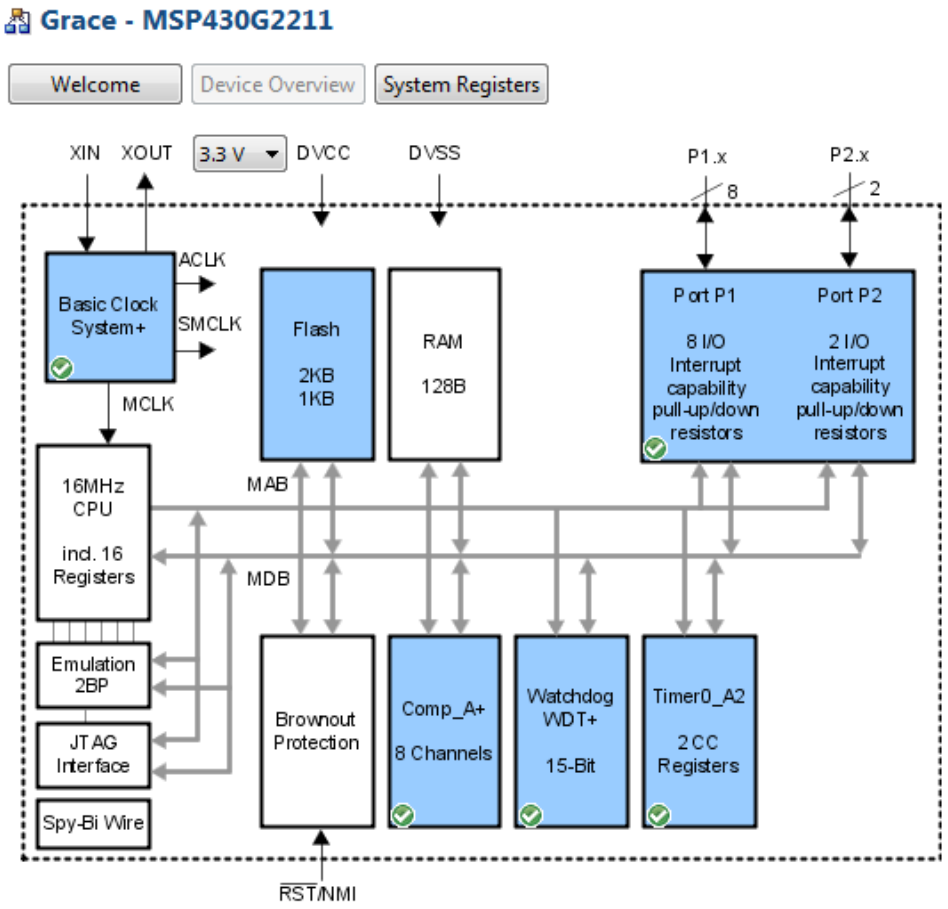
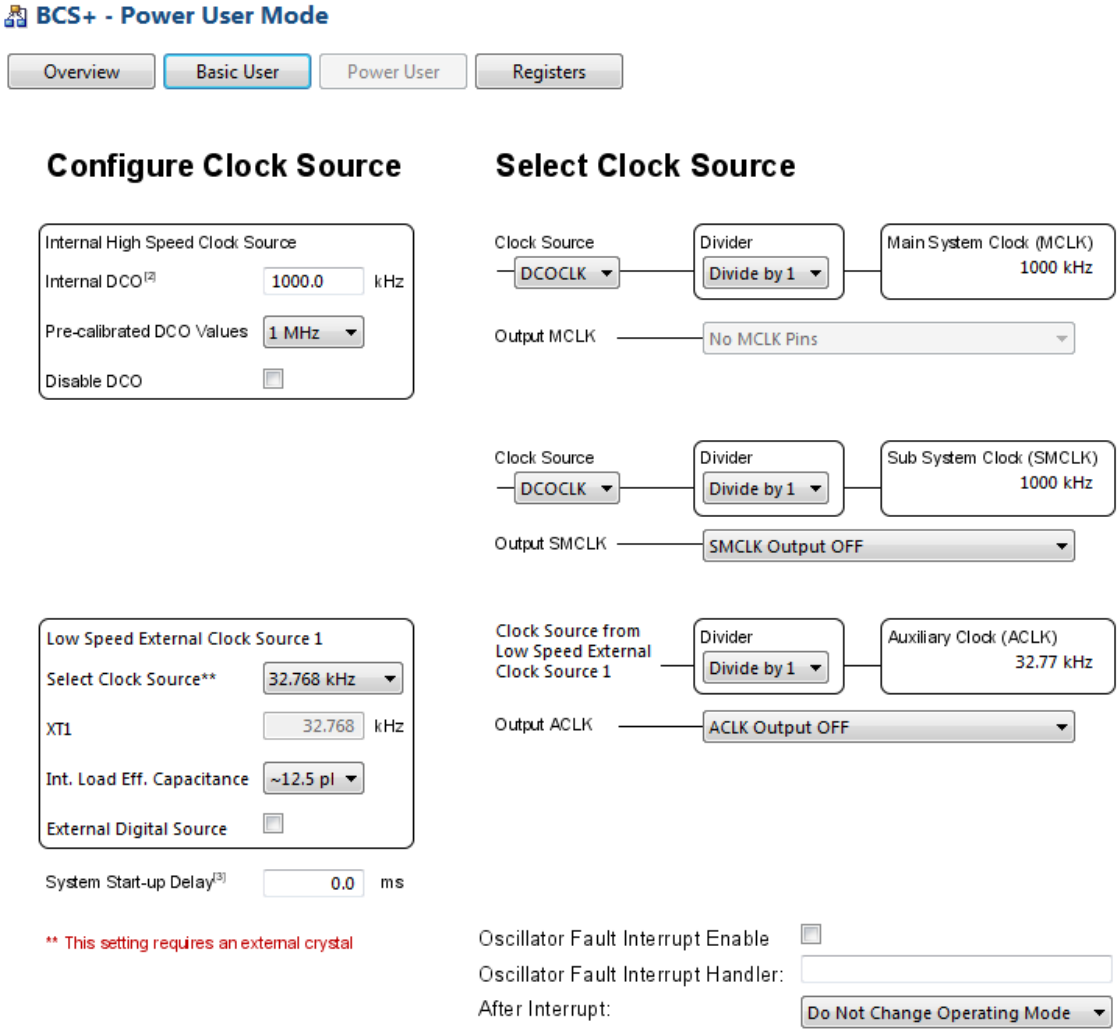
Synchronicity: A wood gear clock with a unique drive mechanism

Synchronicity is a wood gear clock with a unique drive mechanism – a microcontroller-regulated electromagnetic pendulum drive. This document contains listings of the microcontroller software. The clock itself is documented in an Instructable at http://www.instructables.com/id/A-wood-gear-clock-with-a-unique-drive-mechanism/.

This software was developed using Texas instrument's Code Composer Studio Version: 5.1.0.09000. The MSP430 microcontroller was configured using Grace, TI's Graphical Peripheral Configuration Tool. The first section contains screenshots of the Grace configuration. The second section contains the source code listing.


Grace - MSP430G2211
Welcome
Device Overview
System Registers
XIN
XOUT
3.3 V
DVCC
DVSS
P1.x
8
P2.x
2
Basic Clock System+
ACLK
SMCLK
MCLK
Flash
2KB
1KB
RAM
128B
Port P1
8 I/O
Interrupt capability
pull-up/down resistors
Port P2
2 I/O
Interrupt capability
pull-up/down resistors
16MHz CPU
incl. 16 Registers
MAB
MDB
Emulation 2BP
JTAG Interface
Spy-Bi Wire
Brownout Protection
Comp_A+
8 Channels
Watchdog WDT+
15-Bit
Timer0_A2
2 CC Registers
RST/NMI



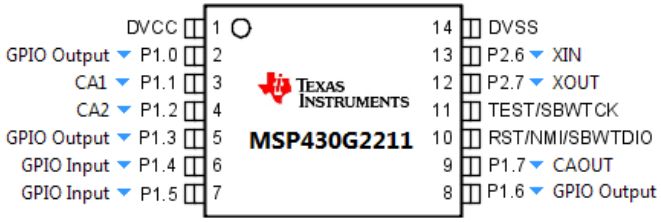
Note 1: Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).

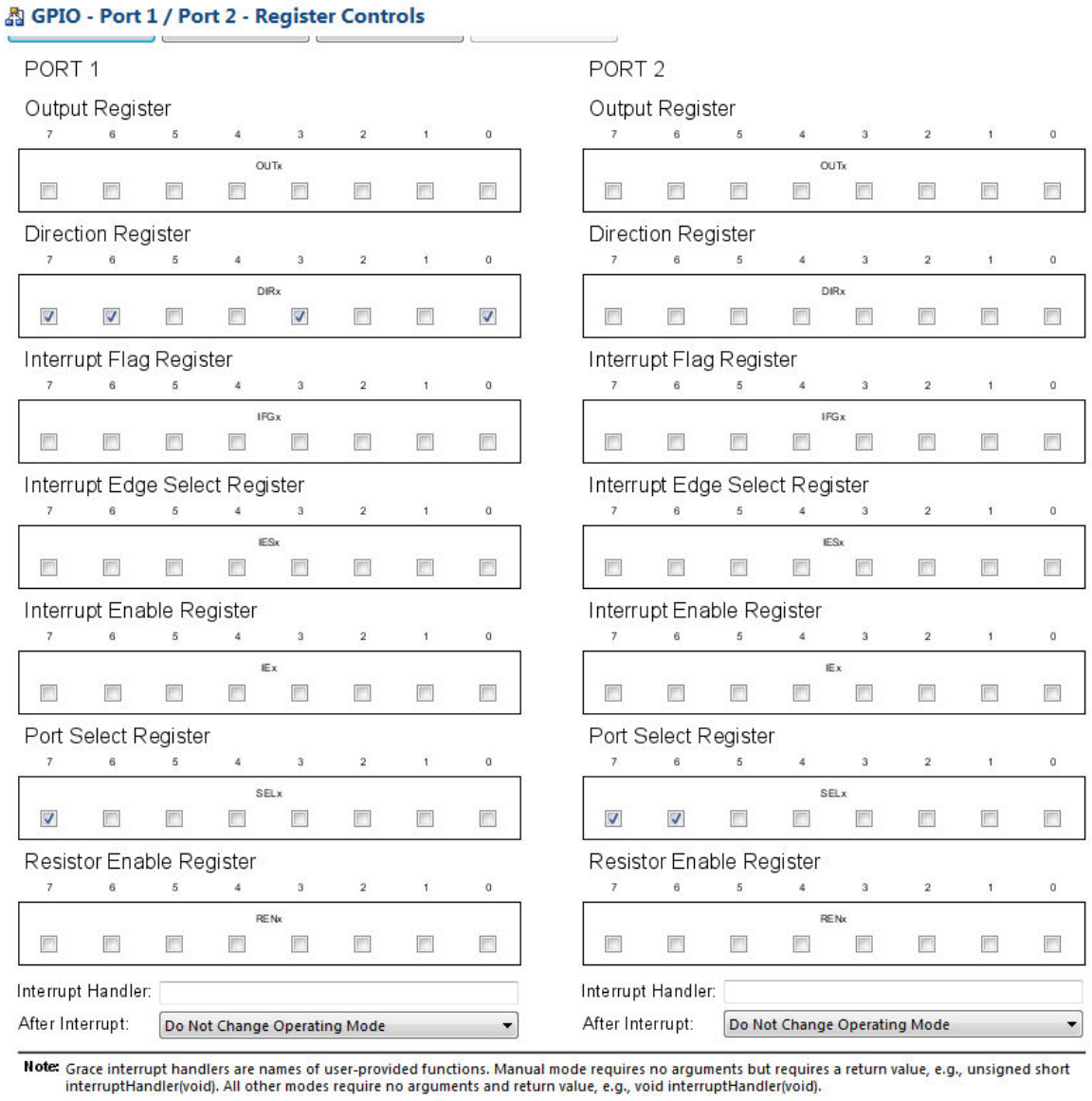
Note 2: Manually configuring the DCO frequency can result in a +/-10% frequency deviation. The Pre-calibrated DCO has a tolerance of +/-3% frequency deviation. See datasheet for more information.

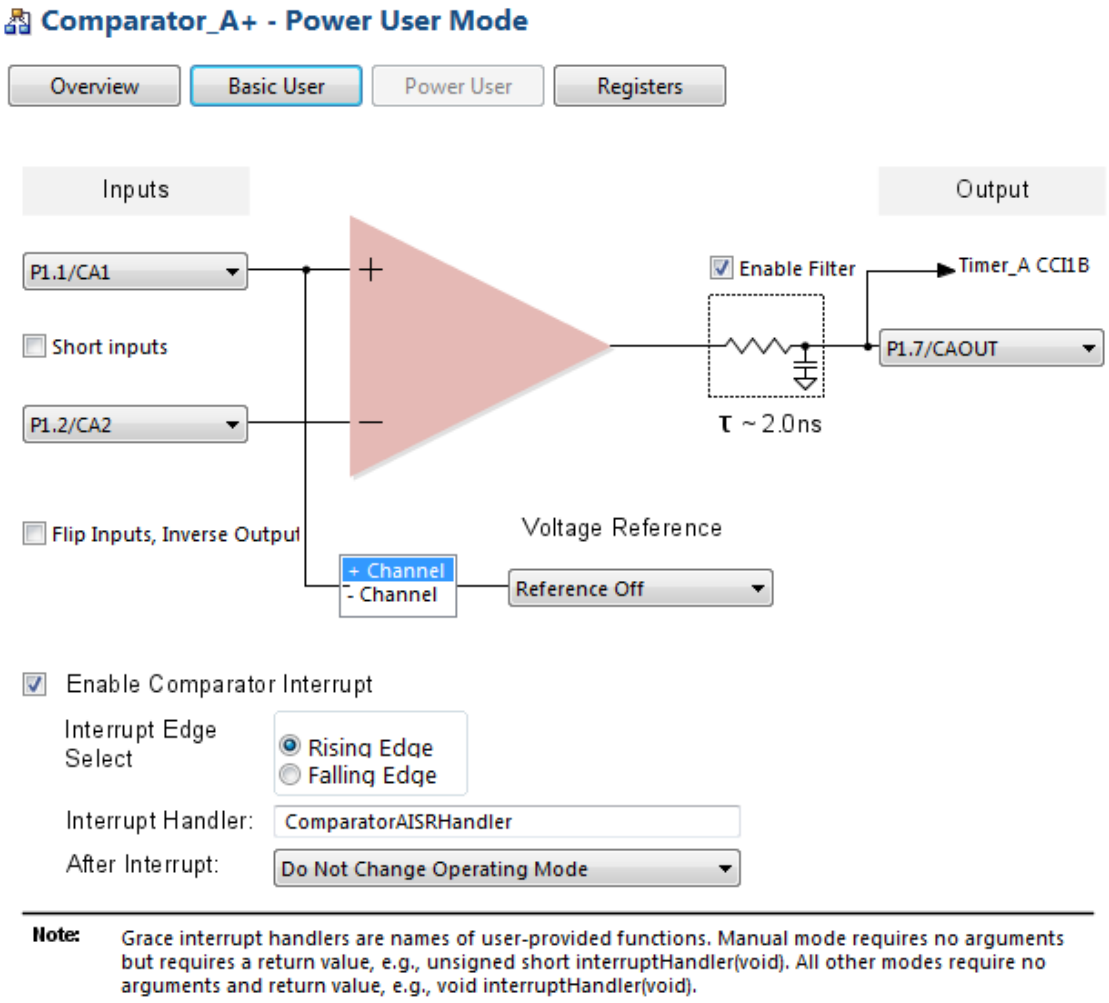
Note 3: Set a delay value in miliseconds based on the system rise time to ensure no violation of VCC vs MCLK. It is highly recommended when setting a non-default system clock frequency to ensure a proper system start-up.

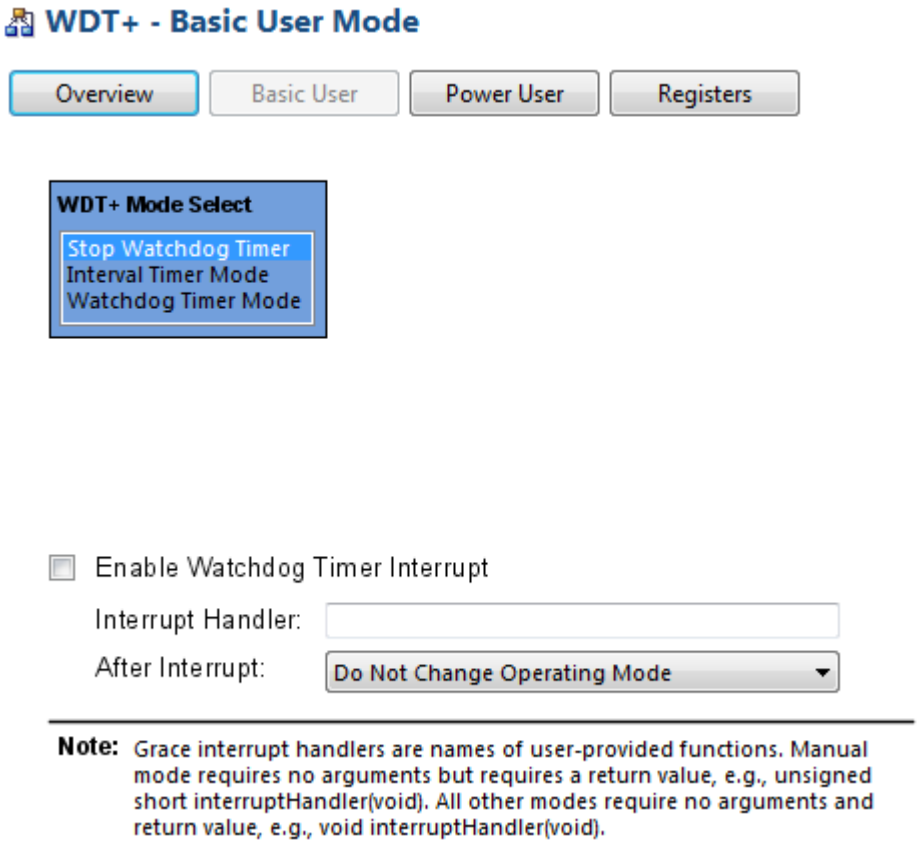
GPIO - Pinout TSSOP/PDIP

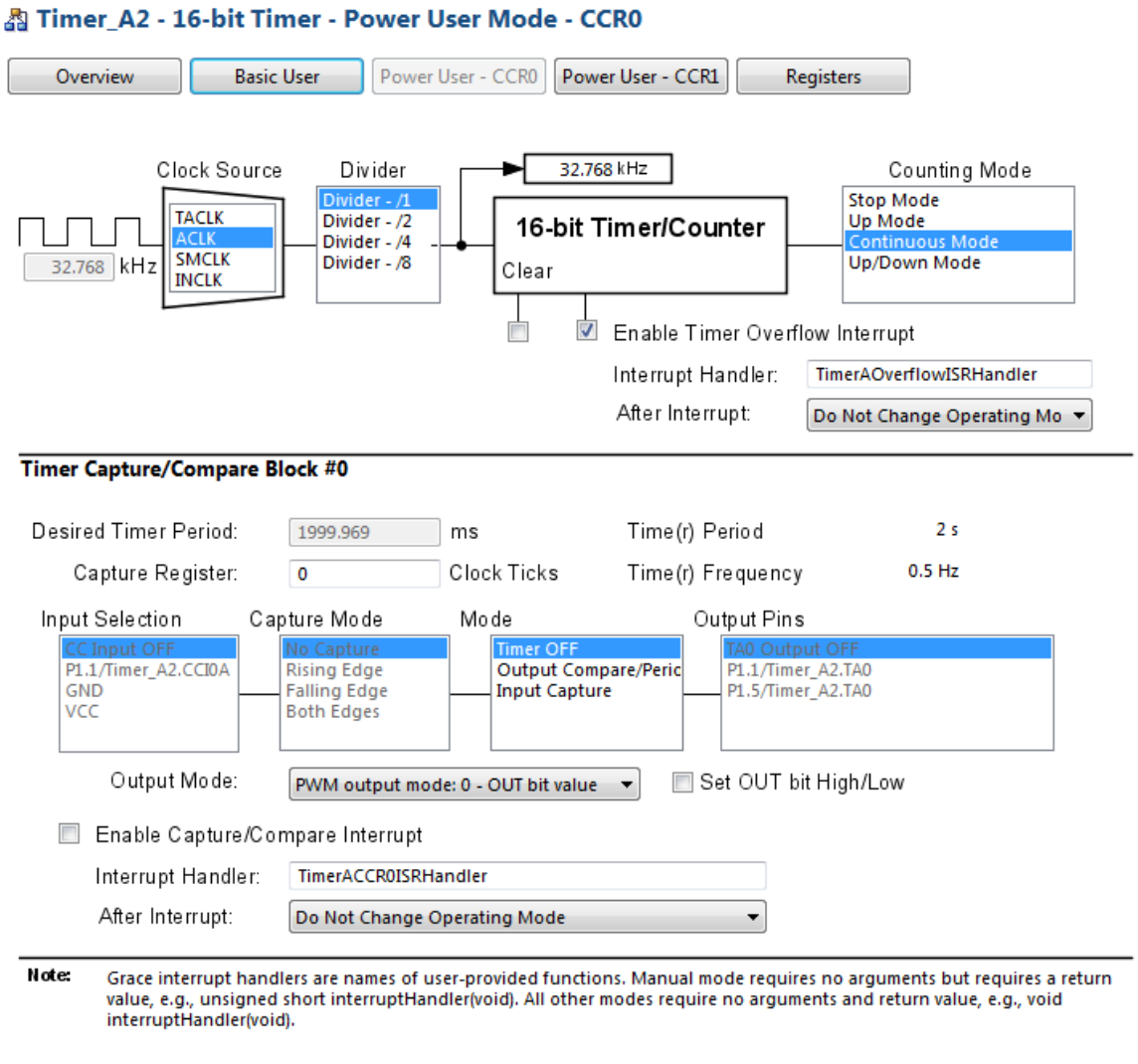
Overview | Pinout QFN | Pinout TSSOP/PDIP | P1/P2

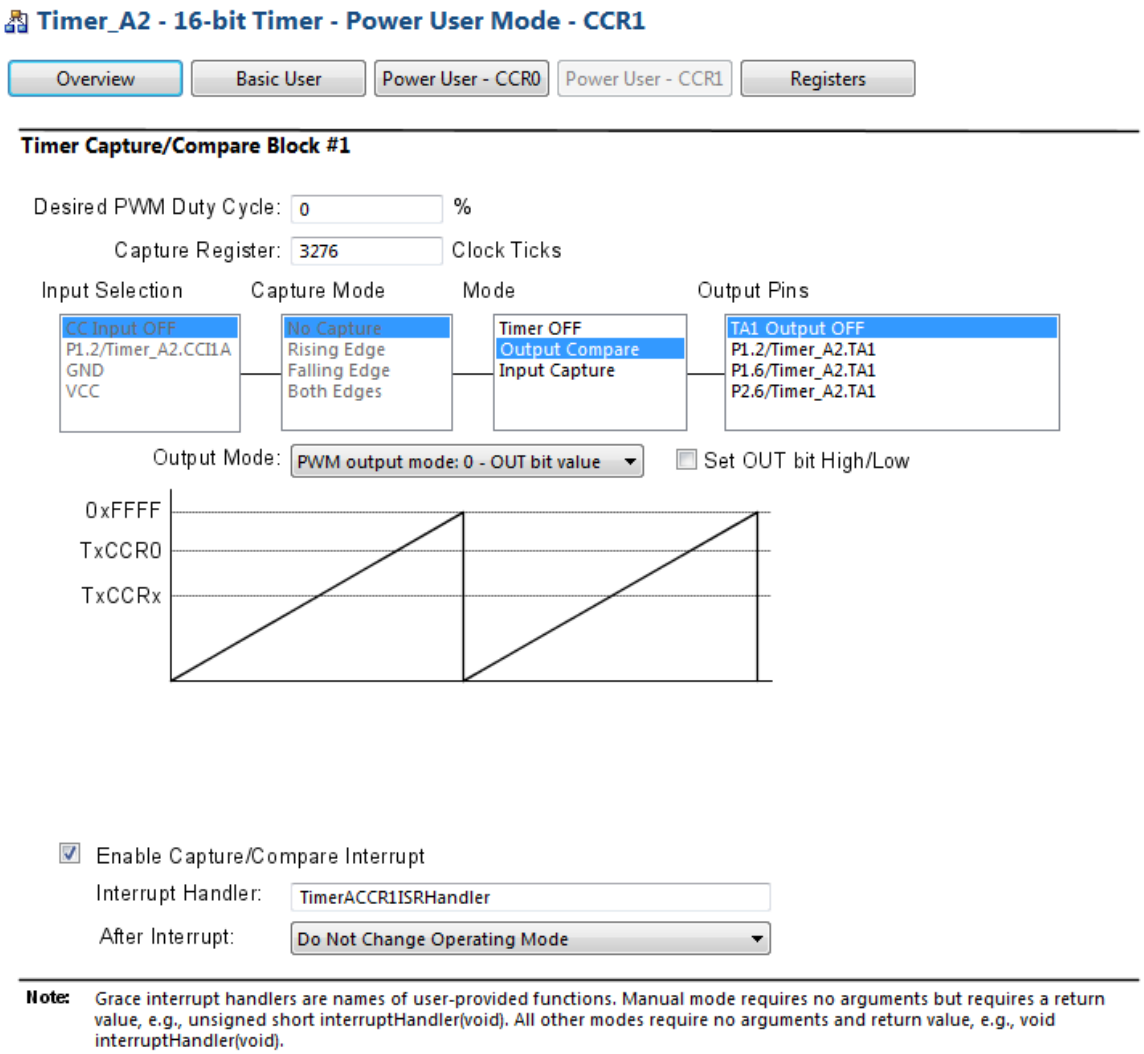



GPIO - Port 1 / Port 2 - Register Controls
PORT 1
Output Register
7 6 5 4 3 2 1 0
OUTx
Direction Register
DIRx
Interrupt Flag Register
IFGx
Interrupt Edge Select Register
IESx
Interrupt Enable Register
IEx
Port Select Register
SELx
Resistor Enable Register
RENx
Interrupt Handler:
After Interrupt:
Do Not Change Operating Mode
PORT 2
Output Register
OUTx
Direction Register
DIRx
Interrupt Flag Register
IFGx
Interrupt Edge Select Register
IESx
Interrupt Enable Register
IEx
Port Select Register
SELx
Resistor Enable Register
RENx
Interrupt Handler:
After Interrupt:
Do Not Change Operating Mode
Note: Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).


Comparator_A+ - Power User Mode
Overview
Basic User
Power User
Registers
Inputs
Output
P1.1/CA1
Short inputs
P1.2/CA2
Flip Inputs, Inverse Output
Enable Filter
Timer_A CCI1B
P1.7/CAOUT
τ ~ 2.0ns
Voltage Reference
+ Channel
- Channel
Reference Off
Enable Comparator Interrupt
Interrupt Edge Select
Rising Edge
Falling Edge
Interrupt Handler:
ComparatorAISRHandler
After Interrupt:
Do Not Change Operating Mode
Note:
Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).


WDT+ - Basic User Mode
Overview
Basic User
Power User
Registers
WDT+ Mode Select
Stop Watchdog Timer
Interval Timer Mode
Watchdog Timer Mode
Enable Watchdog Timer Interrupt
Interrupt Handler:
After Interrupt:
Do Not Change Operating Mode
Note: Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).


Timer_A2 - 16-bit Timer - Power User Mode - CCR0
Overview
Basic User
Power User - CCR0
Power User - CCR1
Registers
Clock Source
Divider
32.768 kHz
Counting Mode
32.768 kHz
TACLK
ACLK
SMCLK
INCLK
Divider - /1
Divider - /2
Divider - /4
Divider - /8
16-bit Timer/Counter
Clear
Stop Mode
Up Mode
Continuous Mode
Up/Down Mode
Enable Timer Overflow Interrupt
Interrupt Handler:
TimerAOverflowISRHandler
After Interrupt:
Do Not Change Operating Mo
Timer Capture/Compare Block #0
Desired Timer Period:
1999.969
ms
Time(r) Period
2 s
Capture Register:
0
Clock Ticks
Time(r) Frequency
0.5 Hz
Input Selection
Capture Mode
Mode
Output Pins
CC Input OFF
P1.1/Timer_A2.CCI0A
GND
VCC
No Capture
Rising Edge
Falling Edge
Both Edges
Timer OFF
Output Compare/Peric
Input Capture
TA0 Output OFF
P1.1/Timer_A2.TA0
P1.5/Timer_A2.TA0
Output Mode:
PWM output mode: 0 - OUT bit value
Set OUT bit High/Low
Enable Capture/Compare Interrupt
Interrupt Handler:
TimerACCR0ISRHandler
After Interrupt:
Do Not Change Operating Mode
Note:
Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).


Timer_A2 - 16-bit Timer - Power User Mode - CCR1
Overview
Basic User
Power User - CCR0
Power User - CCR1
Registers
Timer Capture/Compare Block #1
Desired PWM Duty Cycle: 0 %
Capture Register: 3276 Clock Ticks
Input Selection
Capture Mode
Mode
Output Pins
CC Input OFF
P1.2/Timer_A2.CCI1A
GND
VCC
No Capture
Rising Edge
Falling Edge
Both Edges
Timer OFF
Output Compare
Input Capture
TA1 Output OFF
P1.2/Timer_A2.TA1
P1.6/Timer_A2.TA1
P2.6/Timer_A2.TA1
Output Mode: PWM output mode: 0 - OUT bit value
Set OUT bit High/Low
0xFFFF
TxCCR0
TxCCRx
Enable Capture/Compare Interrupt
Interrupt Handler: TimerACCR1ISRHandler
After Interrupt: Do Not Change Operating Mode
Note: Grace interrupt handlers are names of user-provided functions. Manual mode requires no arguments but requires a return value, e.g., unsigned short interruptHandler(void). All other modes require no arguments and return value, e.g., void interruptHandler(void).

```
/*
 *  Electromagnetic Pendulum Driver
 *
 *  Version 1.1
 *
 *  This software pulses an electromagnetic coil to drive a clock pendulum.
 *  The software precisely measures the period of each and every swing of the pendulum, and
 *  uses a modified PID (proportional - integral - differential) control algorithm to adjust the swing angle
 *  of a clock pendulum to speed up or slow down the pendulum and therefore the clock.
 *
 *
 *
 *  Dick Bipes
 *  dick@carveshop.com
 *
 *
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 *
 *
 */


/*
 * ======== Standard MSP430 includes ========
 */
#include <msp430.h>

/*
 * ======== Grace related includes ========
 */
#include <ti/mcu/msp430/csl/CSL.h>

/*
 * ======== Definitions ========
 */
#define RedLED      (BIT0)       // Red LED on the LaunchPad
#define GreenLED    (BIT6)       // Green LED on the LaunchPad
                                 // For the clock, a red/green bi-directional LED is connected to these two port pins
#define CoilDriver  (BIT3)       // Base to driver transistor
```

```
#define DataLog     (BIT5)       // Datalog output pin

#define CrystalFreq 32768        // timer counts per second, based on the external watch crystal
#define _600uS      20
#define _2mS        66
#define _5mS        164
#define _7mS        229
#define _10mS       328
#define _12mS       393
#define _15mS       492
#define _18mS       589
#define _20mS       655
#define _22mS        721
#define _23mS        753
#define _25mS       819
#define _30mS       983
#define _35mS       1147
#define _100mS      3277
#define NominalPulseDelay _10mS  // Delay time after voltage compare interrupt (magnet passes by coil) to coil on
#define NominalPulse      _15mS  // Nominal coil pulse width
#define MinPulse          _10mS  // Minimum pulse width to make sure the pendulum keeps moving
#define MaxPulse          _35mS  // Maximum pulse width to limit current draw
#define QuiescePeriod     _100mS // Quiesce time after magnet pass with interrupt disabled

#define GraceTicks        50     // Number of timer ticks fast or slow that's OK (no warning LED)
                                 // Experiments show that we can change the pendulum speed about 0.5% or about 150 ticks in 32768
#define LEDTime           600    // Time to keep the LEDs enabled, in seconds
#define ControlLimit      300    // Maximum time in seconds to allow the pulse width at a limit before lighting an LED
#define ControlError      5      // Minimum error required to flash a long-term pendulum speed LED, in seconds

#define Kp   20                  // Proportional constant, empirically derived
#define Ki   .1                  // Integral constant, empirically derived

/*
 * ======== Variables ========
 */

int          stage = 0;              // state machine stage
unsigned int timer_capture;          // current value of TAR (timer counter)
```

```
unsigned int last_capture = 0;          // previous value of TAR
unsigned int crystal_secs = 0;          // elapsed seconds based upon the crystal oscillator (reference)
unsigned int pendulum_secs = 0;         // elapsed seconds based upon the pendulum
int timer_overflow = 0;                 // timer overflow counter (generally >0, but may go to -1 in a race condition)
int error_ticks;                        // difference between crystal ticks and pendulum ticks (1 tick = 1/32768 second)

unsigned int pendulum_passes = 0;       // pendulum pass counter, incremented when the pendulum passes the coil (twice per period)

int error = 0;                          // error, the difference between reference time base and the pendulum (clock)
float i_error = 0;                      // integral of the error

int pulse = NominalPulse;               // coil pulse width
int pulse_delay = NominalPulseDelay;    // delay time from detecting magnet to turning coil on
unsigned int control_count = 0;         // number of consecutive seconds the pulse is set to its limit
unsigned int LEDs = 0;                  // port bit mask to turn on or off either LED
unsigned int enable_short_LEDs = 1;     // flag to enable/disable the LEDs

/*
 *  Timer A is regulated by a 32.768 kHz watch crystal.  The timer is always running, and overflows exactly every two seconds.
 */
      // Timer_A Overflow Interrupt Handler
      void TimerAOverflowISRHandler(void)
      {
            // Count seconds based on the watch crystal reference.  This count is compared against the pendulum swings
            // to yield an error signal, which allows the pendulum period to be accurately controlled.
            crystal_secs += 2;              //  count the number of seconds that have passed based upon the crystal

            // Count of timer overflows.  We expect the timer to overflow during normal operation.
            // If the pendulum is stopped for any length of time, the timer will overflow repeatedly.
            // A large overflow count in fact tells us that the pendulum has stopped, and we need to reset our software
            // and restart.
            if (timer_overflow < 1000)// increment the number of times the timer overflows, up to an arbitrary maximum
                  timer_overflow++;
      }

/*
 *  Sequencer for running the coil.
 *  The first state or stage is a delay, from the time induced current is detected in the coil, to when we turn
 *    on current to the coil.
```

```
 *     The second stage is coil on time.
 *     The third stage is a delay to let the coil quiesce and avoid triggering a second, undesired pulse.
*/
      // Timer_A Capture/Compare 0 Interrupt Handler
      void TimerACCR0ISRHandler(void)
      {
            switch(stage)
            {
            case 1: // turn on the coil
                  P1OUT |= CoilDriver + LEDs;      // turn on the coil driver (active high) and LEDs
                  TACCR0 +=pulse;                  // set the coil on time
                  break;
            case 2:      // turn off the coil
                  P1OUT &= ~(CoilDriver + RedLED + GreenLED);   // turn off the coil driver (active high) and LEDs
                  TACCR0 += QuiescePeriod;         // wait for the coil to settle down
                  break;
            case 3:      // enable the next cycle
                  TACCTL0 &= ~CCIE;          // disable timer interrupts
                  CACTL1 &= ~CAIFG;          // clear any spurious compare interrupt that may have occurred
                  CACTL1 |= CAIE;            // enable comparator interrupts for the next swing

                  // The control loop calculation uses floating point math and can take some time to process.
                  // The calculation is placed here, just after the coil is turned off, where we have sufficient time to do it
                  // as nothing critical is happening.
                  pulse = NominalPulse - (Kp*error + Ki*i_error);     //  standard PID algorithm, but with no differential term
                  //pulse = _25mS;                 // set a fixed pulse width for tuning - normally commented out
                  if (pulse > MaxPulse)            // limit the max pulse to conserve battery
                        {
                        pulse = MaxPulse;
                        control_count++;           // this counter can tell us if we are out of control
                        }
                  else if (pulse < MinPulse)// limit the minimum pulse, to ensure that the pendulum does not stop
                        {
                        pulse = MinPulse;
                        control_count++;
                        }
                  else
                        control_count = 0;
                  if (pulse < _15mS)
```

```
                        {
                        pulse_delay = _10mS;      // for short pulses, wait until the magnet is away from the coil a bit
                        }
                  else if (pulse > _23mS)
                        {
                        pulse_delay = _2mS;       // for long pulses, trigger the coil right away
                        }
                  else
                  {
                        pulse_delay = _25mS - pulse;  // for intermediate pulses, delay an intermediate amount
                  }
                  break;
            }
            stage++;                  // advance to the next state
      }

/*
 *  PWM output for logging purposes.
 */
      // Timer_A Capture/Compare 1 Interrupt Handler
      void TimerACCR1ISRHandler(void)
      {     // This routine sends a PWM output in proportion to the pulse width or error for data logging
            static int sw = 0;

            if (sw++ & 0x01)
            {
                  P1OUT |= DataLog;         // set the port pin high
//                  TACCR1 += 50 + (MaxPulse - pulse);
                  TACCR1 += 100 + (5*error);
            }
            else
            {
                  P1OUT &= ~DataLog;        // set the port pin low
                  TACCR1 += 100 - (5*error);
            }
      }

/*
 * Pendulum magnet has induced a current in the coil and triggered the comparator
```

```
*/
      // Comparator_A+ Interrupt Handler
      void ComparatorAISRHandler(void)
      {
            timer_capture = TAR;                    // capture the timer value
            CACTL1 &= ~CAIE;                        // disable comparator interrupts to prevent a second trigger
            stage = 1;                              // set the sequencer to initial state
            TACCR0 = timer_capture + pulse_delay;   // set the delay time from detecting the magnet to coil on
            TACCTL0 |= CCIE;                        // enable timer interrupts

            if  (pendulum_passes & 0x01)            // every other pendulum pass (e.g. a full swing)
            {
                  pendulum_secs ++;                 // keep track of the elapsed time based on the pendulum
                  if (pendulum_secs > LEDTime)      // disable the LEDs after a period of time
                        enable_short_LEDs = 0;

                  // Check for more than one timer overflow, which means the pendulum had stopped.  In that case, restart.
                  if (timer_capture < last_capture)             // OK if the timer has rolled over once
                        timer_overflow-- ;                      //  expected, so decrement the overflow count
                  // Note that rarely the timer may overflow while in this interrupt service routine, and timer_overflow goes
                  // negative
                  if ( timer_overflow > 0 )                     // any other overflow means the pendulum was stopped
                  {
                        // Reset after the pendulum was stopped and restarted
                        timer_overflow = 0;
                        pendulum_passes = 0;
                        crystal_secs = 0;
                        pendulum_secs = 0;
                        error = 0;
                        i_error = 0;
                        enable_short_LEDs = 1;
                        //P1OUT ^= RedLED;          // debug - toggle red LED
                  }
                  if  (pendulum_secs & 0x01)        // every other full pendulum swing  (same frequency as timer overflow)
                  {
                        // Warn of either short-term or long-term pendulum speed problems.  Short term has priority.
                        LEDs = 0;                   // assume neither LED should be lit
                        // If within the short-term window after start-up, blink an LED if the pendulum is too fast or too slow
                        if (enable_short_LEDs)      // only turn on LEDs for the first few minutes
```

```
                        {
                              error_ticks = CrystalFreq - (timer_capture - last_capture);  // compute the short-term error
                              if (error_ticks > GraceTicks)    // if the pendulum is significantly faster than the reference,
                                                               //enable the green LED
                                    LEDs |= GreenLED;
                              if (error_ticks < -GraceTicks)   // if the pendulum is significantly slower than the reference,
                                                               // enable the red LED
                                    LEDs |= RedLED;
                        }
                        //  If the pulse width has been at its limit for an extended period of time,
                        //  and were more than a few seconds fast or slow, we're probably out of control
                        else if (control_count > ControlLimit) // if it hasn't been too long at the limit, don't turn the LED on
                        {
                              if (error > ControlError)        // if we're more than a few seconds off, a positive error means
                                                               // too few pendulum ticks -
                                    LEDs |= RedLED;            //  too slow
                              if (error < -ControlError)       // a negative error means too many pendulum ticks -
                                    LEDs |= GreenLED;          //  too fast
                        };
                        // Capture values for the control loop
                        error = crystal_secs - pendulum_secs;  // error term
                        i_error += error;                      // integral of the error
                  }
                  last_capture = timer_capture;    // remember the timer count
            }
            pendulum_passes++;                     // count swings of the pendulum past the coil (we act on every other one only)

      }

/*
 * Wait about a second and optionally light an LED or activate the coil
 */
         void WaitABit(unsigned int LED)
         {
               unsigned int i;
                  for (i=0; i<50000; i++)          // wait a while
                        P1OUT |= LED;              // turn the LED on while waiting
                  P1OUT &= ~LED;                   // turn the LED off
         }
```

```
/*
 *  ======== main ========
 *
 *  Set up the microcontroller using Grace-generated configuration.
 *  Blink the LED and pulse the coil.
 *  Then go to sleep and wait for interrupts.
 *
 */
int main(int argc, char *argv[])
{

      CSL_init();             // Activate Grace-generated configuration

      P1OUT = 0;                      // make sure the port pins, particularly the coil driver, is off
                                      //  (not sure why Grace is not doing this)

      TACCTL0 &= ~CCIE;         // disable timer interrupts while we play with the LEDs
    WaitABit(RedLED);           // turn the red LED on for a while
    WaitABit(0);                // no LED
    WaitABit(GreenLED);         // likewise with the green LED
    WaitABit(0);                // no LED
    WaitABit(CoilDriver); // activate the coil for a second so that the clock builder can determine if the
                                //  magnet polarity is correct

      CACTL1 |= CAIE;           // enable comparator interrupts for the pendulum swing

    // Enter Low Power Mode with global interrupt enabled
    __bis_SR_register(LPM0_bits + GIE);

    return (0);
}
```