MSP430 Advanced Technical Conference 2006

Designing for Ultra-Low Power with MSP430

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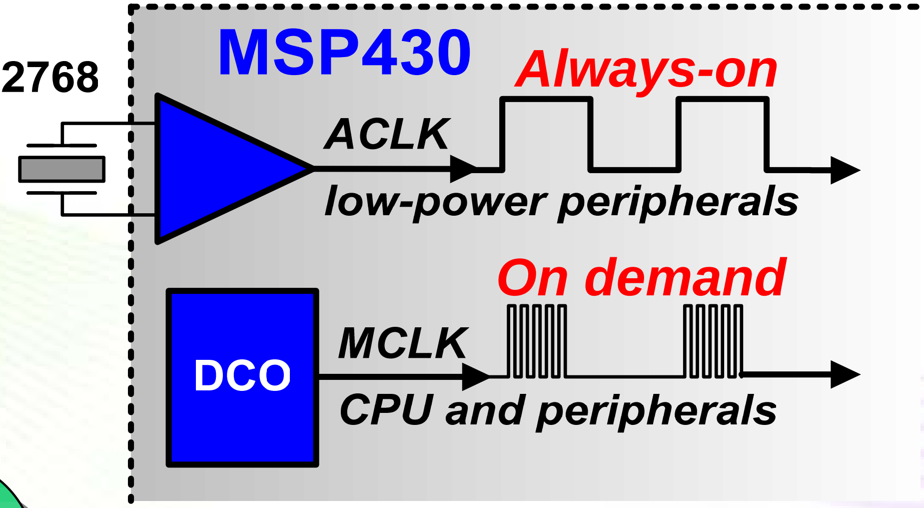
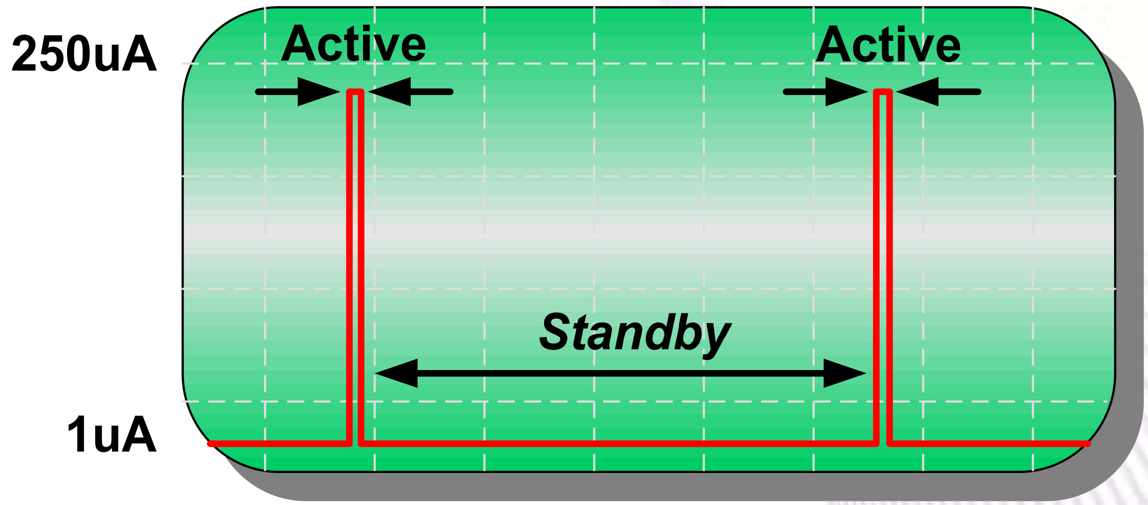
Agenda

- Introduction to Ultra-Low Power
- Looking for Ultra-Low Power Parts
- MSP430 – The Ultra-Low Power MCU
- Low-Power Efficient Coding Techniques
- Summary

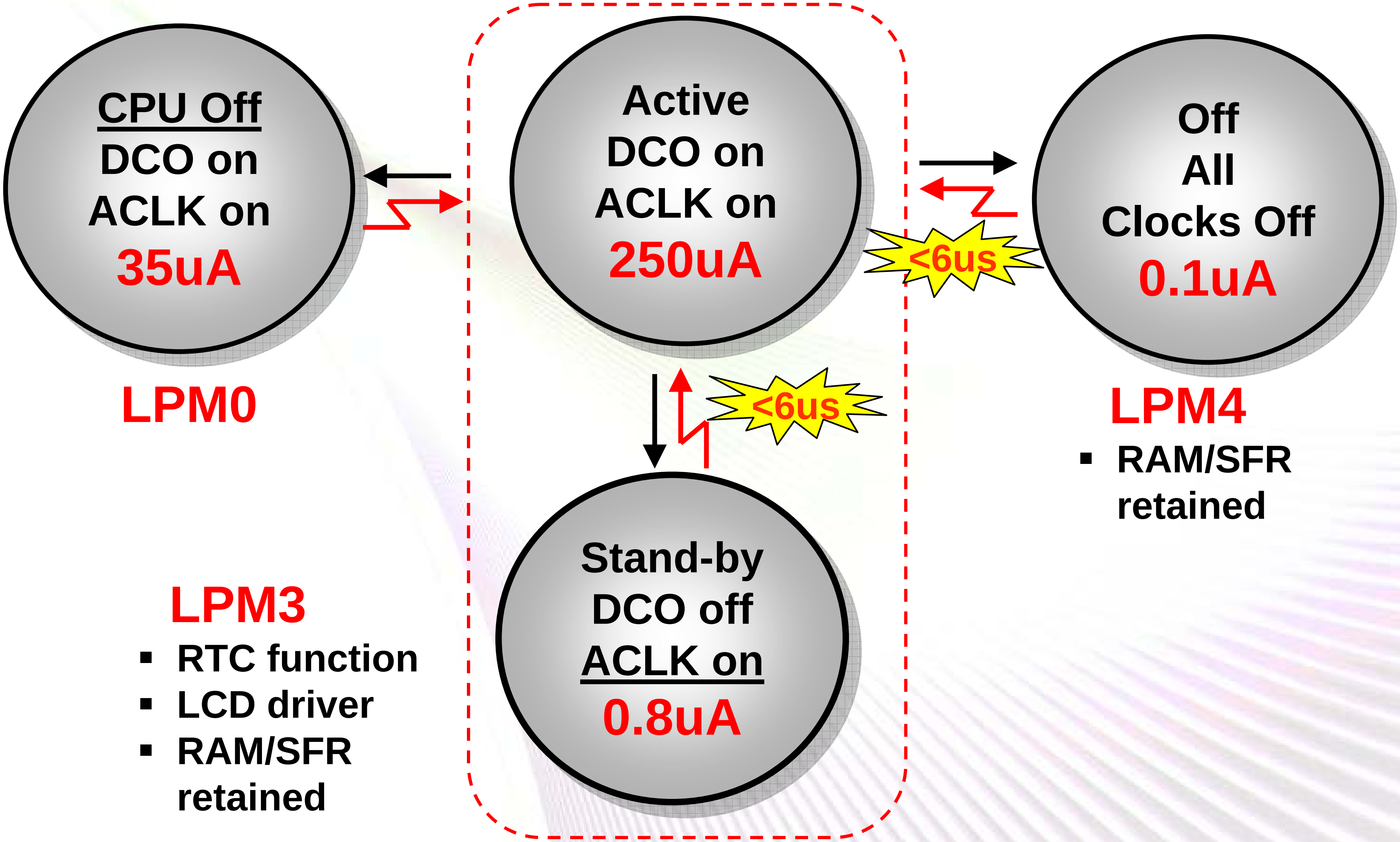
Achieving *Ultra-low Power*

- **Extended Ultra-low Power standby mode**
- **Minimum active duty cycle**
- **Performance on-demand**





Ultra-low Power Clock Control



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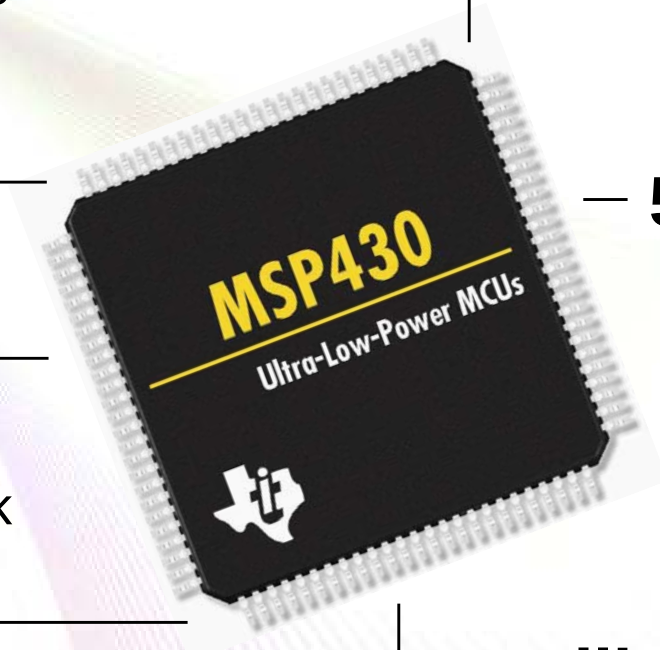
Ultra-Low Power Architecture

Multiple operating modes

- 0.1uA power down
- 0.7uA standby mode
- 250uA / 1MIPS

Zero-power BOR



50nA pin leakage

Modern CPU

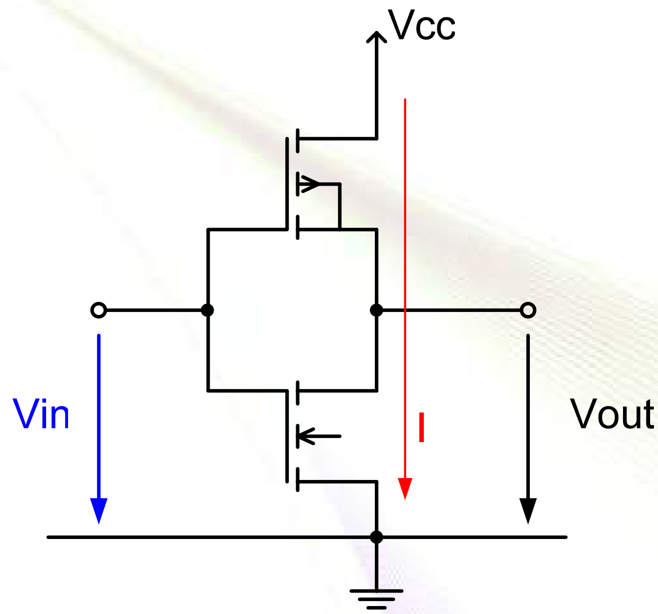
Minimum cycles per task

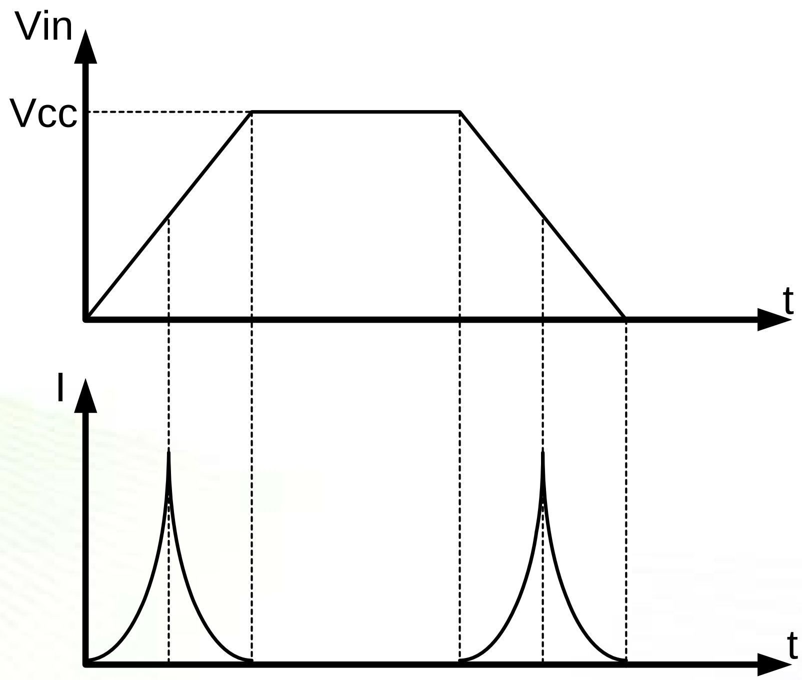
Intelligent peripherals

Instant-on stable high-speed clock

Power Consumption in CMOS Designs

- **CMOS Inverter:**





- **Power Consumption of a CMOS Inverter:**

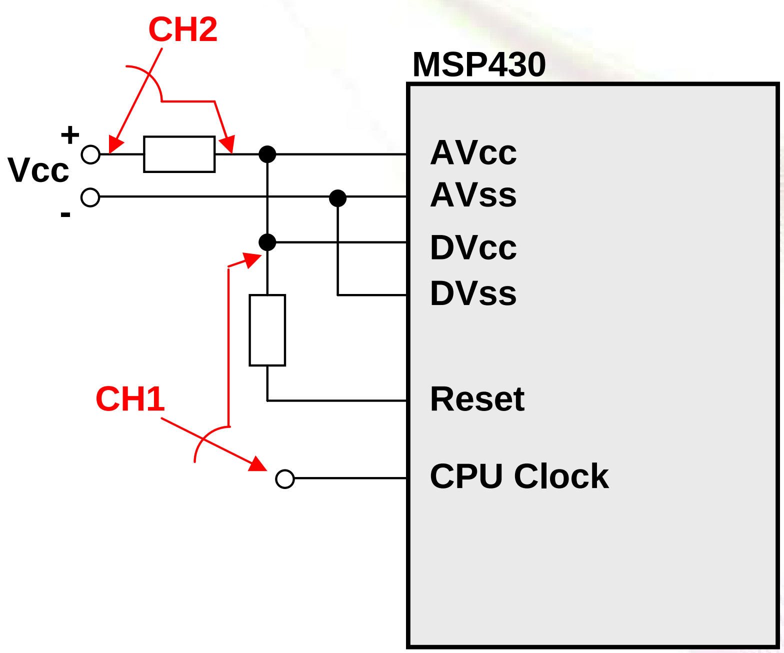
$$P = P_{stat} + P_Q + P_{dyn}$$

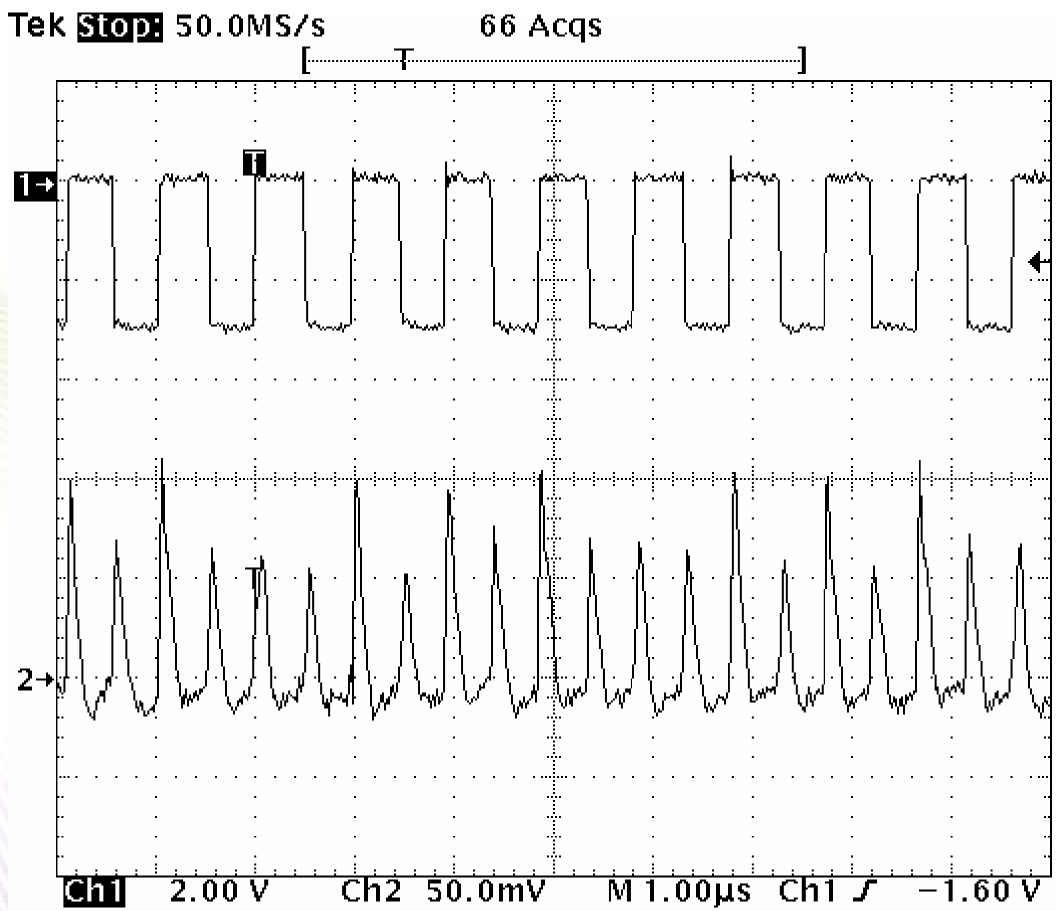
$$P_{stat} = Vcc * I_{LL}$$

$$P_Q = \beta / 12 * (Vcc - 2*U_{Tn})^3 * \tau / T$$

$$P_{dyn} = C_L * f * Vcc^2$$

MCU's Digital Supply Current





MSP430 Active Mode Supply Current

- **MSP430F2131 data sheet [slas439a]:**

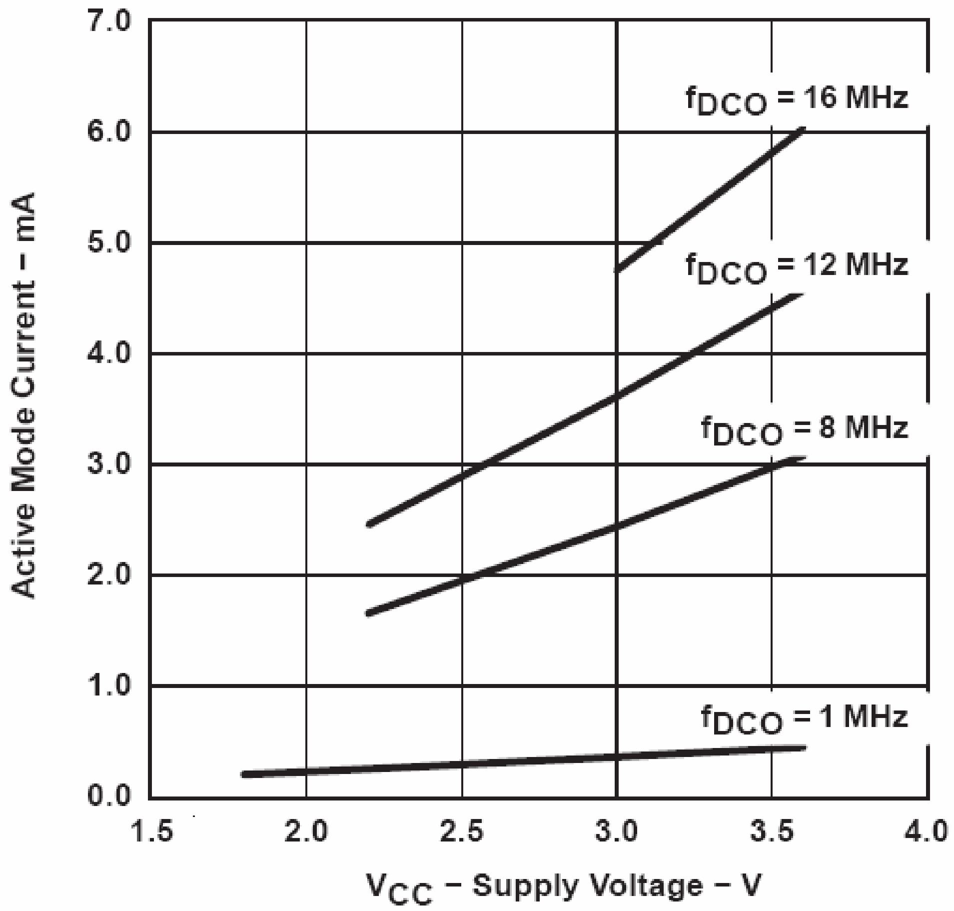


Figure 2. Active mode current vs V_{CC}, $T_A = 25°C$

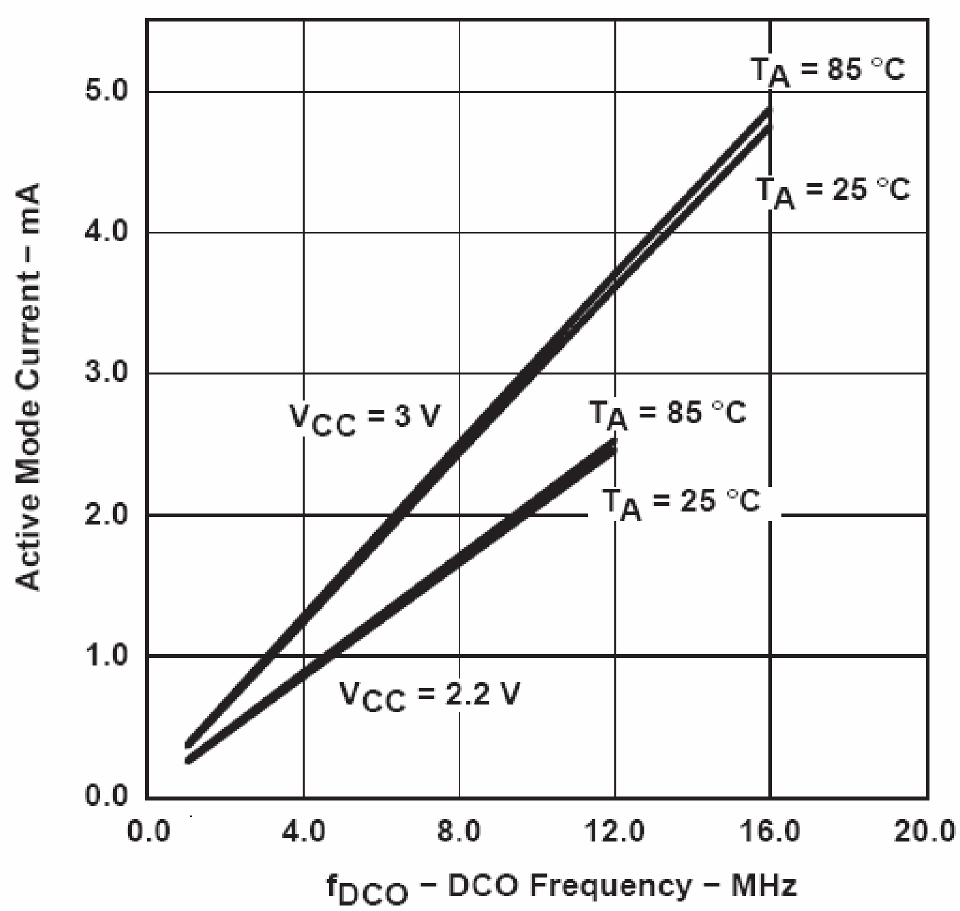


Figure 3. Active mode current vs DCO frequency

Device, Voltage, Temperature & Clock

MSP430F16x LPM3

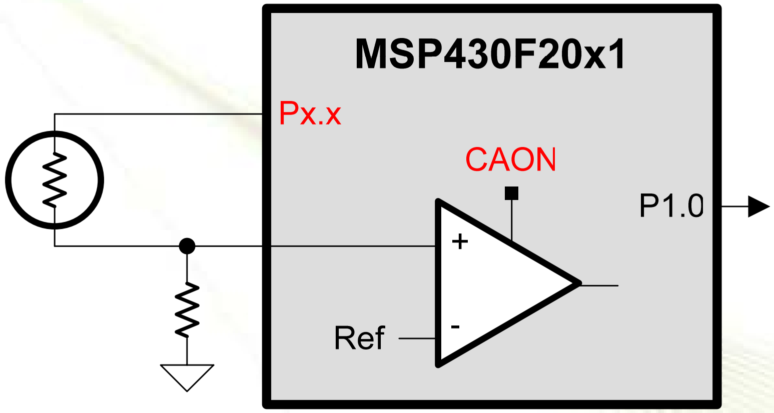
T_A = −40°C	V_{CC} = 2.2 V	1.1	1.6	µA
T_A = 25°C		1.1	1.6	
T_A = 85°C		2.2	3.0	
T_A = −40°C	V_{CC} = 3 V	2.2	2.8	
T_A = 25°C		2.0	2.6	
T_A = 85°C		3.0	4.3	

MSP430F20xx LPM3

LFXT1	T_A = −40°C	2.2 V	0.7	1.2	µA
	T_A = 25°C		0.7	1.0	
	T_A = 85°C		1.4	2.3	
	T_A = −40°C	3 V	0.9	1.2	
	T_A = 25°C		0.9	1.2	
	T_A = 85°C		1.6	2.8	
VLO	T_A = −40°C	2.2 V	0.4	0.7	µA
	T_A = 25°C		0.5	0.7	
	T_A = 85°C		1.0	1.6	
	T_A = −40°C	3 V	0.5	0.9	µA
	T_A = 25°C		0.6	0.9	
	T_A = 85°C		1.3	1.8	

- **Die size and # pins**
- **Family architectures and clock system**

Power Manage Internal Peripherals



Comparator_A

VCC	MIN	TYP	MAX	UNIT
2.2 V		25	40	µA
3 V		45	60	

```
P1OUT |= 0x02;                              // Power divider
CACTL1 = CARSEL + CAREF_2 + CAON;  // Comp_A on
if (CAOUT & CACTL2)
 P1OUT |= 0x01;                             // Fault
else
  P1OUT &= ~0x01;
P1OUT &= ~0x02;                             // de-power divider
CACTL1 = 0;                                 // Disable Comp_A
```

Integrated Analog Power Managing

ADC10

I_{ADC10}	Operating supply current into V_{CC} terminal (see Note 3)	$f_{ADC10CLK}$ = 5.0 MHz ADC10ON = 1, REFON = 0 ADC10SHT0=1, ADC10SHT1=0, ADC10DIV=0	V_{CC} = 2.2 V		0.52	1.05	mA
			V_{CC} = 3 V		0.6	1.2	
I_{REF+}	Reference operating supply current, reference buffer disabled (see Note 4)	$f_{ADC10CLK}$ = 5.0 MHz ADC10ON = 0, REFON = 1, REF2_5V = x; REFOUT = 0	V_{CC} = 2.2V/3 V		0.25	0.4	mA

DAC12

DAC12AMPx=2, DAC12IR=1, DAC12_xDAT=0800h , $V_{eREF+}=V_{REF+}= AV_{CC}$	2.2V/3V		50	110	µA
DAC12AMPx=5, DAC12IR=1, DAC12_xDAT=0800h, $V_{eREF+}=V_{REF+}= AV_{CC}$	2.2V/3V		200	440	
DAC12AMPx=7, DAC12IR=1, DAC12_xDAT=0800h, $V_{eREF+}=V_{REF+}= AV_{CC}$	2.2V/3V		700	1500	

OA

Fast Mode, RRIP OFF	2.2 V/3 V	180	290	
Medium Mode, RRIP OFF	2.2 V/3 V	110	190	
Slow Mode, RRIP OFF	2.2 V/3 V	50	80	µA
Fast Mode, RRIP ON	2.2 V/3 V	300	490	
Medium Mode, RRIP ON	2.2 V/3 V	190	350	
Slow Mode, RRIP ON	2.2 V/3 V	90	190	

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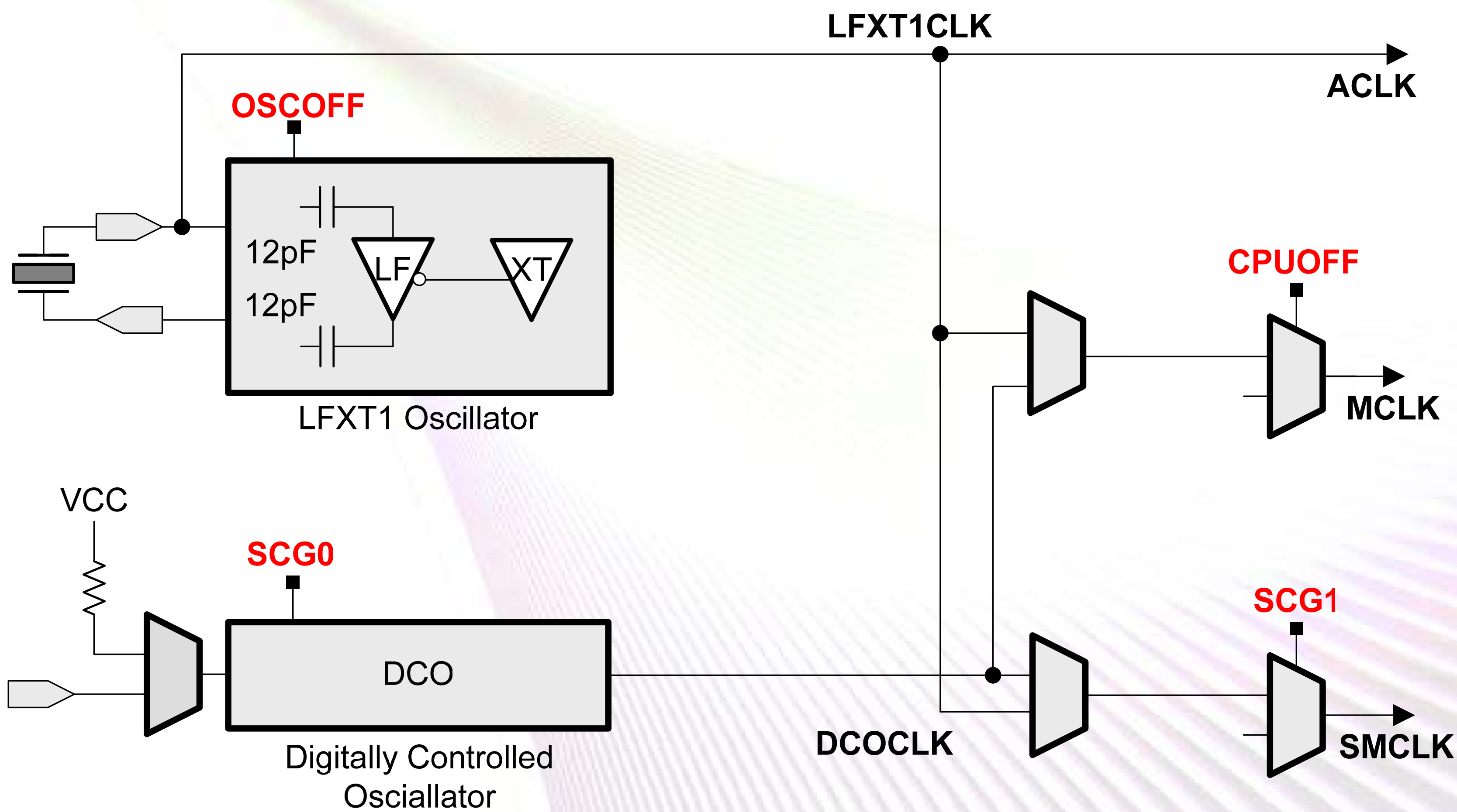
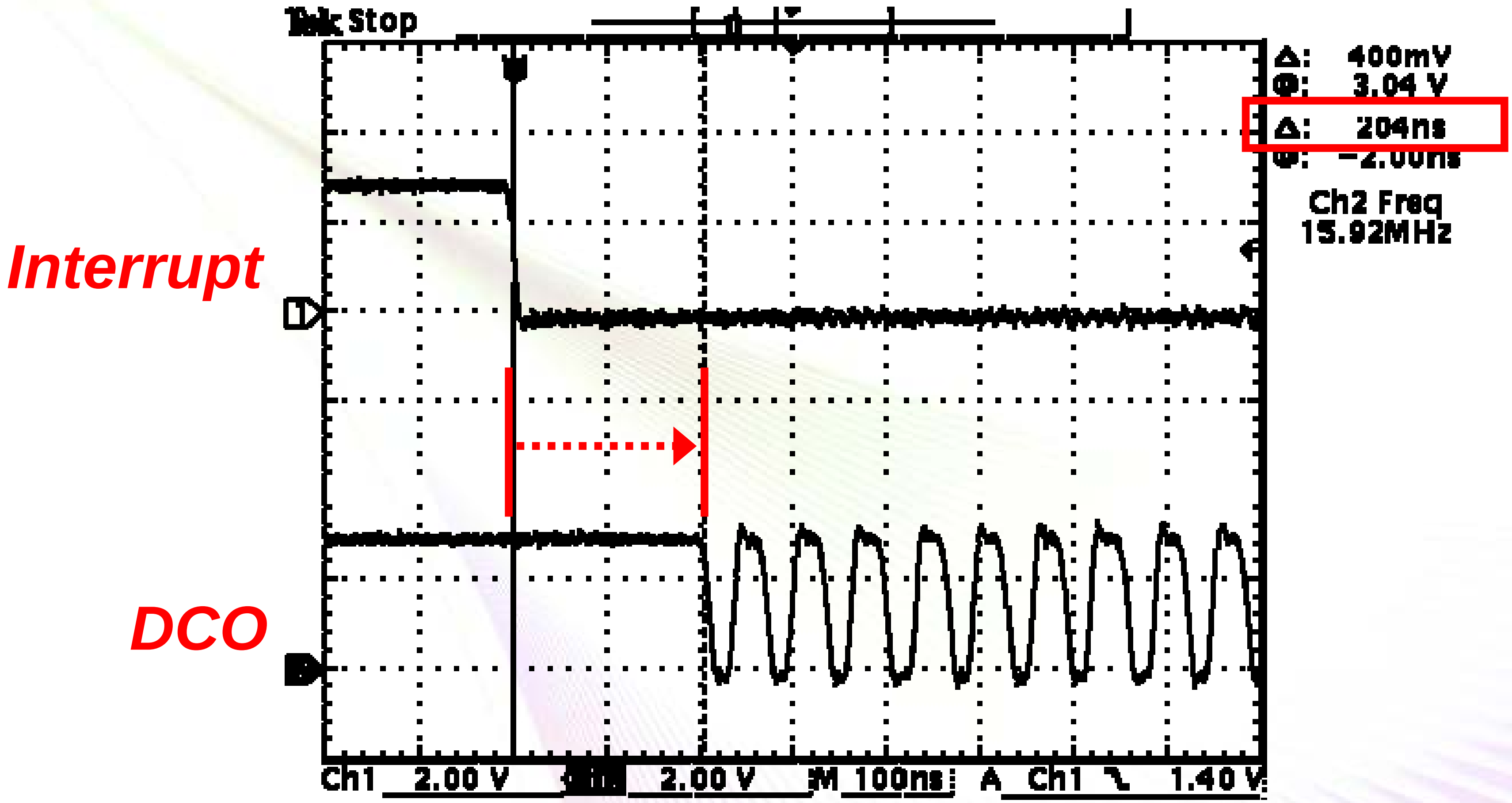
MSP430x11x/12x Basic Clock

R2/SR:	Reserved	V	SCG1	SCG0	OSC OFF	CPU OFF	GIE	N	Z	C



Performance on Demand



- **Immediate-stable clock start for reaction to events**

Low Power Mode Configuration

R2/SR:

Reserved	V	SCG1	SCG0	OSC OFF	CPU OFF	GIE	N	Z	C

	SCG1	SCG0	OSC OFF	CPU OFF	
Active Mode	0	0	0	0	~ 250uA
LPM0	0	0	0	1	~ 35uA
LPM3	1	1	0	1	~ 0.8uA
LPM4	1	1	1	1	~ 0.1uA

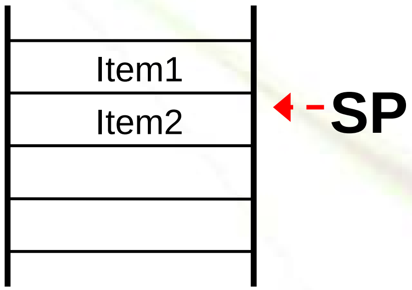
- **Assembler Code Example:**

```
bis.w    #CPUOFF,SR      ; LPM0
```

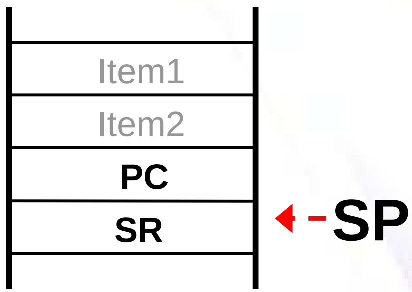
- **C Code Example:**

```
_BIS_SR (CPUOFF);        // LPM0
```

Interrupt Processing

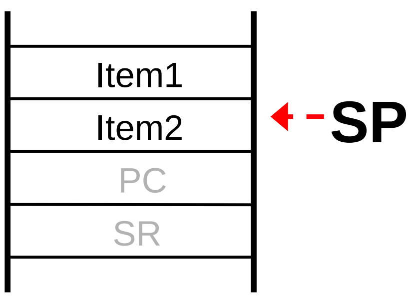


Prior to ISR



ISR hardware - automatically

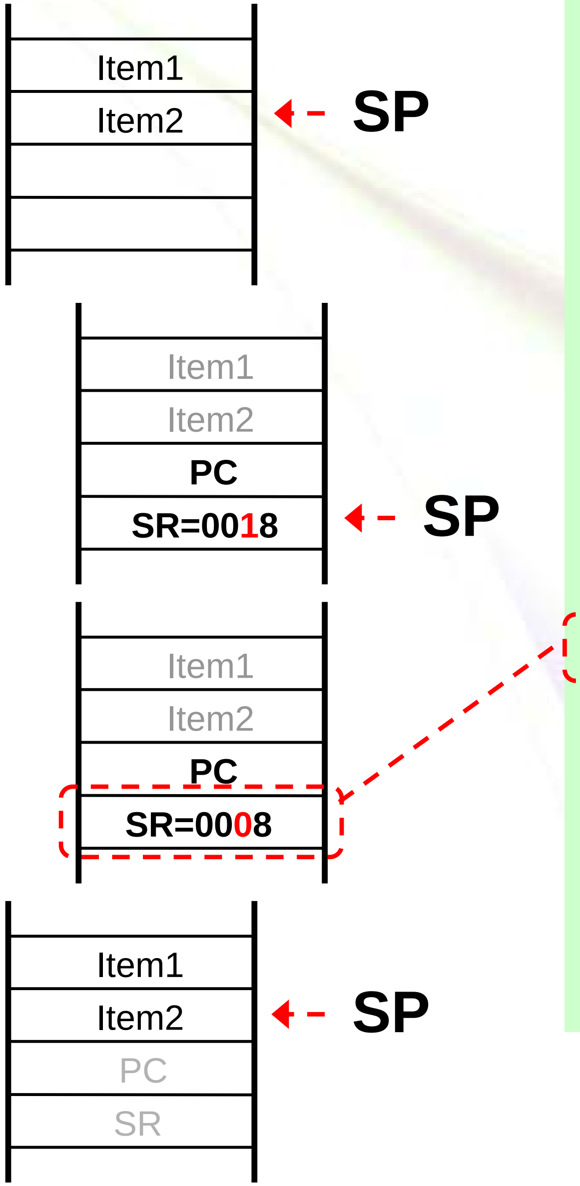
- **PC** pushed
- **SR** pushed
- Interrupt vector moved to PC
- **SR** is cleared
- IFG flag cleared on single source flags



`reti` - automatically

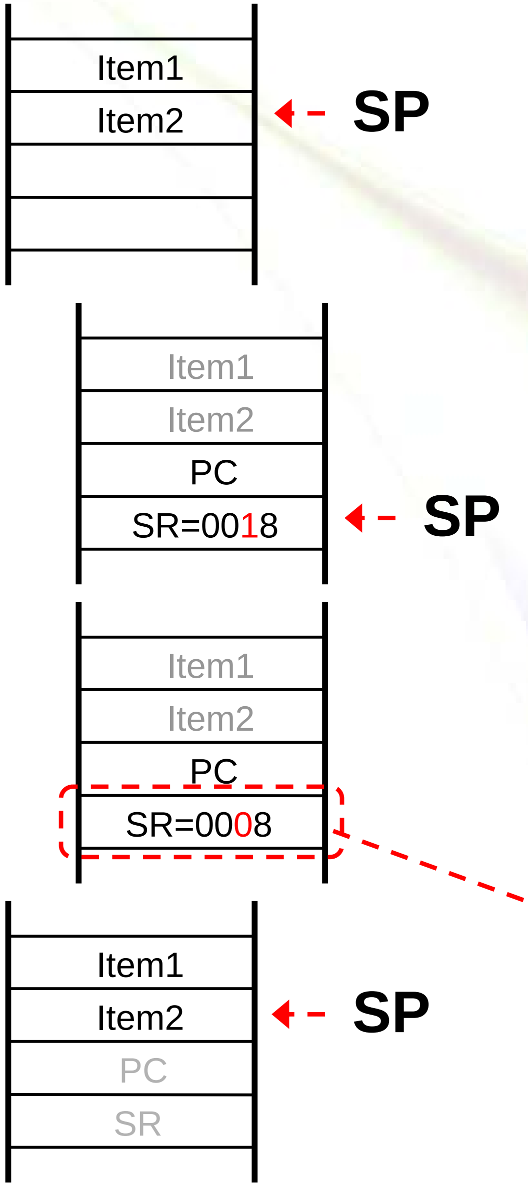
- SR popped - *original*
- PC popped

Low Power Modes In Assembler




```
      ORG      0F000h
RESET         mov.w    #300h,SP
              mov.w
#WDT_MDLY_32,&WDTCTL
              bis.b    #WDTIE,&IE1
              bis.b    #01h,&P1DIR

Mainloop      bis.w    #CPUOFF+GIE,SR
              xor.b    #01h,&P1OUT
              jmp      Mainloop

WDT_ISR       bic.w    #CPUOFF,0(SP)
              reti

              ORG      0FFFEh
              DW       RESET
              ORG      0FFF4h
              DW       WDT_ISR
```

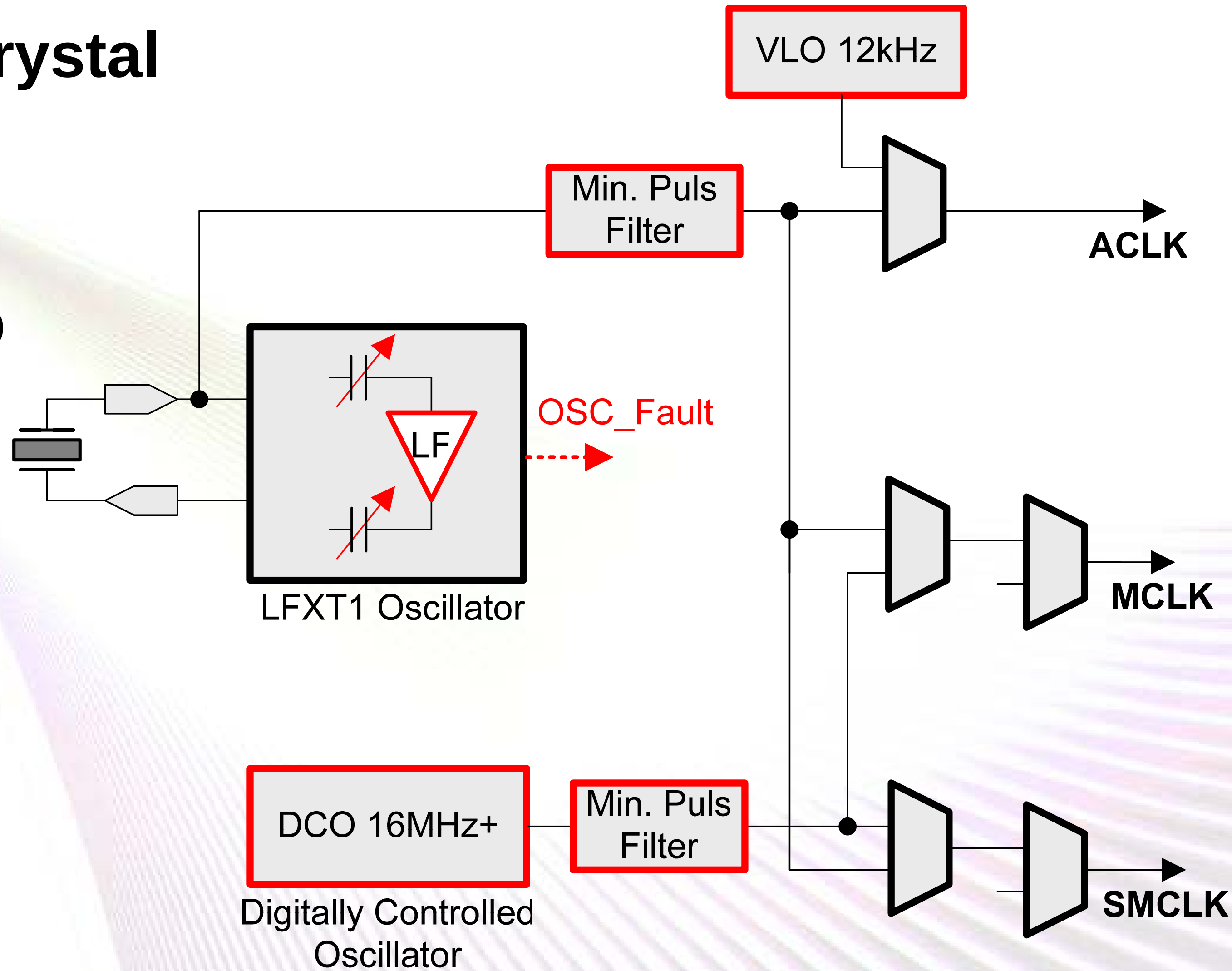
Low Power Modes In C



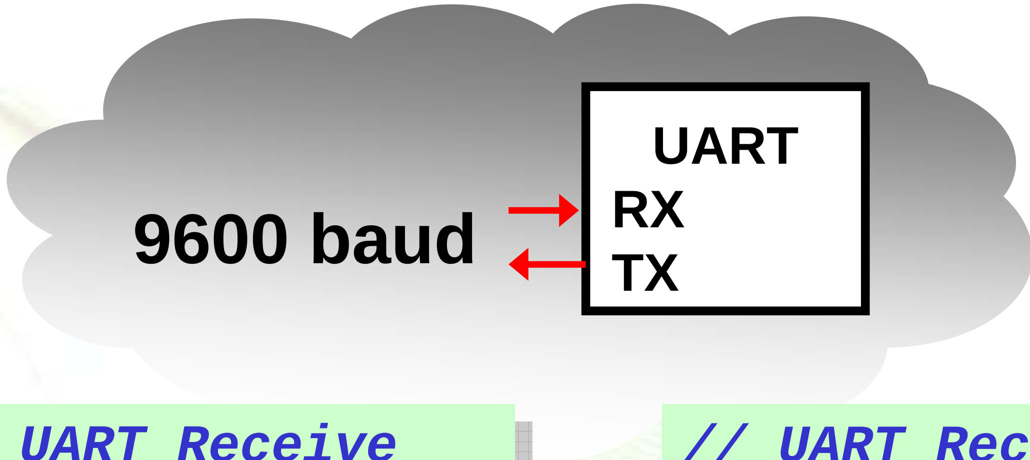

```
void main(void)
{
  WDTCTL = WDT_MDLY_32;
  IE1 |= WDTIE;
  P1DIR |= 0x01;

  for (;;)
  {
    _BIS_SR(CPUOFF + GIE);
    P1OUT ^= 0x01;
  }
}
#pragma vector=WDT_VECTOR
__interrupt void
watchdog_timer(void)
{
    _BIC_SR_IRQ(CPUOFF);
}
```


2xx *Basic Clock Module*+ with VLO Clock

- **VLO provides crystal alternative**
- **Lower power**
- **< 500 nano-amp**



Interrupts Control Program Flow



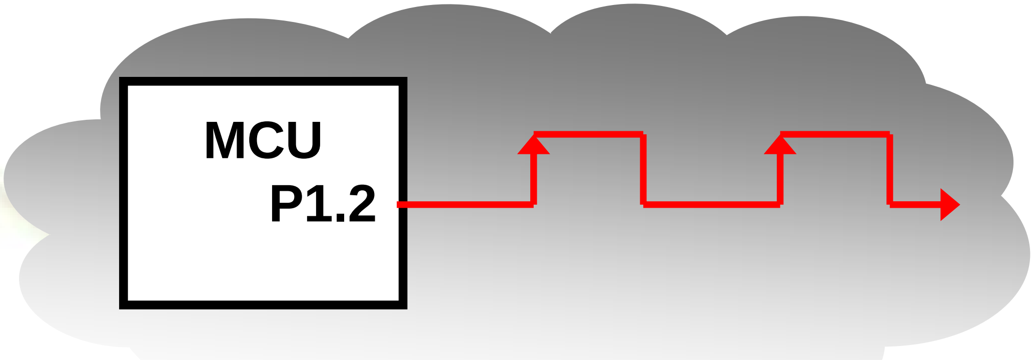

```
// Polling UART Receive
for (;;)
{
 while (!(IFG2&URXIFG0));
 TXBUF0 = RXBUF0;
}
```

100% CPU Load

```
// UART Receive Interrupt
#pragma vector=UART_VECTOR
__interrupt void rx (void)
{
 TXBUF0 = RXBUF0;
}
```

0.1% CPU Load

Software Functions >> Peripherals




```
// Endless Loop
for (;;)
{
 P1OUT |= 0x04;  // Set
 delay1();
 P1OUT &= ~0x04; // Reset
 delay2();
}
```

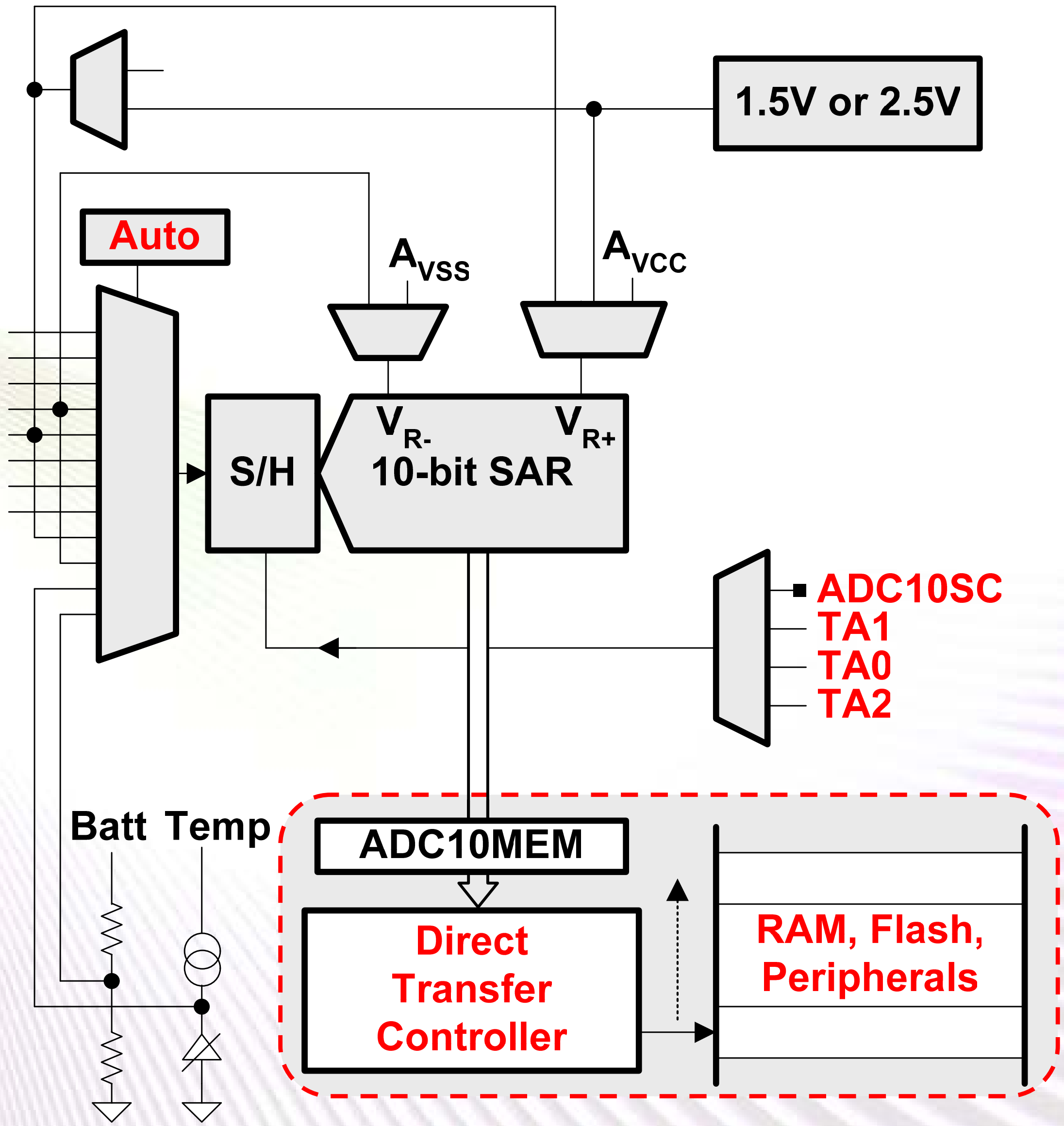
100% CPU Load

```
// Setup output unit
 CCTL1 = OUTMOD0_1;
 _BIS_SR(CPUOFF);
```

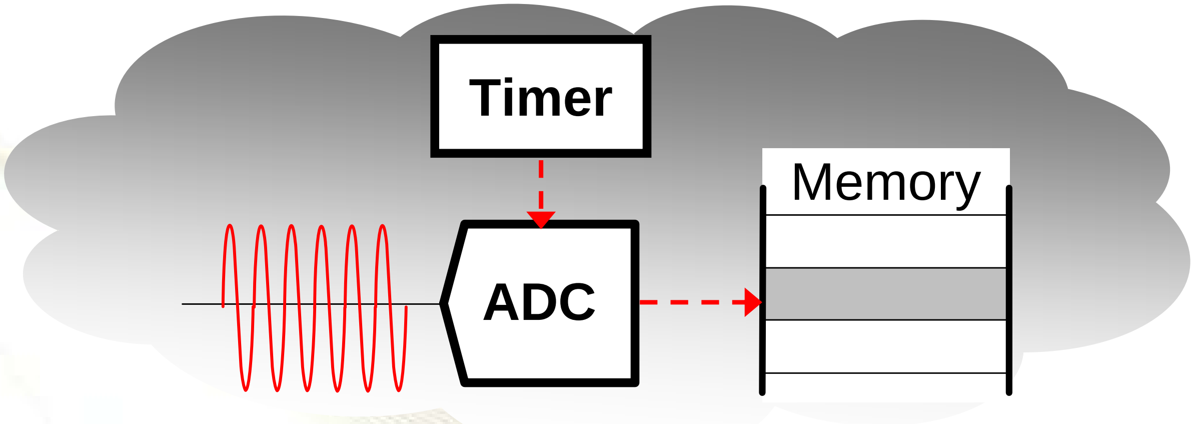
Zero CPU Load

MSP430 ADC10

- 10-bit ADC
- 200ksps+
- Autoscan
- Single
  Sequence
  Repeat-single
  Repeat-sequence
- Internal/external reference
- TA SOC triggers
- Direct transfer controller (DTC)

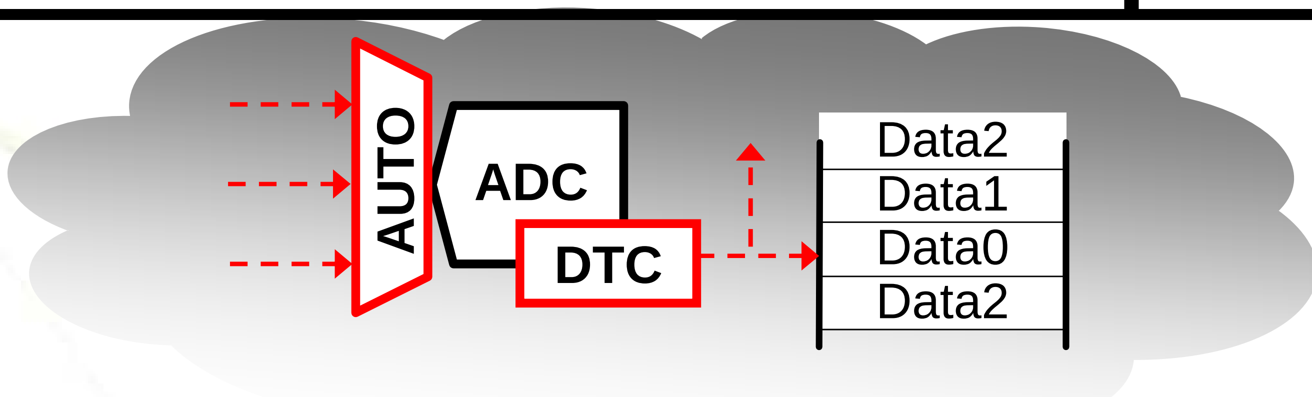


Is Timer-Triggered ADC Important?




```
// Interrupt                                       CPU cycles
; MSP430 ISR to start conversion                       6
BIS  #ADC12SC,&ADC12CTL0 ; Start conversion            5
RETI                     ; Return                      5
                         ;                            16
```

Why Is Autoscan + DTC Important?



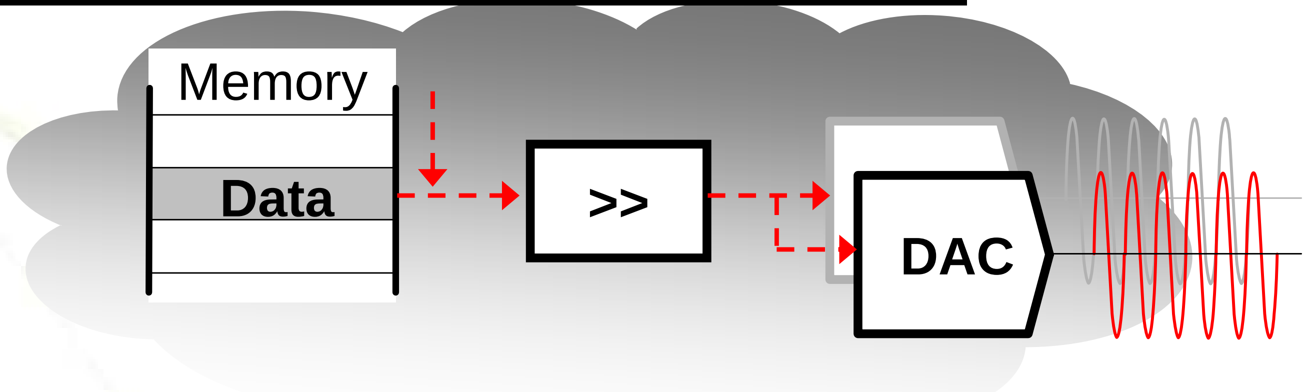

```
// Software
Res[pRes++] = ADC10MEM;
ADC10CTL0 &= ~ENC;
if (pRes < NR_CONV)
 {
 CurrINCH++;
 if (CurrINCH == 3)
   CurrINCH = 0;
 ADC10CTL1 &= ~INCH_3;
 ADC10CTL1 |= CurrINCH;
 ADC10CTL0 |= ENC+ADC10SC;
 }
```

```
// Autoscan + DTC
 _BIS_SR(CPUOFF);
```

70 cycles/Sample

Fully Automatic

Why Is DMA Important?



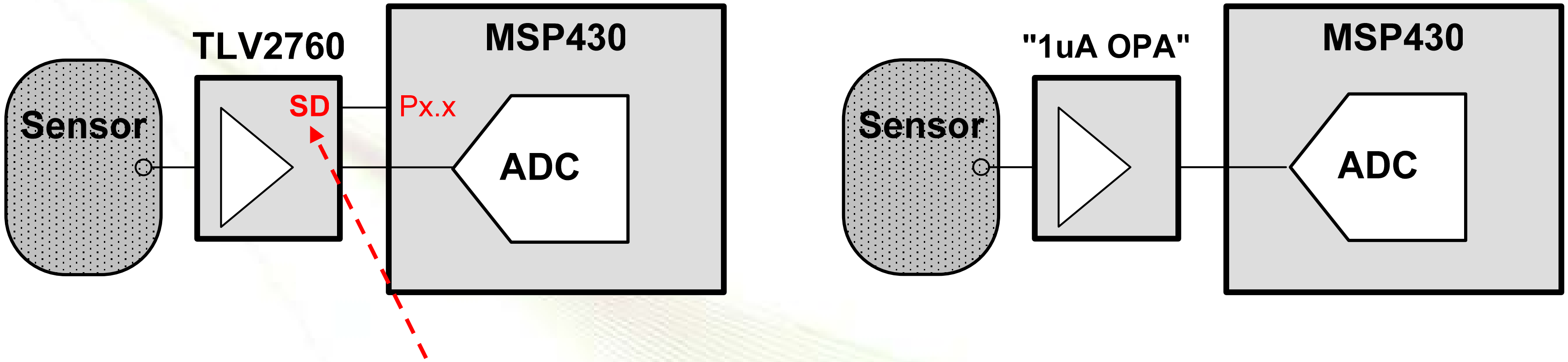

```
// Interrupt                                          CPU cycles  DMA clocks
; MSP430 ISR for one output waveform                       6          0
MOV   @R5+,&DAC12_0DAT ; Update DAC0                       5          2
AND   #1F,R5           ; Modulo pointer                    2          0
RETI                   ; Return                            5          0
                       ;                                  18          2

; MSP430 ISR for two output waveforms                      6          0
MOV   @R5+,&DAC12_0DAT ; Update DAC0                       5          2
MOV   @R5+,&DAC12_1DAT ; Update DAC1                       5          2
AND   #3F,R5           ; Modulo pointer                    2          0
RETI                   ; Return                            5          0
                       ;                                  23          4
```

Low-Power Peripheral Features

- ADC10 reference buffer automatically controlled
- ADC10, ADC12, SD16 cores automatically controlled
- Auto-scan ADC modes
- Timer-triggered data conversion
- I2C and USCI modules automatically enable clock
- DAC and OA have speed vs. power settings

What can I do without the CPU?

Power Manage External Devices



0.01uA = Shutdown

20uA = Active

0.06uA = Average

1uA = Quiescent

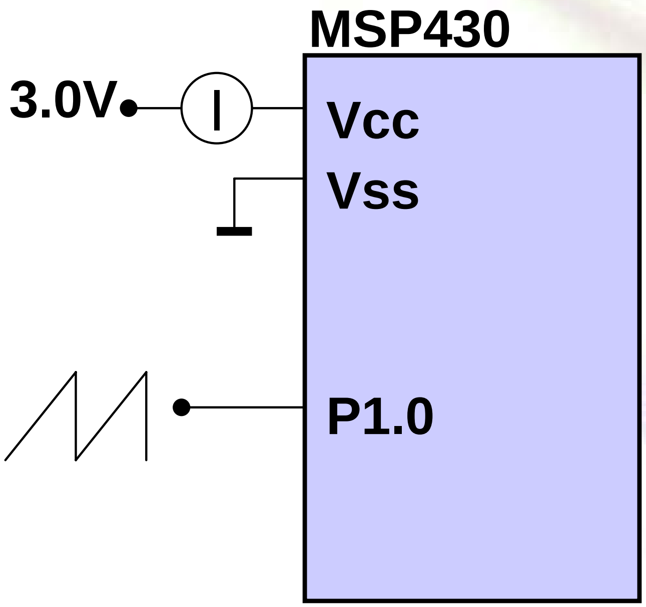
1uA = Active

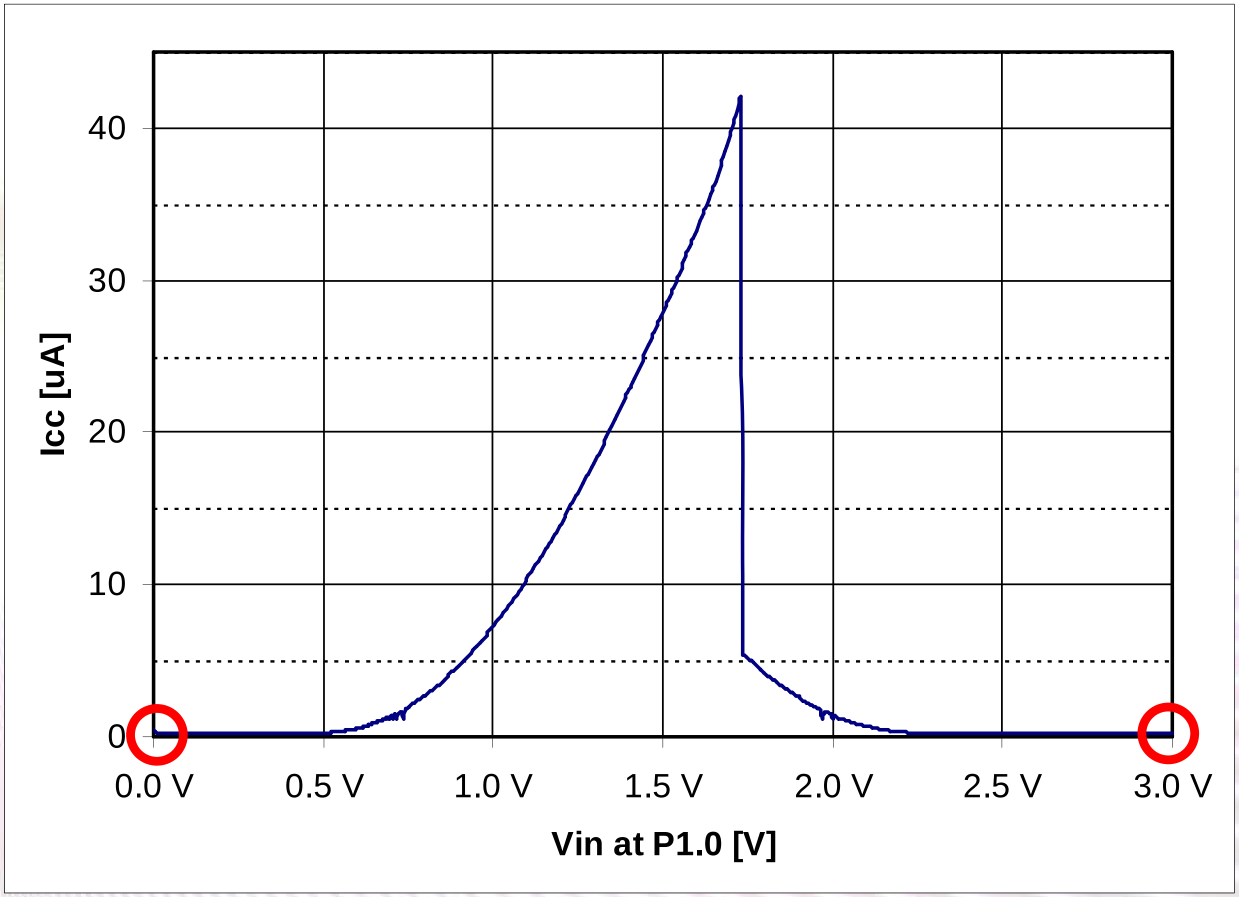
1uA = Average

- **OPA with shutdown can be 20x lower total power**

How To Terminate Unused Pins?

- **Floating inputs cause additional current consumption!**





- **Please see last page of chapter 2 in User's Guide**

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Bytes, Words & CPU Registers

```
; 16-bit addition                                    Code/Cycles
5405               add.w   R4,R5                      ; 1/1
529202000202       add.w   &0200,&0202                ; 3/6

; 8-bit addition
5445               add.b   R4,R5                      ; 1/1
52D202000202       add.b   &0200,&0202                ; 3/6
```

- **Use CPU registers for calculations and dedicated variables**
- **Same code size for word or byte**
- **Use word operations when possible**

Effect Of The Constant Generator

```
D3E20021         bis.b   #002h,&P1OUT        ; With CG

D0F200100021     bis.b   #010h,&P1OUT        ; Without CG
```

- **Immediate values 0xFFFF, 0, 1, 2, 4, 8 generated in hardware**
- **Reduces code size and cycles**

Completely Automatic!

Interrupt Vector Generator

15													0	
0	0	0	0	0	0	0	0	0	0	0	0	Interrupt vector	0	TAIV

- TAIV is used to efficiently decode the TIMER_A1 interrupt vector for all other interrupt sources
- Contents is either 0, 2, 4, or 10
- Reading TAIV returns and clears the highest-priority pending interrupt
- Add TAIV to the PC and use a jump-table for TAIV de-mux
- Using TAIV instead of IFG polling greatly reduces interrupt overhead

C Coding Tips

- **Use local variable as much as possible. Local variables use CPU registers whereas global variables use RAM.**
- **Use bit mask instead of bitfields for unsigned int and unsigned char.**
- **Use unsigned data types where possible**
- **Use pointers to access structures and unions**
- **Use "`static const`" class to avoid run-time copying of structures, unions, and arrays.**
- **Avoid modulo**
- **Count down "`for`" loops**
- **Get to know your C code and its disassembly!**

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Principles For ULP Applications

- **Maximize the time in standby (LPM3)**
- **Use interrupts to control program flow**
- **Replace software functions with peripheral hardware**
- **Power manage internal peripherals**
- **Power manage external devices**
- **Device choice can make a difference**
- **Effective code is a must. Every unnecessary instruction executed is a portion of the battery wasted that will never return.**

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