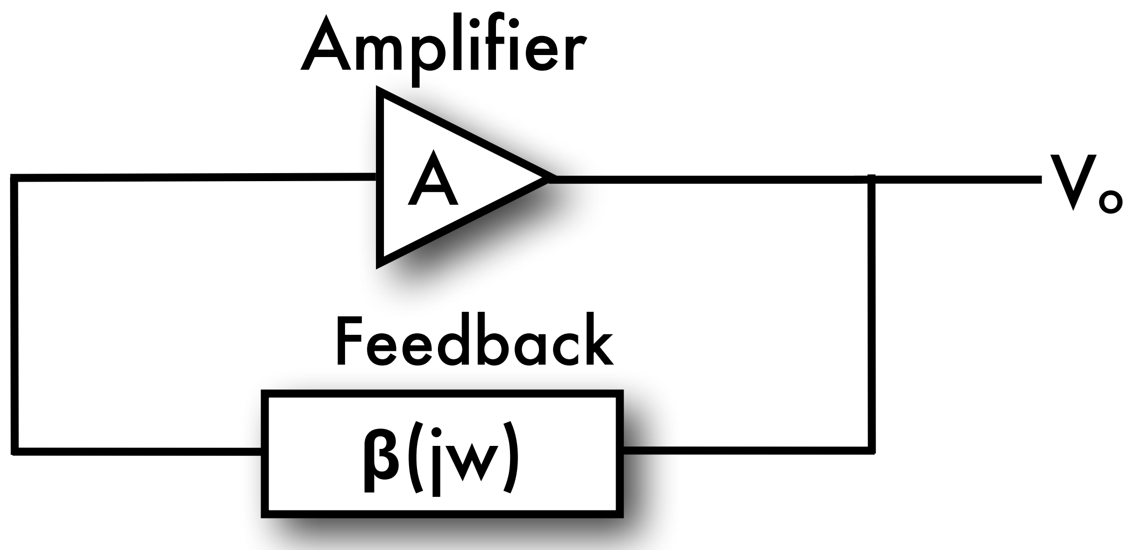
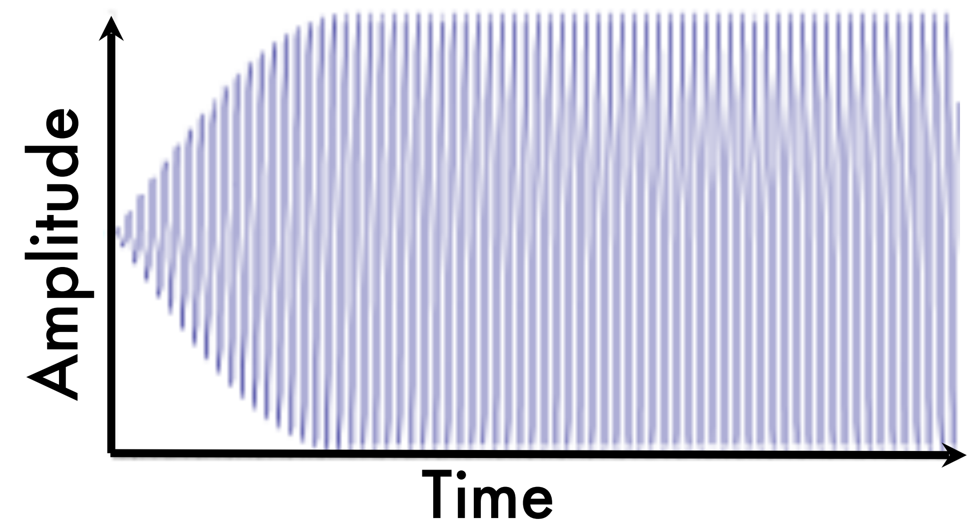
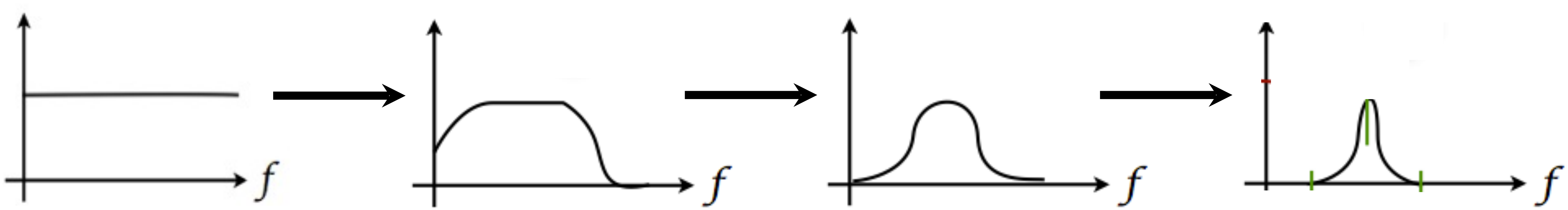
Oscillator Basics

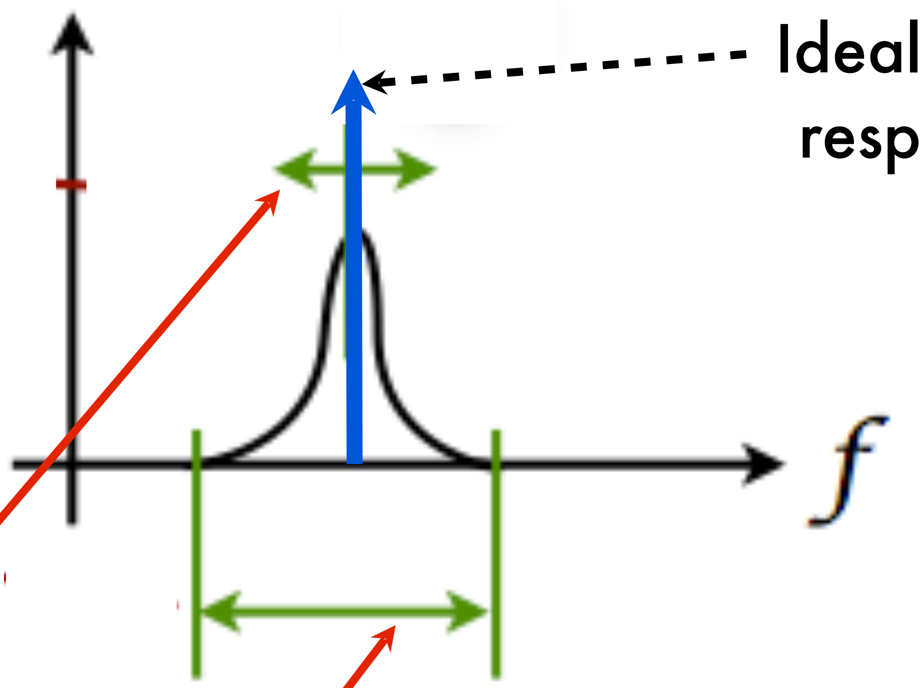




- Barkhausen criterion: A linear circuit with a feedback loop will sustain steady-state oscillations only for frequencies at which the loop gain (product of forward gain and feedback gain) has a magnitude equal to one and a phase shift equal to zero or an integer multiple of 2π
- In effect, feedback network acts as a band-pass filter
  - Initially, only noise present at amplifier input; feedback network only allows the oscillation frequency through, amplitude increases till stable oscillations start



Metrics for Oscillators



- Q factor: measure of energy loss within the resonating structure
- Frequency Stability: How much the peak frequency moves (long term)
- Phase Noise: Energy around the peak (short term)
- Startup Time: How long it takes for oscillations to start

Ring Oscillator

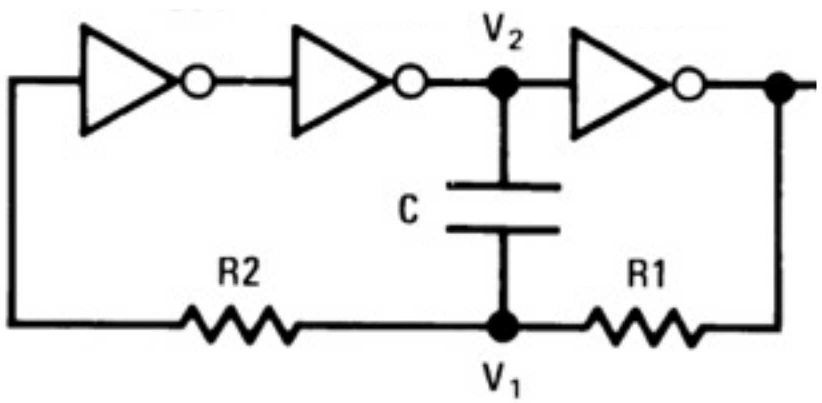
- An odd number of inverters arranged in a ring produce a frequency

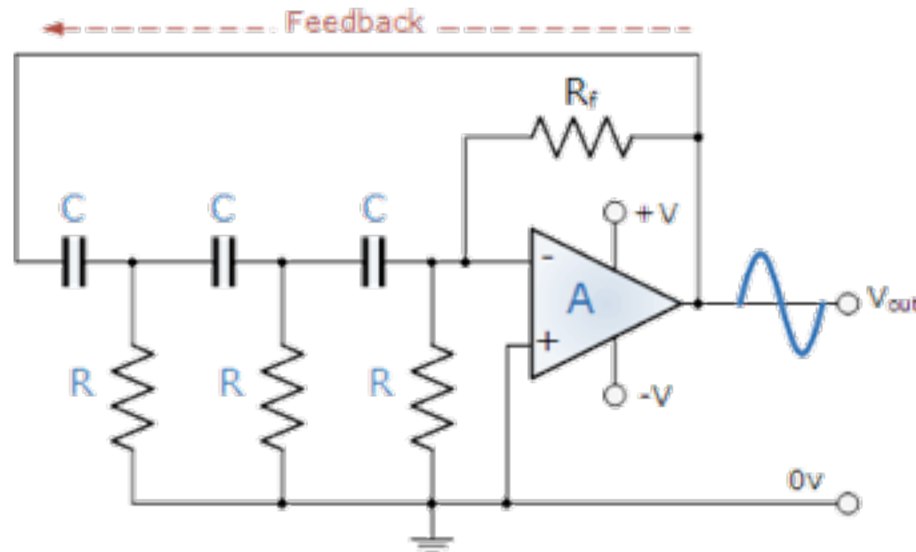
$$f_{CLK} = 1 / (2 \times N \times t_{pd})$$

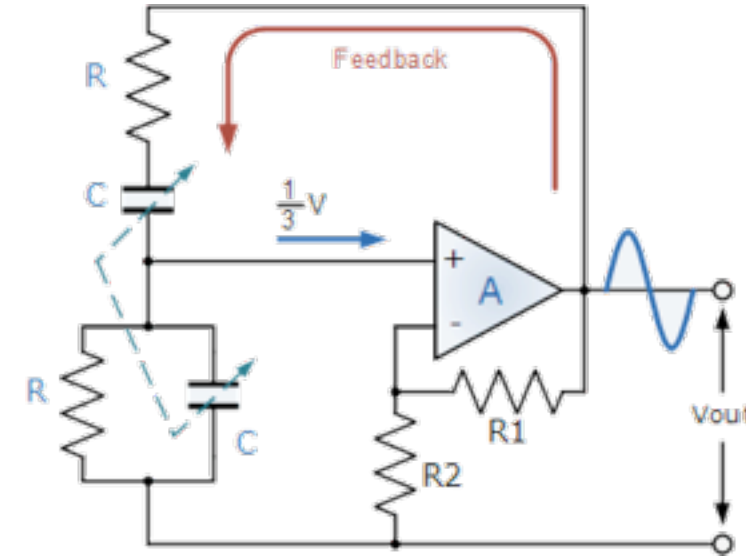
- Inverter propagation delay has a strong dependence on temperature, supply voltage, and load capacitance, leading to high frequency drift

- Advantages:
  - Very high frequencies possible (t_{pd} < 10ps for 45nm), high integration, low cost, nearly arbitrary frequency choice
- Disadvantages:
  - Very low Q-factor, very low stability ≈ 10^5 ppm (affected by temperature and voltage), very high phase noise

RC/LC Oscillators



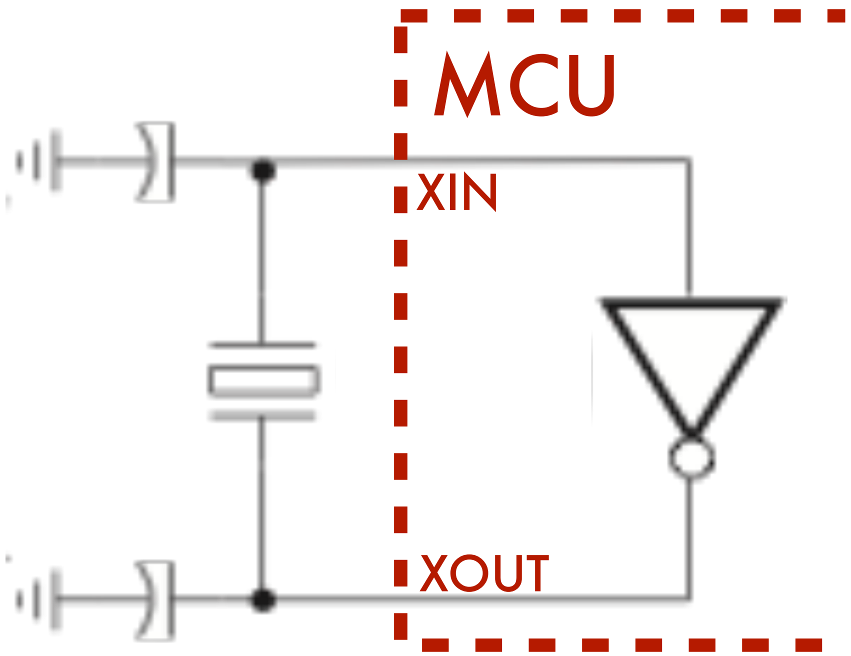




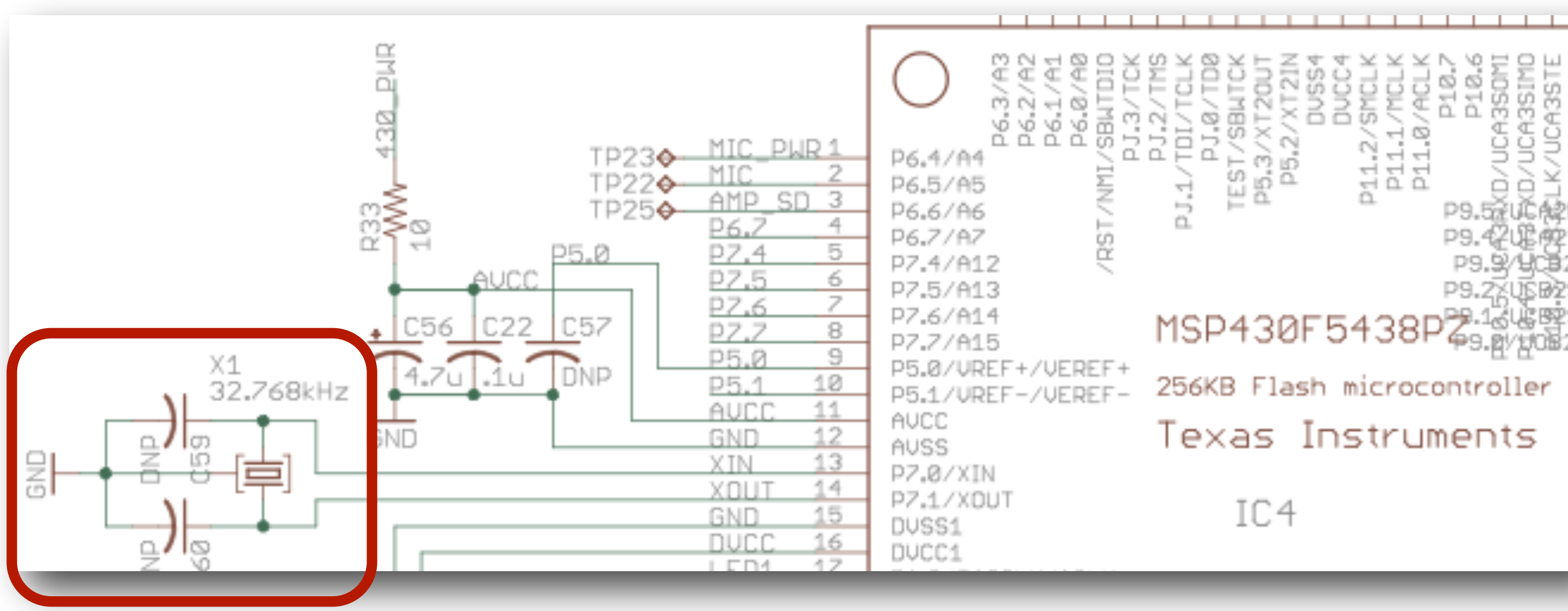
- Lots of different circuits exist for RC oscillators to produce sinusoidal as well as non-sinusoidal waveforms
- Almost all MCUs have one or more RC oscillators integrated on chip
- Also available as Si oscillator modules, with the benefits of matched components and temperature-compensation for increased stability
- Advantages:
  - Low cost, no external components, insensitive to humidity, vibration, EMI
- Disadvantages:
  - Low stability (1000 - 10000 ppm), high supply current (some types)

Crystal Oscillators

- Use the mechanical resonance of a vibrating piezoelectric material to achieve frequency-selective phase shift in the feedback network
- If properly cut and mounted, piezoelectric material distorts when an electric field is applied; if the field is removed, it generates an electric field as it returns to its original shape
- Most common type of piezoelectric material used is the quartz crystal; hence these oscillators are called crystal oscillators



Pierce Oscillator

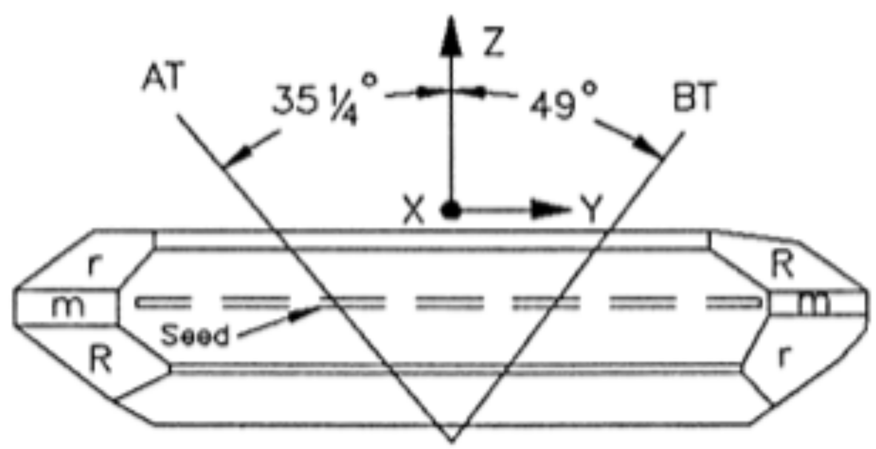


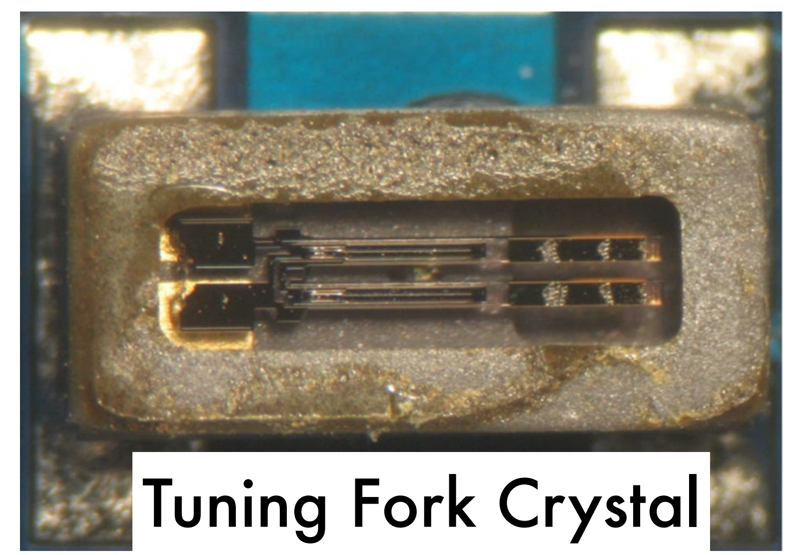
Schematic of MSP430F5438 EXP board

Quartz Crystals

- The resonance frequency of a quartz crystal depends on its length, thickness, and angle of cut with respect to the crystallographic axes
- Quartz crystals are manufactured for frequencies from a few tens of kilohertz to tens of megahertz
- Most common for 32 kHz clock: XY-cut, tuning fork crystal
- Most common for > 400 kHz clock: AT-cut crystal

Quartz





Tuning Fork Crystal

- Advantages:
  - Very high Q-factor (≈ 10^6), high stability (10 - 100 ppm), low phase noise
- Disadvantage:
  - Expensive, precision engineering, not all frequencies, susceptible to vibrations

Ceramic Resonators

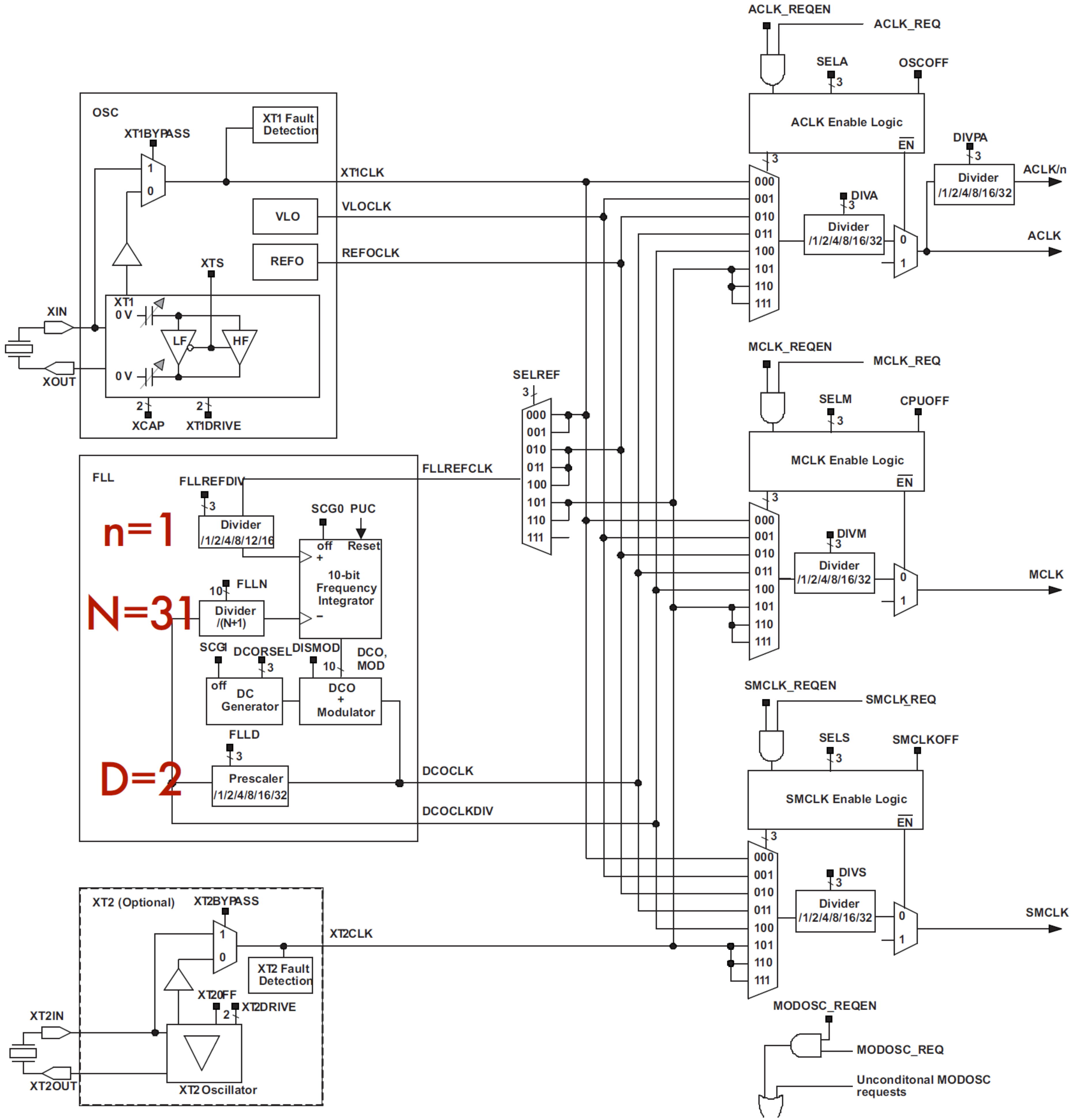
- Ceramic resonators are made of high-stability piezoelectric ceramics, generally lead zirconium titanate (PZT)
  - Principle of operation similar to quartz crystals, but cheaper to produce

- Ceramic resonators stand between quartz crystals and LC/RC oscillators in regard to accuracy

- Often have built-in load capacitors, so no external capacitors needed

- Advantages:
  - Lower cost than crystals

- Disadvantage:
  - Medium stability (100 - 1000 ppm), sensitive to EMI, vibrations, hum



ACLK_REQEN
ACLK_REQ
SELA
OSCOFF
ACLK Enable Logic
EN
DIVPA
Divider /1/2/4/8/16/32
ACLK/n
DIVA
ACLK
OSC
XT1BYPASS
XT1 Fault Detection
XT1CLK
VLO
VLOCLK
REFO
REFOCLK
XTS
XT1
0 V
LF
HF
XIN
XOUT
XCAP
XT1DRIVE
SELREF
MCLK_REQEN
MCLK_REQ
SELM
CPUOFF
MCLK Enable Logic
DIVM
MCLK
FLL
FLLREFDIV
FLLREFCLK
Divider /1/2/4/8/12/16
n=1
SCG0
PUC
off
Reset
10-bit Frequency Integrator
FLLN
Divider /(N+1)
N=31
SCG1
DCORSEL
DISMOD
DCO, MOD
DC Generator
DCO + Modulator
FLLD
Prescaler /1/2/4/8/16/32
D=2
DCOCLK
DCOCLKDIV
SMCLK_REQEN
SMCLK_REQ
SELS
SMCLKOFF
SMCLK Enable Logic
DIVS
SMCLK
XT2 (Optional)
XT2BYPASS
XT2CLK
XT2 Fault Detection
XT2OFF
XT2DRIVE
XT2IN
XT2OUT
XT2 Oscillator
MODOSC_REQEN
MODOSC_REQ
Unconditonal MODOSC requests

MSP4305xx Clock Subsystem

- Five different clock sources: 3 internal oscillators, 2 crystal oscillators
- Three different clocks: ACLK, MCLK, SMCLK

- XT1CLK: Low-frequency/high-frequency Pierce oscillator that can be used either with low-frequency 32768 Hz crystals, standard crystals, resonators, or external clock sources in the 4 MHz to 32 MHz range

- VLOCLK: Internal very low power, low frequency oscillator with 10 kHz typical frequency

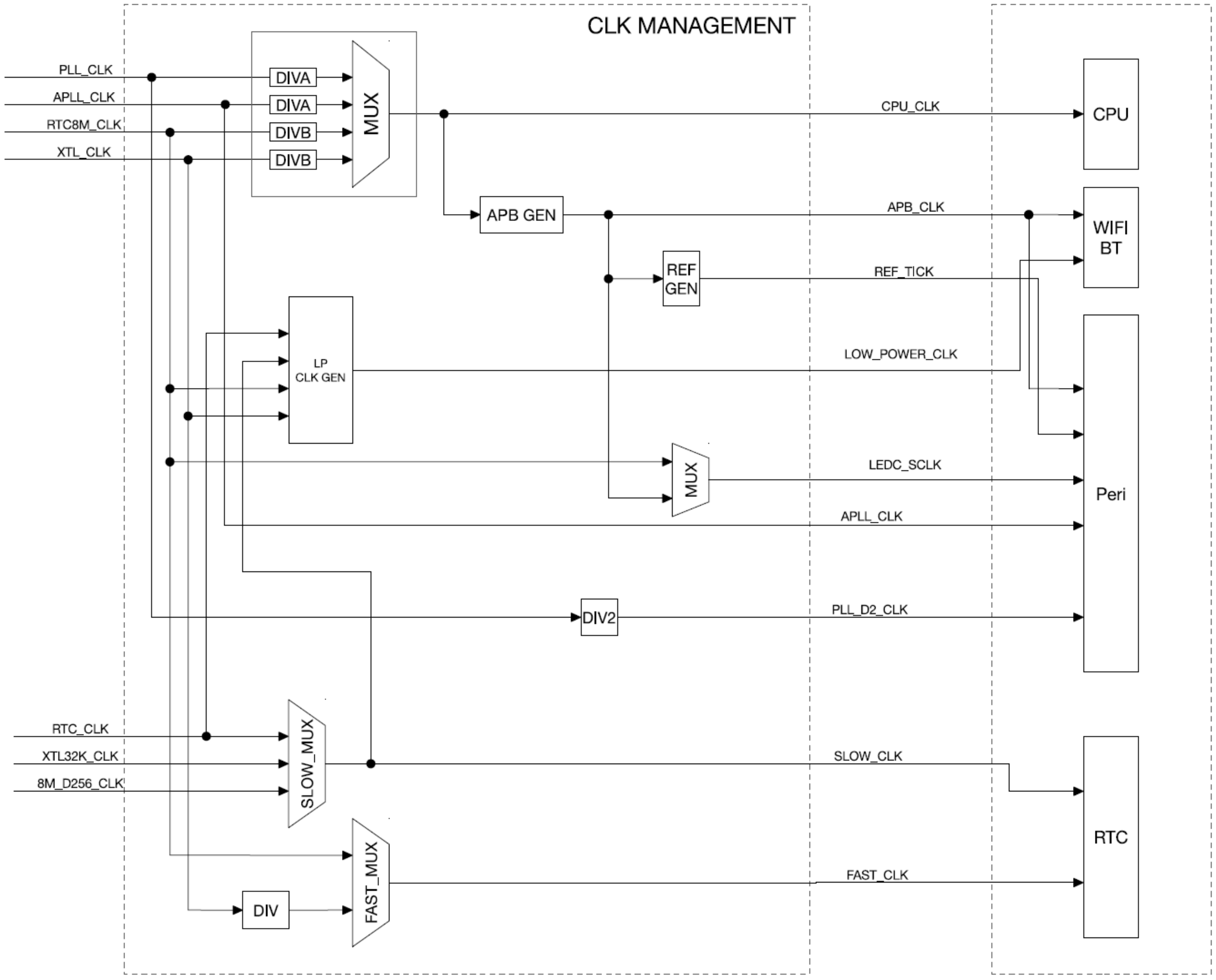
- REFOCLK: Internal, trimmed, low-frequency RC oscillator with 32768 Hz typical frequency

- DCOCLK: Internal digitally-controlled oscillator (DCO)

- XT2CLK: Optional high-frequency osc.; can be used with standard crystals, resonators, or external clocks in the 4 MHz to 32 MHz range

ESP32 Clock Subsystem

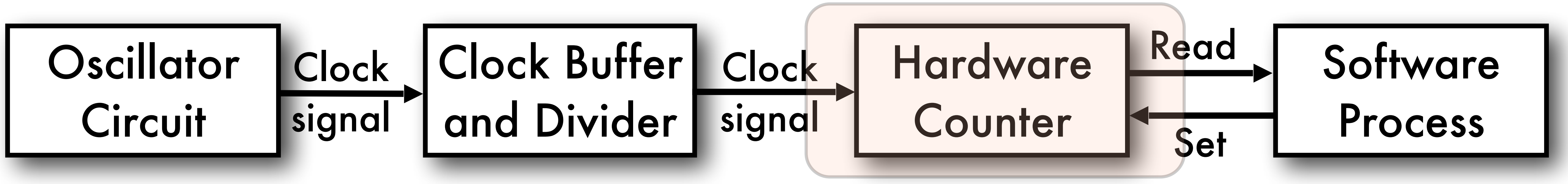
- The ESP32 integrates multiple clock sources for the CPU cores, the peripherals and the RTC. These clocks can be configured to meet different requirements.
- The ESP32 can use an external crystal oscillator, an internal PLL or an oscillating circuit as a clock source.



ESP32 Clock Subsystem

- High Speed Clocks
  - PLL_CLK is an internal PLL clock with a frequency of 320 MHz.
  - XTL_CLK is a clock signal generated using an external crystal with a frequency range of 2 ~ 40 MHz.
- Low Power Clocks
  - XTL32K_CLK is a clock generated using an external crystal with a frequency of 32 KHz.
  - RTC8M_CLK is an internal clock with a default frequency of 8 MHz.
  - RTC8M_D256_CLK is divided from RTC8M_CLK. Its frequency is (RTC8M_CLK / 256). With the default RTC8M_CLK frequency of 8 MHz, this clock runs at 31.250 KHz.
  - RTC_CLK is an internal low power clock with a default frequency of 150 KHz.
- Audio Clock
  - APLL_CLK is an internal Audio PLL clock with a frequency range of 16 ~ 128 MHz.

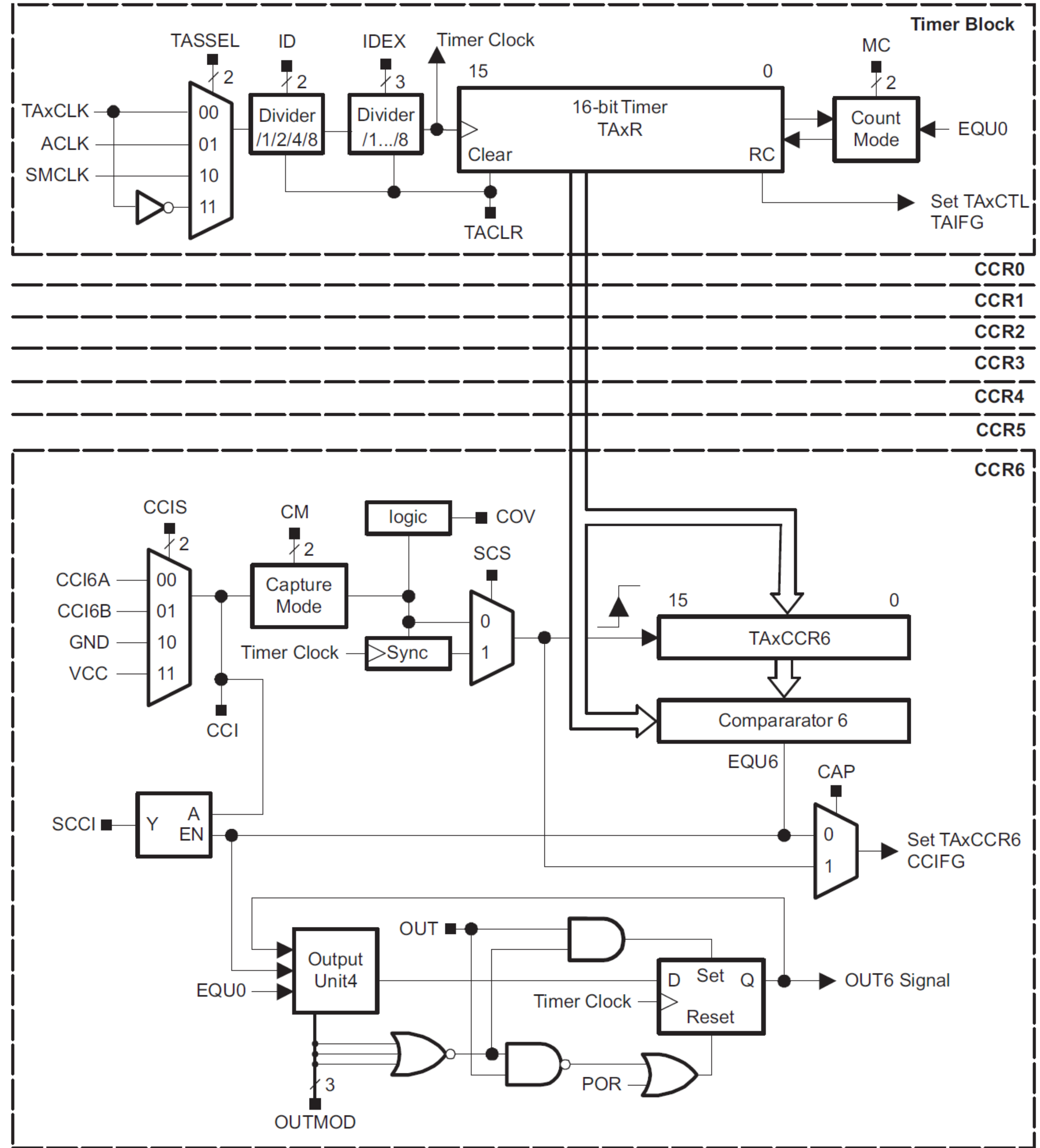
Timers: How do we Keep Time?



Timer Basics

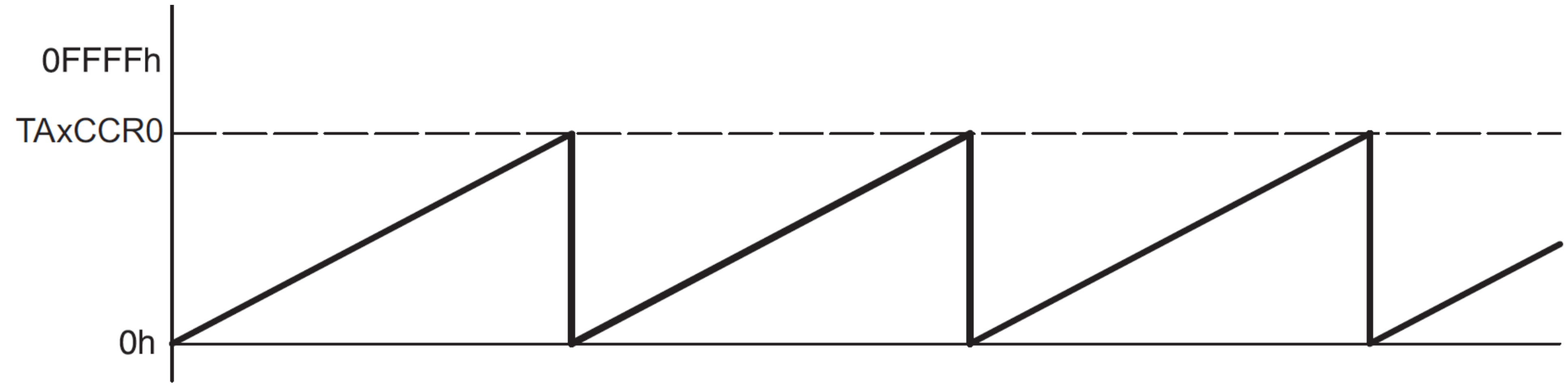
- 16-bit Counter
  - Clock source selector
  - Dividers
  - Counter Register
  - Count Mode (up, down, up/down)

- Capture/Compare Unit
  - Capture Register
  - Compare Register
  - Capture/Compare Inputs – Interrupt
  - Output Unit

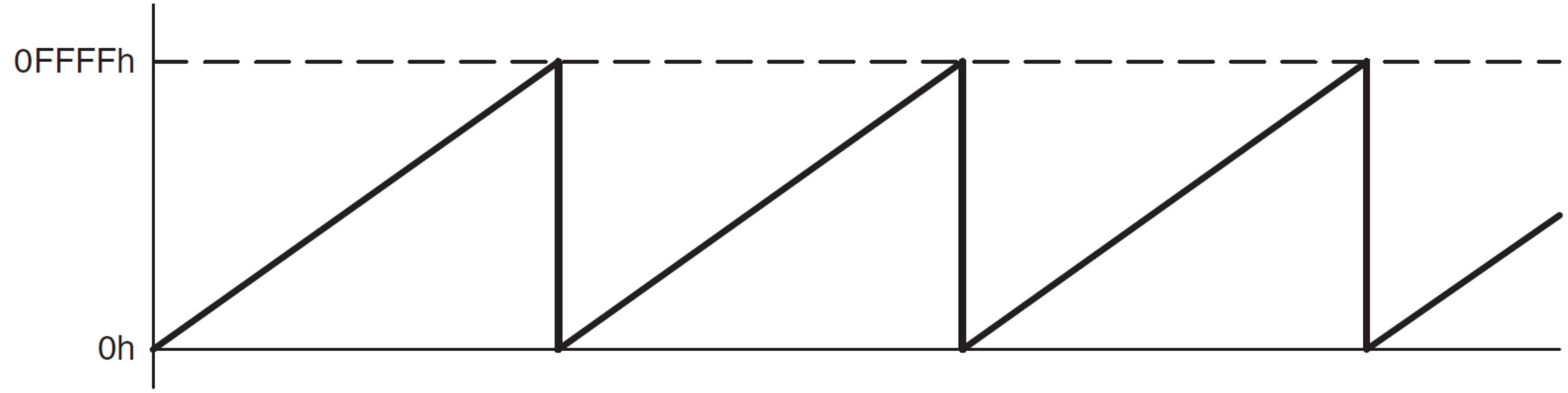


Timer counting modes

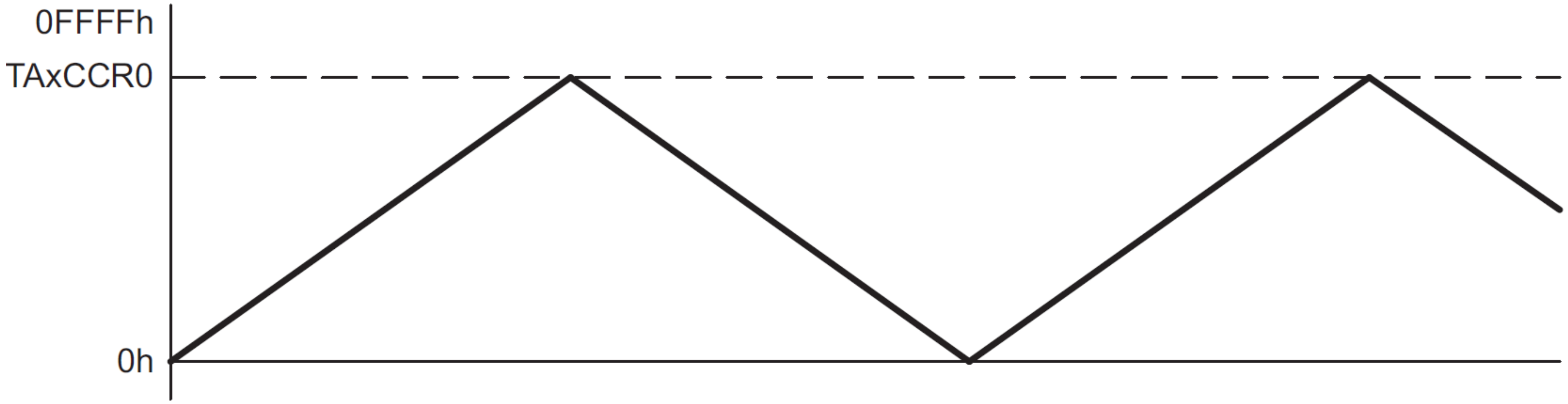
Up mode



Continuous mode



Up/Down mode



Capture, Compare, PWM

- Input Capture Mode: Save time when a specific event occurs and signal interrupt

- Output Compare Mode: Generate interrupt when counter reaches a specific value
  - Can set/reset/toggle a GPIO when counter reaches a specific value

- Output/ Pulse Width Modulated (PWM): Special case of Output Compare Mode
  - Set I/O when reaching a specific counter value
  - Clear I/O when reaching LOAD value
  - Usually used in continuous mode