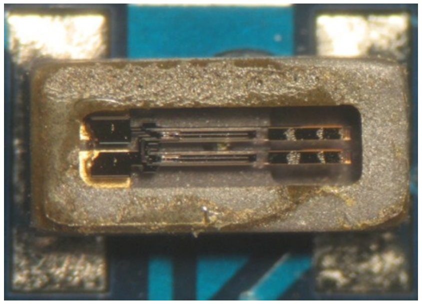
EECS 373
Design of Microprocessor-Based Systems

Thomas Schmid
University of Michigan



Lecture 8: Timers: count, compare, capture, PWM
September 28, 2010

http://home.netcom.com/~swansont/science.html

Minute Quiz...

Announcements

- Homework 1 posted on website
  - Due date October 7th

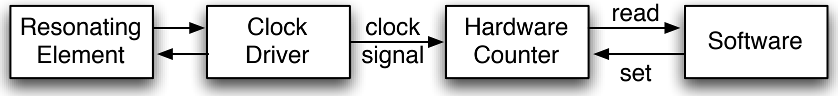
Where do we use time in an embedded system?

Why do we need accurate time?

- Scheduling of computation
  - Scheduler in operating systems
  - Real time operating systems
- Signal sampling
  - Audio sampling at 44.1 kHz
  - Sampling CCD at 30 fps
- Signal generation
  - 120 Hz TV refresh rate
  - Pulse Width Modulated (PWM) signals
- Communication
  - Media Access Control (MAC) protocols
  - Modulation
- Navigation
  - GPS
- Coordination

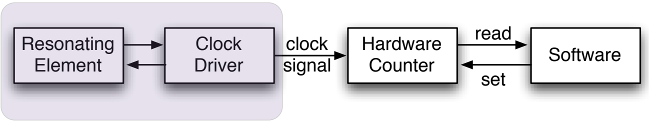
ABB Motion Control

Time in Embedded Systems



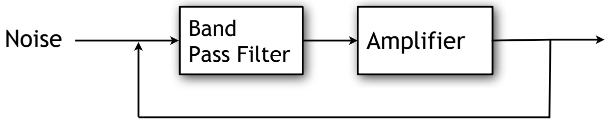
- Time is kept by a hardware counter, updated by a clock signal
- The clock signal increments the counter every $1/f$ seconds (**resolution**)
- The counter reads $c(t) = \lfloor f \cdot t \rfloor \bmod 2^n$
  - n: size of counter
- Smallest increment at which software can reader counter: **precision**
- How close is timer to UTC: **accuracy**

Resonator Technology

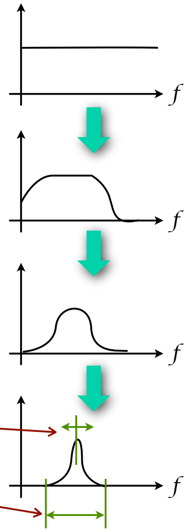


- LC/RC Circuits
- Inverter Ring
- Quartz Crystal
- MEMS Resonators
- Atomic Clock: Hydrogen Maser
- Others: Cesium, Rubidium, Ceramic, Bulk Acoustic Wave, Surface Acoustic Wave, Opto-electronic Oscillator, etc

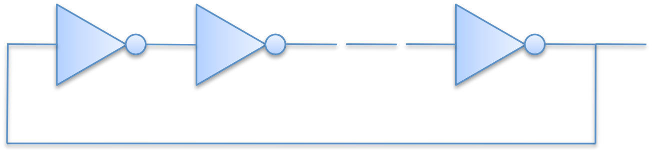
Resonator As Filter


Noise
Band Pass Filter
Amplifier

- Barkhausen Criteria:
  - For a positive feedback system, oscillation will occur when loop gain (product of forward gain and feedback gain) has zero phase shift and a magnitude greater than unity.
- Performance Metrics
  - Quality or Q factor: measure of energy loss within resonating structure.
  - Frequency Stability: How much the center of the peak moves (longer term).
  - Phase Noise: Energy around the peak (short term).



Inverter Ring



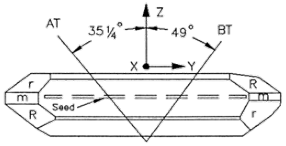
- An odd number of inverters arranged in a ring produce a frequency

$$\boxed{f(T) = 1/2N \cdot t_{pd}(T)}$$

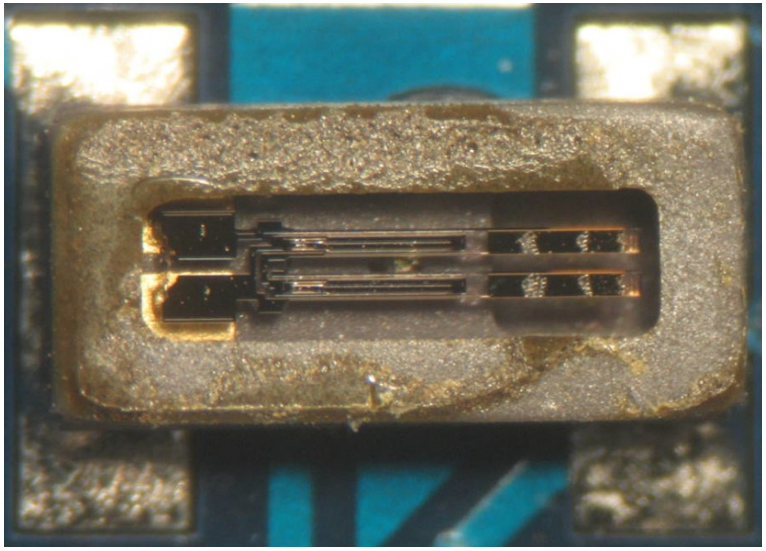
- Inverter propagation delay has strong temperature dependence, leading to frequency drift.
- Advantages:
  - Very high frequencies possible (tpd < 10ps for 90nm technology), high integration, almost zero cost when building a large chip, nearly arbitrary frequency choice.
- Disadvantages:
  - Very low Q-factor, very low stability ≈ 10^5 ppm (affected by temperature and voltage), very high phase noise.

Quartz Crystal

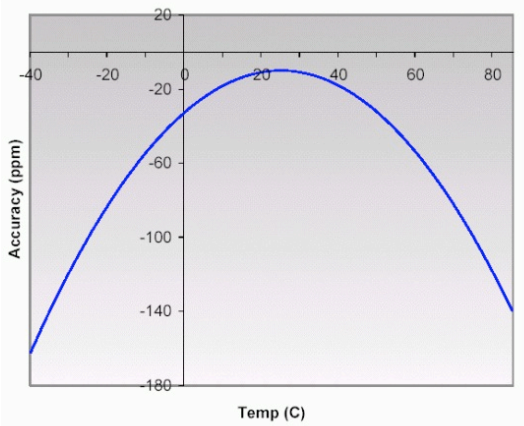
- Chemically, quartz is Silicon Dioxide and displays the Piezoelectric effect.
  - When a crystal of quartz is properly cut and mounted, it can be made to bend in an electric field.
  - When the field is removed, the quartz will generate an electric field as it returns to its previous shape.
- The resonance frequency of a quartz crystal depends on its length, thickness and angle of cut with respect to the crystallographic axes.
- Some angles have high immunity to temperature variations.
- Advantages:
  - Very high Q factor ≈ 10^6, high stability < 10^2 ppm, low phase noise.
- Disadvantage:
  - Expensive, precision engineering, not all frequencies possible with all cuts.



Tuning Fork Crystal (magnified view)



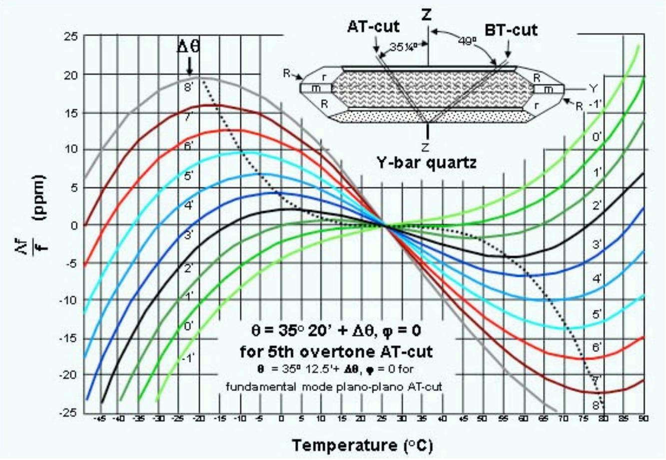
Temperature Dependence of Tuning Fork
Most common 32 kHz clock source



- Quadratic curve with zero ppm set at room temperature.

[Maxim-IC]

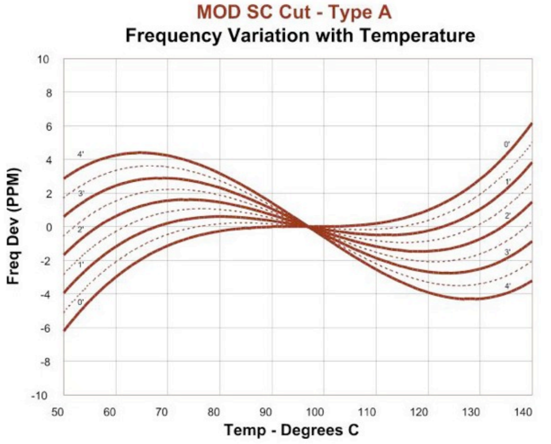
Temperature Dependence of AT-cut Quartz
Most common clock source >400 kHz



- Follows a cubic curve with parameters highly dependent on the angle of cut.

Z-Cut, SC-Cut, and many others...

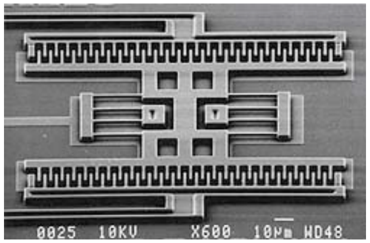
- SC-Cut is a doubly-rotated
- Can be excited in two modes at the same time!



[Bliley Technologies Inc]

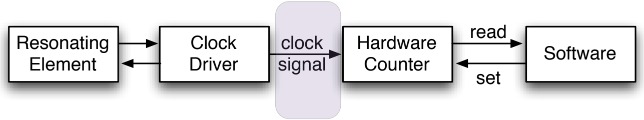
MEMS Resonator

- Micromachined structure designed for a specific resonant frequency - a tiny tuning fork.
- Exploiting silicon fabrication processes to precision engineer resonant structures at very low cost.
- Advantages: high Q-factor: 10^3-10^4, arbitrary frequency choice, large design space for future optimizations.
- Disadvantage: susceptible to temperature variations, high phase noise.

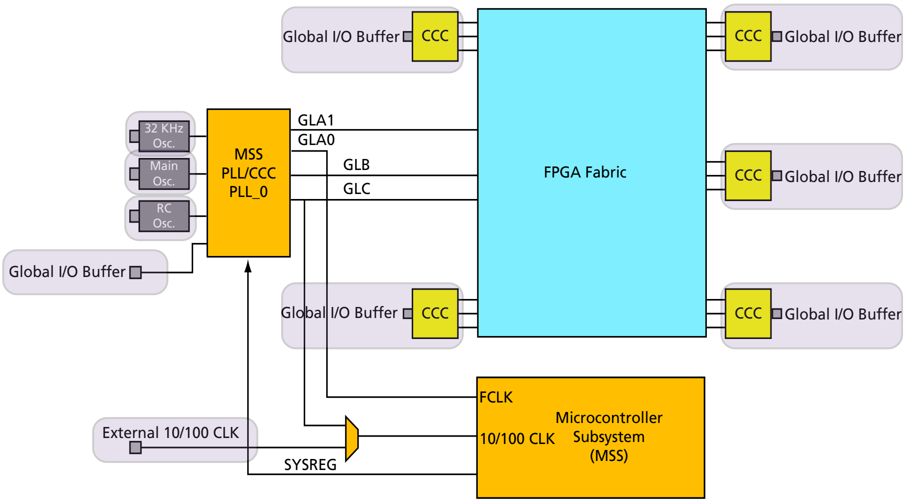


Clock Signals

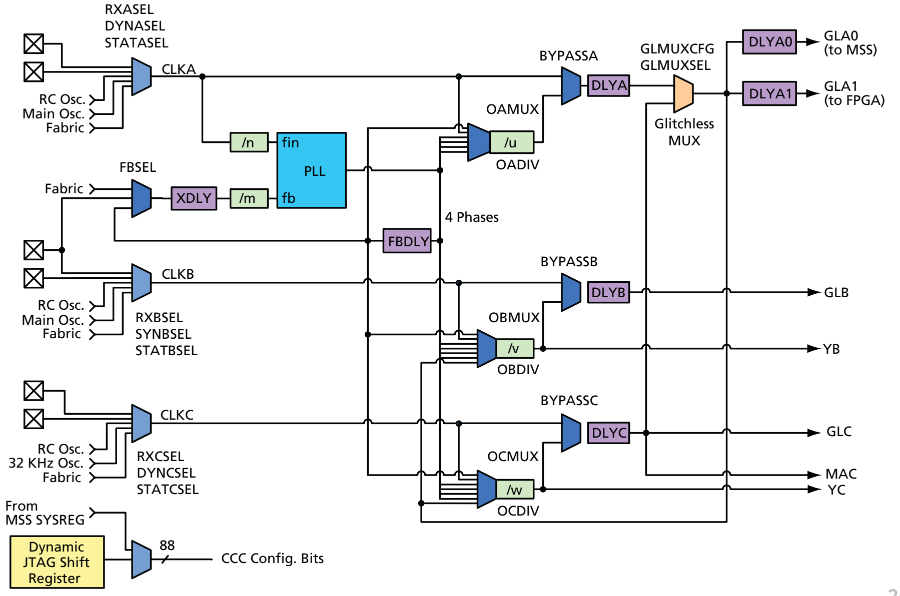
- How do we distribute and generate different clock signals?



SmartFusion Clock Hierarchy



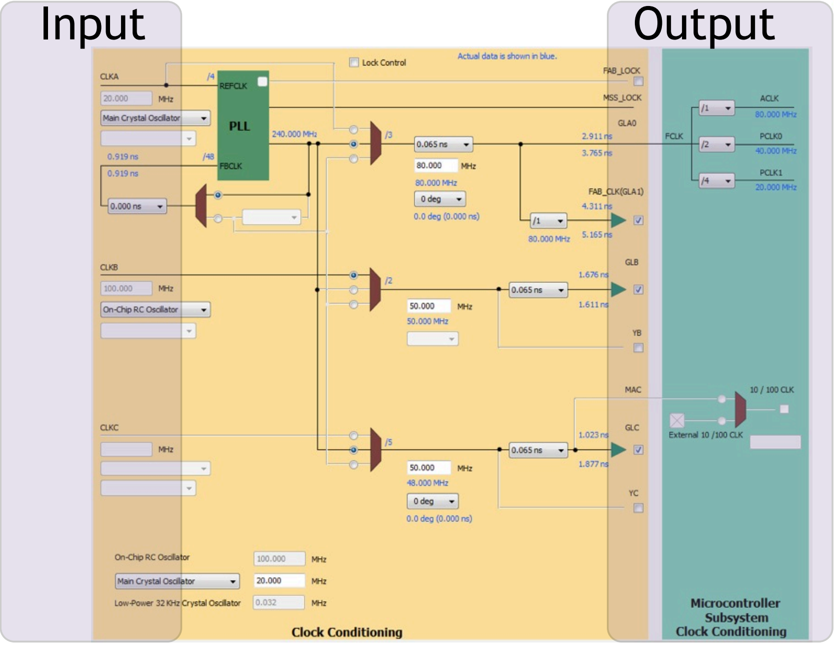
SmartFusion MSS Clock Conditioning Circuit



MSS Clock(s) Configurator

Input

Output



CLKA 20.000 MHz Main Crystal Oscillator

/4 /48 0.919 ns 0.919 ns 0.000 ns

240.000 MHz

/3 0.065 ns 80.000 MHz 80.000 MHz 0 deg 0.0 deg (0.000 ns)

GLA0 2.911 ns 3.765 ns

FAB_CLK(GLA1) /1 80.000 MHz 4.311 ns 5.165 ns ☑

FCLK: ACLK /1 80.000 MHz; PCLK0 /2 40.000 MHz; PCLK1 /4 20.000 MHz

CLKB 100.000 MHz On-Chip RC Oscillator

/2 50.000 MHz 50.000 MHz 0.065 ns

GLB 1.676 ns 1.611 ns ☑

YB ☐

CLKC MHz

/5 50.000 MHz 48.000 MHz 0 deg 0.0 deg (0.000 ns) 0.065 ns

GLC 1.023 ns 1.877 ns ☑

YC ☐

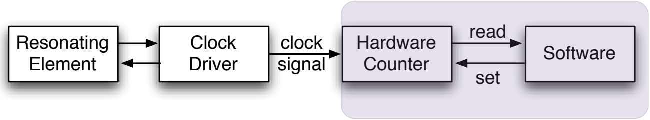
On-Chip RC Oscillator 100.000 MHz

Main Crystal Oscillator 20.000 MHz

Low-Power 32 KHz Crystal Oscillator 0.032 MHz

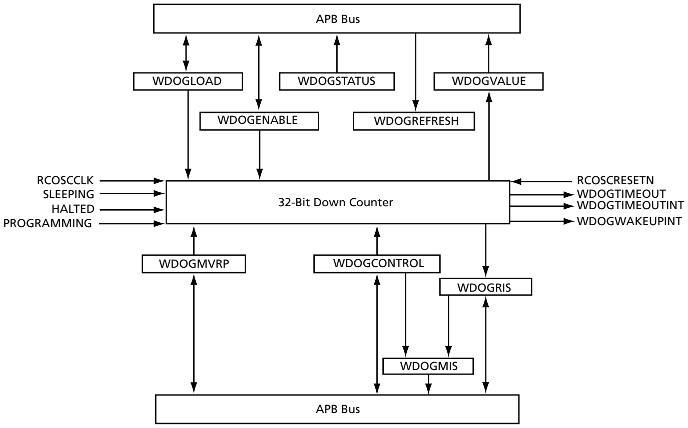
Timers, Capture, Compare, PWM

- How do we keep time?



Timers on the SmartFusion

- Watchdog Timer
  - 32-bit down counter
  - Either reset system or NMI Interrupt if it reaches 0!



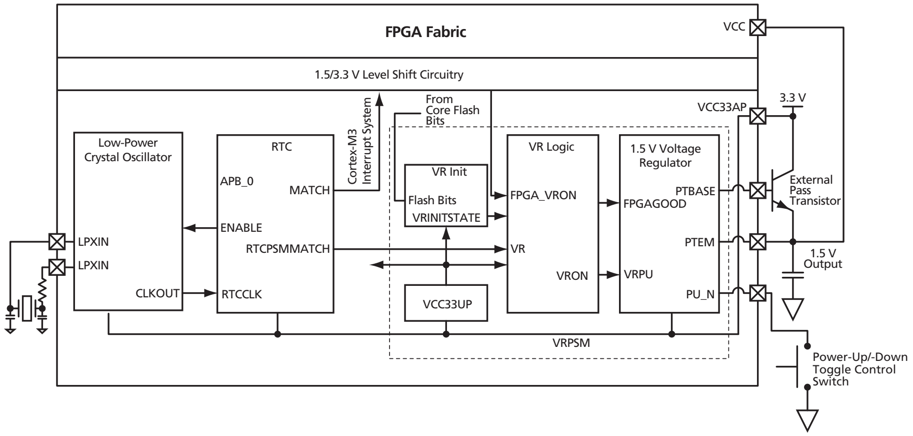
Timers on the SmartFusion (2)

- SysTick Timer
  - ARM requires every Cortex-M3 to have this timer
  - Essentially a 24-bit down-counter to generate system ticks
  - Has its own interrupt
  - Clocked by FCLK with optional programmable divider
- See Actel SmartFusion MSS User Guide for register definitions

---

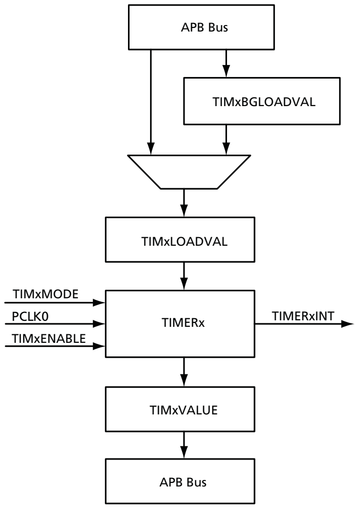
Timers on the SmartFusion (3)

- Real-Time Counter (RTC) System
  - Clocked from 32 kHz low-power crystal
  - Automatic switching to battery power if necessary
  - Can put rest of the SmartFusion to standby or sleep to reduce power
  - 40-bit match register clocked by 32.768 kHz divided by 128 (256 Hz)



Timers on the SmartFusion (4)

- System Timer
  - Two 32-bit timers that can be concatenated to one 64-bit timer
  - Clocked by PCLK0
  - One-shot or periodic interrupts
  - Load value defines upper bound



Interaction with the Outside World?

- Capture
  - Safe the time when a specific event happened, and signal an interrupt
- Compare
  - Generate an interrupt when counter reaches a specific value
  - Can set/reset/toggle a GPIO when counter reaches a specific value
- Pulse Width Modulated signal (PWM)
  - Special case of Compare
  - Set I/O when reaching a specific counter value
  - Clear I/O when reaching LOAD value
  - Usually used in continuous mode

- The SmartFusion is NOT a typical embedded MCU
- None of the timers has capabilities to interface with the outside world
- BUT: we have the FPGA fabric

Detailed View of Timer A on TI MSP430

- 16-bit Counter
  - Clock source selector
  - Dividers
  - Counter Register
  - Count Mode
    (up, down, up/down)
- Capture/Compare Unit
  - Capture Register
  - Compare Register
  - Capture/Compare Inputs
  - Interrupt
  - Output Unit

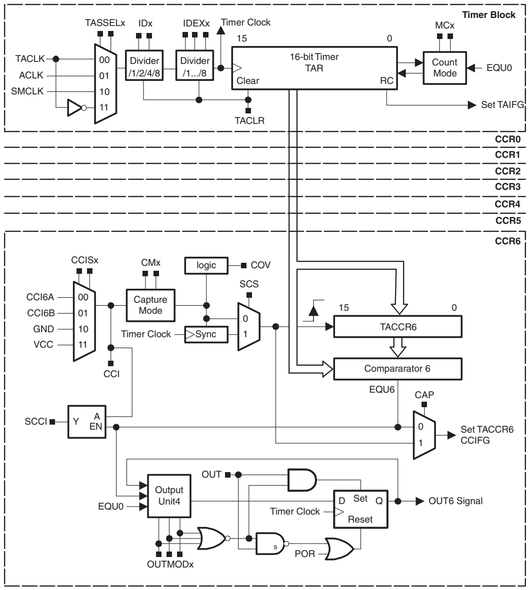
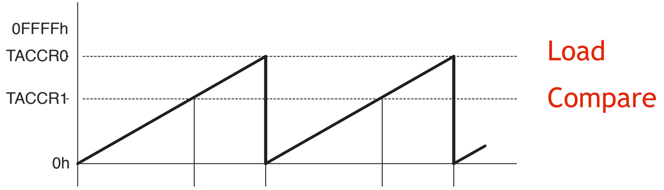


Figure 12-1. Timer_A Block Diagram

Timed Signal Generation (Timer UP mode)

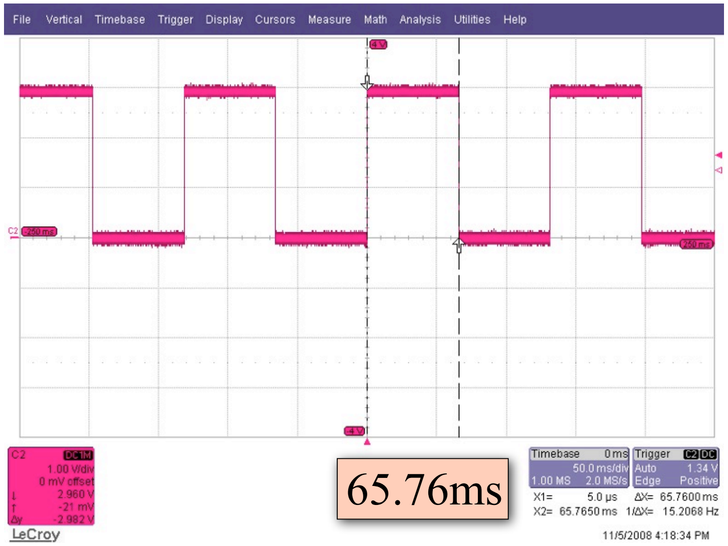


Example Code

- DCO at ~1.045MHz (on-chip RC oscillator of the MSP430)
- DCO clocks SMCLK

```
#include "msp430x54x.h"

void main(void)
{
  WDTCTL = WDTPW + WDTHOLD;                // Stop WDT
  P1DIR |= 0x01;                           // P1.0 output
  TA1CCTL0 = CCIE;                         // CCR0 interrupt enabled
  TA1CCR0 = 50000;
  TA1CTL = TASSEL_2 + MC_2 + TACLR;        // SMCLK, contmode, clear TAR

  __bis_SR_register(LPM0_bits + GIE);      // Enter LPM0, enable interrupts
  __no_operation();                        // For debugger
}

// Timer A0 interrupt service routine
#pragma vector=TIMER1_A0_VECTOR
__interrupt void TIMER1_A0_ISR(void)
{
  P1OUT ^= 0x01;                           // Toggle P1.0
  TA1CCR0 += 50000;                        // Add Offset to CCR0
}
```

Example Output



65.76ms

Timer Virtualization

- What if we don’t have enough hardware timers?
- Virtual timer library interface

```
typedef void (*timer_handler_t)(void);

/* initialize the virtual timer */
void initTimer();

/* start a timer that fires at time t */
error_t startTimerOneShot(timer_handler_t handler, uint32_t t);

/* start a timer that fires every dt time interval*/
error_t startTimerContinuous(timer_handler_t handler, uint32_t dt);

/* stop timer with given handler */
error_t stopTimer(timer_handler_t handler);
```

Timer Virtualization (2)

```
typedef struct timer
{
    timer_handler_t handler;
    uint32_t        time;
    uint8_t         mode;
    timer_t*        next_timer;
} timer_t;

timer_t* current_timer;

void initTimer() {
    setupHardwareTimer();
    initLinkedList();
    current_timer = NULL;
}

error_t startTimerOneShot(timer_handler_t handler, uint32_t t) {
    // add handler to linked list and sort it by time
    // if this is first element, start hardware timer
}

error_t startTimerContinuous(timer_handler_t handler, uint32_t dt) {
    // add handler to linked list for (now+dt), set mode to continuous
    // if this is first element, start hardware timer
}

error_t stopTimer(timer_handler_t handler) {
    // find element for handler and remove it from list
}
```

Timer Virtualization (3)

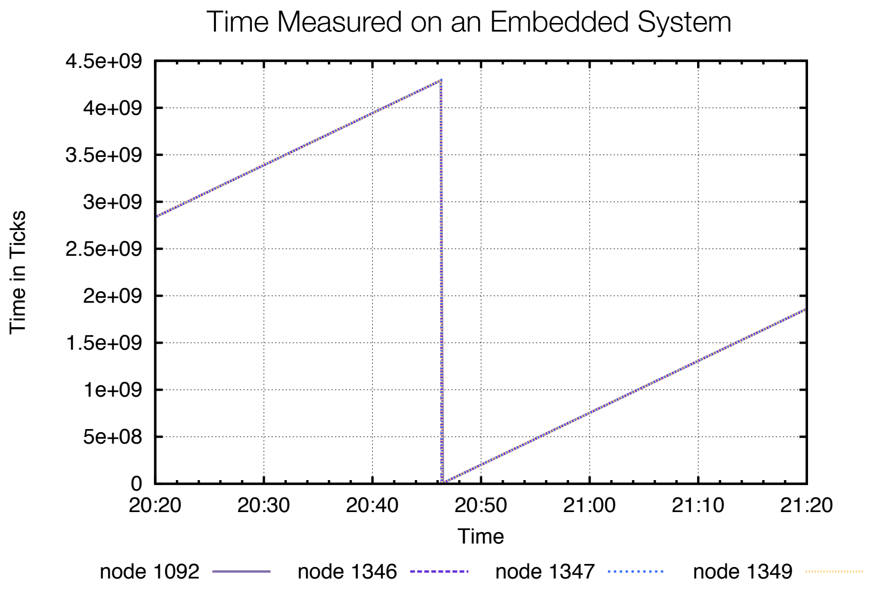
```
__attribute__((__interrupt__)) void Timer1_IRQHandler() {
    timer_t * timer;
    MSS_TIM1_clear_irq();
    NVIC_ClearPendingIRQ( Timer1_IRQn );
    timer = current_timer;

    if( current_timer->mode == CONTINUOUS ) {
        // add back into sorted linked list for (now+current_timer->time)
    }

    current_timer = current_timer->next_timer;

    if( current_timer != NULL ) {
        // set hardware timer to current_timer->time
        MSS_TIM1_enable_irq();
    } else {
        MSS_TIM1_disable_irq();
    }

    (*timer->handler))(); // call the timer handler

    if( timer->mode != CONTINUOUS ) {
        free(timer); // free the memory as timer is not needed anymore
    }
}
```

More Generic Real-Time Counters (RTC)

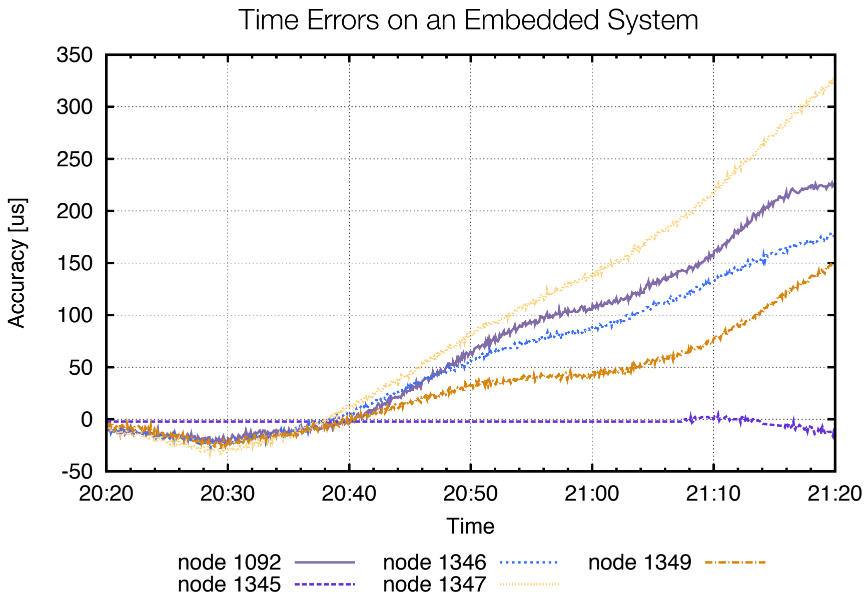
- Often provide a calendar function
- Example:
  - Maxim DS3231: Extremely Accurate I2C-Integrated RTC/TCXO/Crystal
- Accuracy
  - ±2ppm from 0˚C to +40˚C
  - ±3.5ppm from -40˚C to +85˚C
- Battery Backup Input for Continuous Timekeeping
- Low-Power Consumption (< 3.5 uA while outputing 32 kHz clock)
- Real-Time Clock
  - Counts Seconds, Minutes, Hours, Day, Date, Month, and Year
  - Leap Year Compensation Valid Up to 2100
- Two Time-of-Day Alarms
- Programmable Square-Wave Output
- Fast (400kHz) I²C Interface
- 3.3V Operation
- Digital Temp Sensor Output: ±3˚C Accuracy
- Register for Aging Trim

Clock accuracy and stability

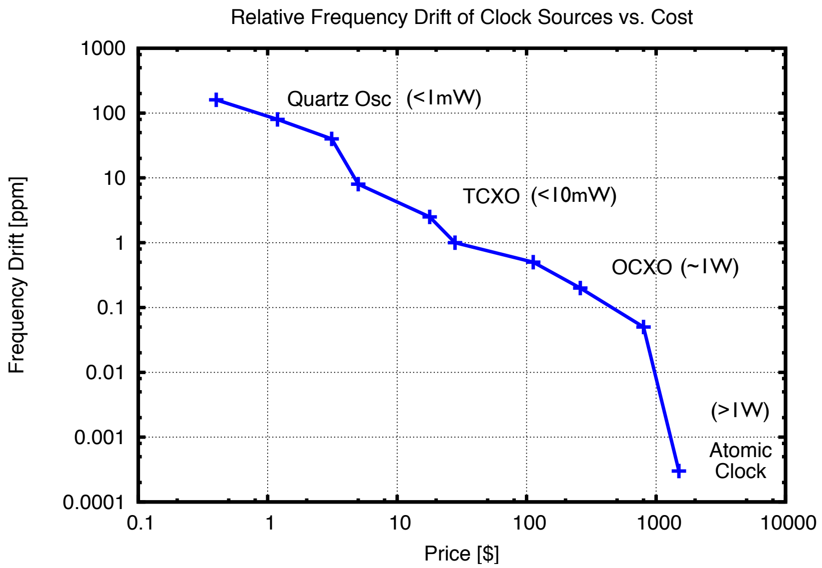
Example
4 clocks, 32 kHz clock, 32-bit counter



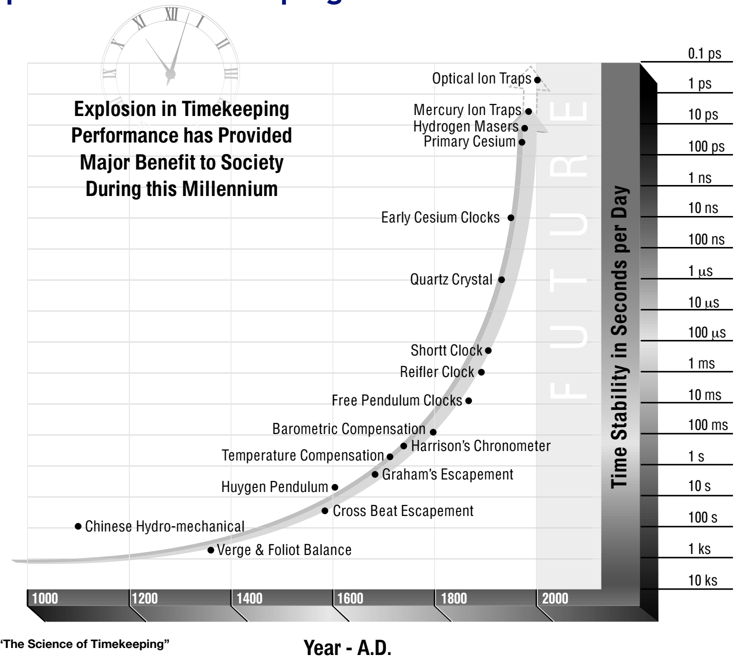
Example Errors



Resonating Elements



Explosion in Timekeeping

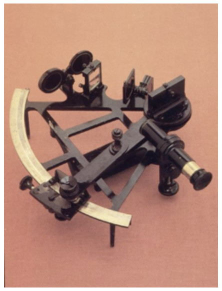


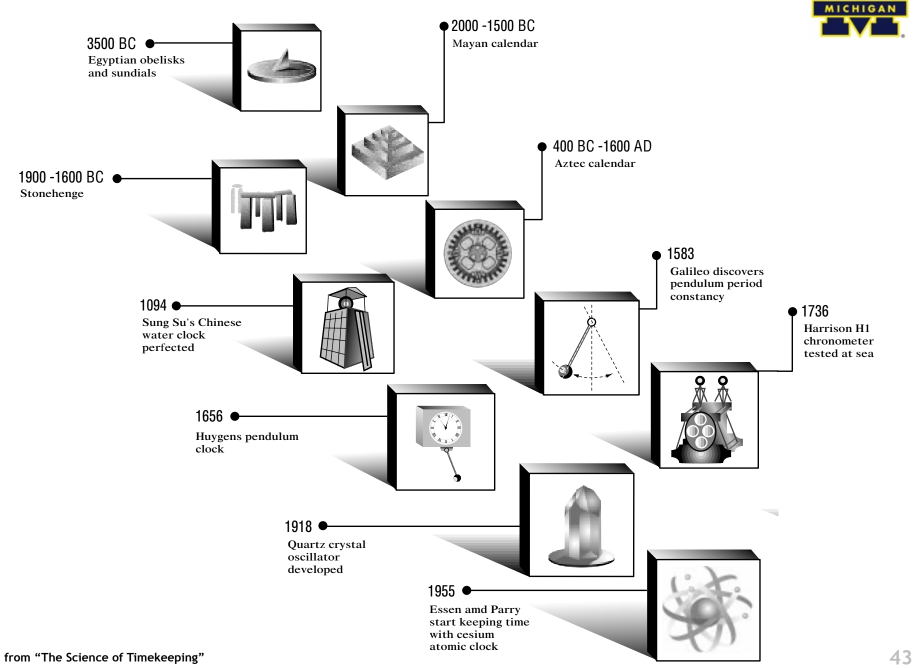
from "The Science of Timekeeping"

A short history of time

Time

- Why do we need to measure or know time?
  - Meeting times, lunch hours, office hours, opening hours
- In the 15th Century, naval exploration navigation drove time accuracy research
  - Latitude could be found with sextant by measuring the position of the sun at midday, or stars at night
  - Longitude is more difficult. You need sextant and accurate time
- 1714, British government established “The Board of Longitude”
  - £20’000 ($2,000,000 today) was offered to the person who could localize a ship within 30 nautical miles
  - This needed a clock that could keep time to within 3 seconds per day.





3500 BC
Egyptian obelisks and sundials

2000 -1500 BC
Mayan calendar

1900 -1600 BC
Stonehenge

400 BC -1600 AD
Aztec calendar

1094
Sung Su’s Chinese water clock perfected

1583
Galileo discovers pendulum period constancy

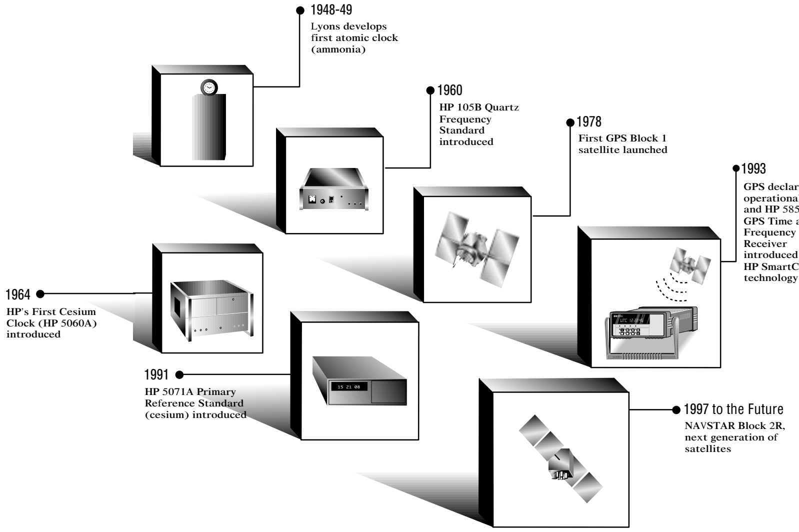
1736
Harrison H1 chronometer tested at sea

1656
Huygens pendulum clock

1918
Quartz crystal oscillator developed

1955
Essen amd Parry start keeping time with cesium atomic clock

from “The Science of Timekeeping”



1948-49
Lyons develops first atomic clock (ammonia)

1960
HP 105B Quartz Frequency Standard introduced

1978
First GPS Block 1 satellite launched

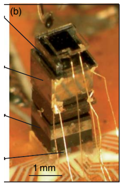
1993
GPS declared operational and HP 58503A GPS Time and Frequency Receiver introduced using HP SmartClock technology

1964
HP’s First Cesium Clock (HP 5060A) introduced

1991
HP 5071A Primary Reference Standard (cesium) introduced

1997 to the Future
NAVSTAR Block 2R, next generation of satellites

2004 Chip Scale Atomic Clocks



from “The Science of Timekeeping”, “A Microfabricated Atomic Clock,” 2004.

Time Fundamentals

- The most accurate measurement to humans is the second
- 1s = Time a cesium atom needs for 9,192,631,770 state transitions at 0°K
- Most accurate clocks can keep time to ±0.3ns, equivalent to ±1 second in 10 million years
- Many other measurements are defined from the second
  - “The length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second (17th CGP, 1983, Resolution 1)”
- International Time Standard: UTC (Coordinated Universal Time)
  - UTC is based on the International Atomic Time (TAI) with leap seconds added
  - TAI is a weighted average of about 300 atomic clocks