Capacitance Meter Using ATmega128

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Motivation

Capacitor tolerances are commonly $\pm 20\%$... does this matter?

- Digital applications ✓
  - Usually just a decoupling cap, precise value doesn't matter
- Analog applications ✗
  - Used in filters, for which cutoff frequency is important
  - Matching requirements in data converters often $< 0.1\%$
  - Exacerbated in high-frequency PLLs and RF transceivers

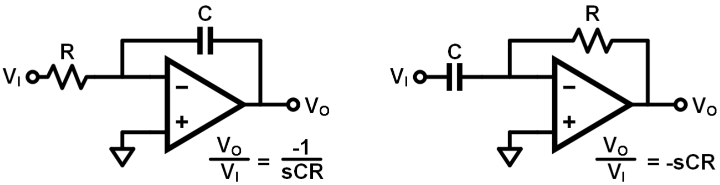

Figure 1: Examples of capacitors used in integrator (left) and differentiator (right)

I-V Characteristics of Capacitor

Integral form of capacitor voltage:

$$V(t) = \frac{1}{C}\int_{t_0}^{t} I(\tau)d\tau + V(t_0)$$

$$C = \frac{1}{V(t) - V(t_0)}\int_{t_0}^{t} I(\tau)d\tau$$

Two assumptions to greatly simplify this: constant current $I(\tau) = I_O$, and initial condition $V(t_0) = 0$. Then:

$$C = \frac{1}{V(t)} \cdot I_O \cdot (t - t_0)$$

$$C = \frac{I_O \cdot \Delta t}{V(t)}$$

I-V Characteristics of Capacitor

$$C = \frac{I_O \cdot \Delta t}{V(t)}$$

Two options to measure unknown C:

1) Measure $V(t)$ after fixed Δt
- Some fixed delay using timer
- Use analog-to-digital (ADC) to read $V(t)$
- $C \propto \frac{1}{V(t)}$ ✗

2) Count Δt to reach fixed $V(t)$
- Fixed threshold voltage with analog comparator
- Count Δt with timer
- $C \propto \Delta t$ ✓

Analog Comparator within ATmega128

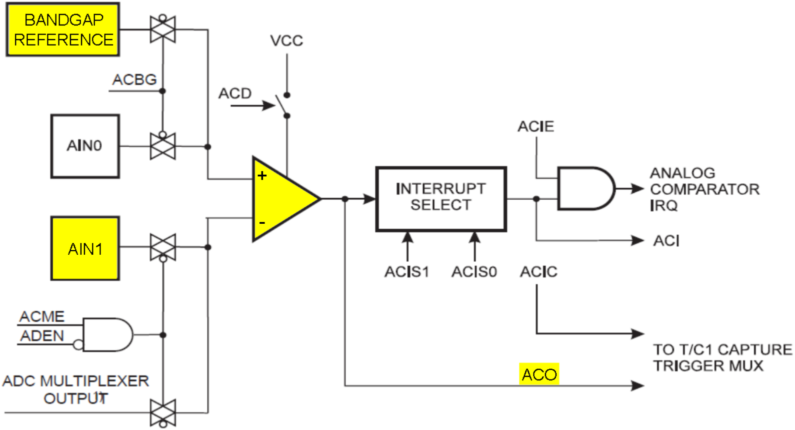

Figure 2: Analog Comparator block diagram[1]

Q: What is so great about having a bandgap reference?

[1] ATmega128 Datasheet (2011), p. 227

Comparator Output Waveform

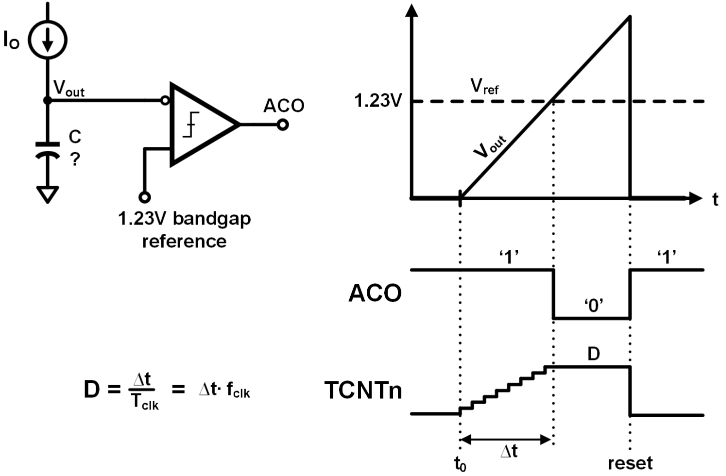

Figure 3: Using analog comparator to track charging progress

Implementing DC Current Source

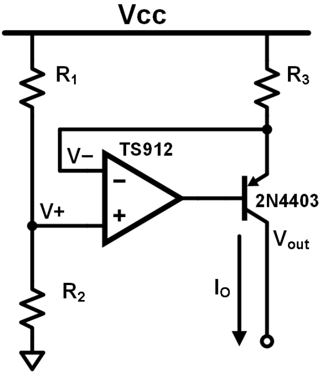

Figure 4: Providing constant current with opamp

Main points:

1. Feedback path forces $V_+ = V_-$
2. Voltage drop over R_3 determines output current
3. BJT acts as unity-gain current buffer
4. Works well for $V_{out} < V_- - V_{ECsat}$
   - $R_2 = 10 \cdot R_1$ gives large headroom

$$I_O = \frac{V_{cc} - V_-}{R_3} = \frac{V_{cc} - V_+}{R_3}$$

$$= \frac{V_{cc} - (\frac{10}{11})V_{cc}}{R_3} = \frac{V_{cc}}{11 \cdot R_3}$$

Determining D→C Transfer Function

From before:

$$C = \frac{I_O \cdot \Delta t}{V(t)}$$

where

$$\Delta t = \frac{D}{f_{clk}} \qquad I_O = \frac{V_{cc}}{11 \cdot R_3}$$

Then transfer function is given by:

$$C = \frac{V_{cc} \cdot D}{11 \cdot R_3 \cdot V_{ref} \cdot f_{clk}}$$

Determining D→C Transfer Function

Assuming[2] $V_{cc} = 5V$ and with $R_3 = 1k$:

$$C = \frac{5 \cdot D}{11 \cdot 1k \cdot 1.23 \cdot 16M} = (2.30968 \cdot 10^{-11})D \quad [F]$$
$$= 0.0230968 \cdot D \quad [nF]$$
$$10 \cdot C = 0.230968 \cdot D \quad [nF]$$

- For digital arithmetic, calculating $10C$ makes result "look like" floating point number
  - Just insert decimal point before writing to LCD
- D comes from 16-bit TCNTn, so range is 23pF to 1.5μF

Q: What are two ways to change this range?

[2] Those of you using USB power may have different value

Final Hardware Design

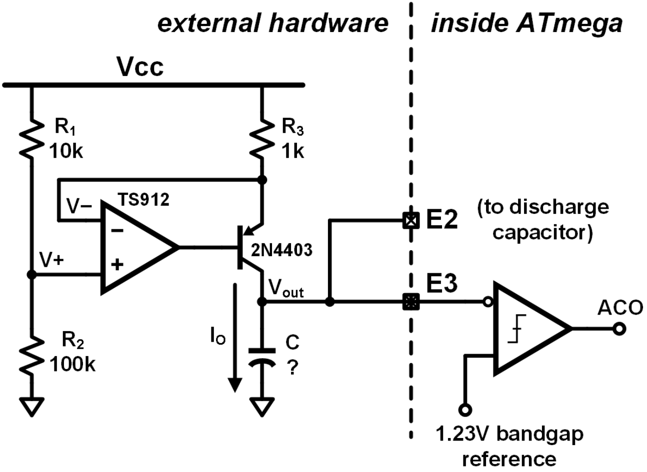

Figure 5: Schematic of capacitance meter with ATmega128

Sources of Error

- Offset errors
  - Capacitor doesn't fully discharge
  - Counter starts before capacitor starts charging
  - Equivalent series resistance (ESR)
  - I/O pin contributes some fixed capacitance
- Gain errors
  - Supply voltage variations
  - Component tolerances
- Nonlinearity
  - Current source nonlinearity
  - Capacitance may change with voltage

Sources of Error

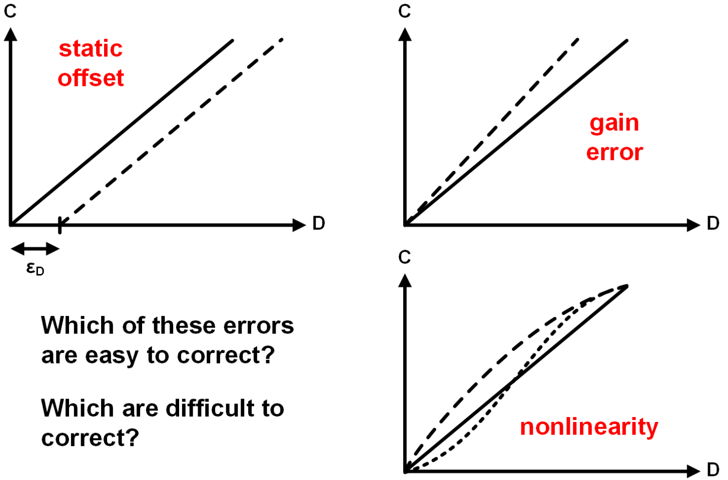

Figure 6: Illustration of D→C errors

Calibrating Errors

$$C = m \cdot (D - \epsilon_D)$$

- Static offset: ϵ_D is count when $C = 0$
- Gain error: nominally 0.230968, but can be determined experimentally using well-known capacitor values
- Nonlinearity: sometimes implemented as piece-wise gain error, or as a look-up table
  - Generally a more complicated beast, outside the scope of this discussion

Relevance to ADC Design

Alternatively, suppose that C is known and reference voltage is unknown V_{IN}:

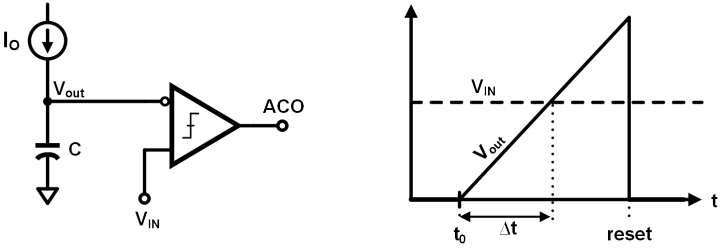

Figure 7: Capacitance meter reconfigured as ADC

ADC transfer function looks like:

$$V_{IN} = \frac{I_O \cdot D}{C \cdot f_{clk}}$$

Relevance to ADC Design

Integrating quantizer is one of many ADC architectures. Others include:

- Flash
- Pipeline
- Successive Approximation
- Incremental
- $\Delta\Sigma$ modulator

ADCs are *inherently* mixed-signal design... requires background in both analog (ECE 422/423/520) and digital (ECE 46x/471/474) circuits, as well as scripting (MATLAB, Bash, HSpice).