TYPICAL} = 0.36mA

$$\frac{1100 \text{ mA}\cdot\text{h}}{0.36 \text{ mA}} = 3055 \text{ Hours}$$

≈ 127 DAYS

On MSP430F5529 Low Power Modes are indicated/selected thru the CPUOFF, OSCOFF, SCG0, and SCG1 bits in the Status Register (SR)

WHAT IF WE GO TO LPM3 FOR 50% OF THE TIME?

Mode	SCG1	SCG0	OSCOFF	CPUOFF
Active	0	0	0	0
LPM0	0	0	0	1
LPM1	0	1	0	1
LPM2	1	0	0	1
LPM3	1	1	0	1
LPM4	1	1	1	1
LPM4.5	1	1	1	1

*PMMREGOFF bit = 1, as well

I_{TYP, LPM3} = 2.1µA

$$(0.5)(0.36 \text{ mA}) + (0.5)(2.1 \mu\text{A})$$

AVG = 181µA AVG

$$\frac{1100 \text{ mA}\cdot\text{h}}{181 \mu\text{A}} = 6058 \text{ HOURS}$$

≈ 253 DAYS!

Status Register Layout:

Reserved	SCG1	SCG0	OSCOFF	CPUOFF	GIE	N	Z	C
----------	------	------	--------	--------	-----	---	---	---

ALMOST DOUBLED BATTERY LIFE!

How do you enter a Low Power Mode?

Can set with the `_BIS_SR()` function:

Ex: `_BIS_SR(LPM3_bits); // set bits to enter LPM3`

`_BIS_SR(LPM3_bits|GIE); // set bits to enter LPM3
// and enable interrupts`

SET BITS IN STATUS REGISTER

When to enter LPM and how do you exit?

- > Ideally want to enter LPM whenever not executing tasks
- > This is made simple if program is organized as a "Scheduler"

↳ EVENT DRIVEN PROGRAMMING.

- > Enter LPM after starting timer in main()

```
// A simple task scheduler for the MSP430F5529
#pragma vector=TIMER2_A0_VECTOR
__interrupt void Timer_A2(void)
{
    // First priority = maintain the time base
    global_time_cnt++;

    // Some app task(s) may execute every time slice
    take_ADC_meas();
    button =checkButtons();
    . . .

    // Other application task(s) execute less frequently
    if ((global_time_cnt % cnt_per_second) == 0)
        displayHHMMSS();
    . . . .
}
```

How do you exit LPM if CPU is OFF?

>> INTERRUPTS!

When an interrupt is received from a certain source, the CPU automatically does the following:

1. Finishes its current (assembly) instruction
2. Saves Status Register (SR) and Program Counter (PC) to stack
3. Clears Status Register (set to 0) ← GOES INTO ACTIVE MODE!
4. Loads address of ISR that was triggered from Interrupt Vector Table (IVT), loads it into PC
5. Execution continues in ISR
6. ← WHEN ISR IS DONE, PREVIOUS PC, SR ARE RESTORED

Returning from an ISR restores the Status Register to its previous values meaning that your program will automatically return to Low Power Mode when exiting the ISR!

POP MONOMALLY: $V_{CC} = 3V, 1MHz, 25^{\circ}C$



MSP430F5529, MSP430F5528, MSP430F5527, MSP430F5526
 MSP430F5525, MSP430F5524, MSP430F5522, MSP430F5521
 MSP430F5519, MSP430F5517, MSP430F5515, MSP430F5514, MSP430F5513

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Low-Power Mode Supply Currents (Into V_{CC}) Excluding External Current

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)^{(1) (2)}

PARAMETER	V_{CC}	PMMCOREV _x	-40°C		25°C		60°C		85°C		UNIT
			TYP	MAX	TYP	MAX	TYP	MAX	TYP	MAX	
$I_{LPM0,1MHz}$ Low-power mode 0 ⁽³⁾⁽⁴⁾	2.2 V	0	73		77	85	80		85	97	μA
	3.0 V	3	79		83	92	88		95	105	
I_{LPM2} Low-power mode 2 ⁽⁵⁾⁽⁴⁾	2.2 V	0	6.5		6.5	12	10		11	17	μA
	3.0 V	3	7.0		7.0	13	11		12	18	
$I_{LPM3,XT1LF}$ Low-power mode 3, crystal mode ⁽⁶⁾⁽⁴⁾	2.2 V	0	1.60		1.90		2.6		5.6		μA
		1	1.65		2.00		2.7		5.9		
		2	1.75		2.15		2.9		6.1		
	3.0 V	0	1.8		2.1	2.9	2.8		5.8	8.3	
		1	1.9		2.3		2.9		6.1		
		2	2.0		2.4		3.0		6.3		
$I_{LPM3,VLO}$ Low-power mode 3, VLO mode ⁽⁷⁾⁽⁴⁾	3.0 V	0	1.1		1.4	2.7	1.9		4.9	7.4	μA
		1	1.1		1.4		2.0		5.2		
		2	1.2		1.5		2.1		5.3		
		3	1.3		1.6	3.0	2.2		5.4	8.5	
I_{LPM4} Low-power mode 4 ⁽⁸⁾⁽⁴⁾	3.0 V	0	0.9		1.1	1.5	1.8		4.8	7.3	μA
		1	1.1		1.2		2.0		5.1		
		2	1.2		1.2		2.1		5.2		
		3	1.3		1.3	1.6	2.2		5.3	8.1	
$I_{LPM4.5}$ Low-power mode 4.5 ⁽⁹⁾	3.0 V		0.15		0.18	0.35	0.26		0.5	1.0	μA

Electrical Characteristics

Active Mode Supply Current Into V_{CC} Excluding External Current

over recommended operating free-air temperature (unless otherwise noted)^{(1) (2) (3)}

PARAMETER	EXECUTION MEMORY	V_{CC}	PMMCOREV _x	FREQUENCY ($f_{DCO} = f_{MCLK} = f_{SMCLK}$)					UNIT					
				1 MHz		8 MHz		12 MHz		20 MHz		25 MHz		
				TYP	MAX	TYP	MAX	TYP	MAX	TYP	MAX	TYP	MAX	
$I_{AM, Flash}$	Flash	3.0 V	0	0.36	0.47	2.32	2.60							mA
			1	0.40		2.65		4.0	4.4					
			2	0.44		2.90		4.3		7.1	7.7			
			3	0.46		3.10		4.6		7.6		10.1	11.0	
$I_{AM, RAM}$	RAM	3.0 V	0	0.20	0.24	1.20	1.30							mA
			1	0.22		1.35		2.0	2.2					
			2	0.24		1.50		2.2		3.7	4.2			
			3	0.26		1.60		2.4		3.9		5.3	6.2	

- (1) All inputs are tied to 0 V or to V_{CC} . Outputs do not source or sink any current.
- (2) The currents are characterized with a Micro Crystal MS1V-T1K crystal with a load capacitance of 12.5 pF. The internal and external load capacitance are chosen to closely match the required 12.5 pF.
- (3) Characterized with program executing typical data processing. USB disabled ($V_{USBEN} = 0, SLDOEN = 0$), $f_{ACLK} = 32786$ Hz, $f_{DCO} = f_{MCLK} = f_{SMCLK}$ at specified frequency. $XTS = CPUOFF = SCG0 = SCG1 = OSCOFF = SMCLKOFF = 0$.

```

void main(void)
{
    WDTCTL = WDTPW | WDTHOLD;

    init_sys();    // initialize system
    _BIS_SR(GIE);

    . . .

    runtimerA2(); // task scheduler runs in Timer A2 ISR

    . . .
    _BIS_SR(LPM0_bits|GIE); // Enter low power mode
    // Arrival of timer interrupt will cause MSP430 to exit low
    // power mode and enable it to execute all tasks within the
    // Timer A2 ISR

    while(1) {
        // Main program loop does nothing!
    }
}

```

Which LPM you enter depends on which clocks you are using for your scheduling Timer.

-- Also, on how quickly you need other clocks

- DEPENDING ON MODE, CLOCKS WILL
BE DISABLED

~~IN~~ - LPM2-LPM4.5 - SMCLK IS OFF

SO COULD STOP TIMER, IF
USING SMCLK.

IN LPM4, ALL CLOCKS ARE OFF,
BUT YOU CAN WAKE UP W/ AN I/O
EVENT (LIKE A BUTTON)!

>> Low Power Modes are great in practice, but can make debugging painful!

-- It's simple so add it last when debugging is complete

-- Then test to see if '430 is waking and executing tasks properly

Computing Power Usage: Example

An MSP430F5529 is being powered by a Duracell 2/3A LiMnO₂ battery, which has a nominal voltage of 3V and a listed capacity of 1550 mAh.

The MSP430F5529 is running an application that is in Active Mode for 5.6 % of the time, in LPM1 for ~~16.7%~~ of the time, and in LPM4 for the rest of the time.

How long can the application run using this battery?

ASSUME 1MHz clock, 25°C, TYPICAL VALUES

1. STATE ASSUMPTIONS

ACTIVE MODE 5.6% $I_{AM} = 0.36 \mu A$

LPM4 1-5.6% $I_{LPM4} = 1.1 \mu A$

2. FIND AVERAGE CURRENT

$$I_{AVG} = (0.056)(0.36 \mu A) + (1 - 0.056)(1.1 \mu A)$$

$$I_{AVG} = 21.198 \mu A$$

DANGER: MIXED UNITS.

3. FIND TIME.

$$\frac{1550 \text{ mA}\cdot\text{h}}{21.198 \mu A} = 73118 \text{ HOURS}$$

$$\approx 3046 \text{ DAYS}$$

$$\approx \boxed{8 \text{ YEARS}}$$

!!
0

2. (10 pts) **An old exam problem on ADCs:** The TI ADS8331 is an IC that provides a 16-bit, low-power sigma-delta ADC. It is being used inside a data recorder to collect data at 250ksps and is powered by a single 1.8V power supply. Answer the questions below about the ADS8331 in this configuration assuming that $V_{CC}=1.8V$ and that it uses an external reference voltage $V_{REF+} = V_{CC}$ and $V_{REF-} = 0V$.
- What is the full-scale range of this ADS8331?
 - What is the resolution of this ADS8331?
 - In this configuration, what was the input voltage to the ADS8331 if the output code is 0x8021?
 - What would the output of the ADS8331 be (in decimal) for an input voltage of 0.87V?

3. (5 pts) Please complete the mid-term course survey, which is available on Canvas in the "Quizzes" section. Your feedback is much appreciated, and will help improve my teaching as well as plan lectures and assignments for the remainder of term. Your responses to the survey are anonymous.

ADC PROBLEM EXAMPLE

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$$- 16 \text{ BIT, } V_{CC} = 1.8 \text{ V}$$

$$V_{REF+} = V_{CC} \quad V_{REF-} = 0 \text{ V}$$

a. FSR?

$$FSR = V_{REF+} - V_{REF-} = 1.8 \text{ V} - 0 \text{ V} = \boxed{1.8 \text{ V}}$$

b. Resolution = $\frac{FSR}{2^k} = \frac{1.8 \text{ V}}{2^{16}} = \boxed{27.466 \text{ } \mu\text{V}/\text{BIT}}$

c. Code = 048021 \Rightarrow 32801

$$\text{Code} = \text{FLOOR} \left(\left(\frac{V_{IN} - V_{REF-}}{V_{REF+} - V_{REF-}} \right) (2^k - 1) \right)$$

$$32801 = \frac{V_{IN}}{1.8 \text{ V}} (2^{16} - 1)$$

$$V_{IN} = 900.92 \text{ mV}$$

d. OUTPUT FOR 0.87 V

$$\text{Code} = \left\lfloor \frac{0.87 \text{ V} - 0 \text{ V}}{1.8 \text{ V} - 0 \text{ V}} (2^{16} - 1) \right\rfloor$$

$$= \lfloor 31675.25 \rfloor$$

$$= \boxed{31675} \leftarrow \text{CODE MUST BE AN INTEGER!}$$