EECS 247

Analog-Digital Interface Integrated Circuits

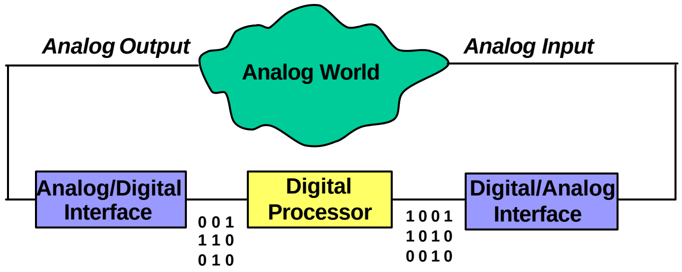
Instructor: Haideh Khorramabadi

UCB
Department of Electrical Engineering and Computer Sciences

Administrative

- Course web page:
  http://www.eecs.berkeley.edu/~EE247
  - All handouts are available on the web
- Office hours for Haideh Khorramabadi
  - Tuesday 2-4pm @ 463 Cory Hall
  - Email: haidehk@eecs.berkeley.edu
- Homework is posted on the course website and are due on Thursdays
- Midterm 10/19

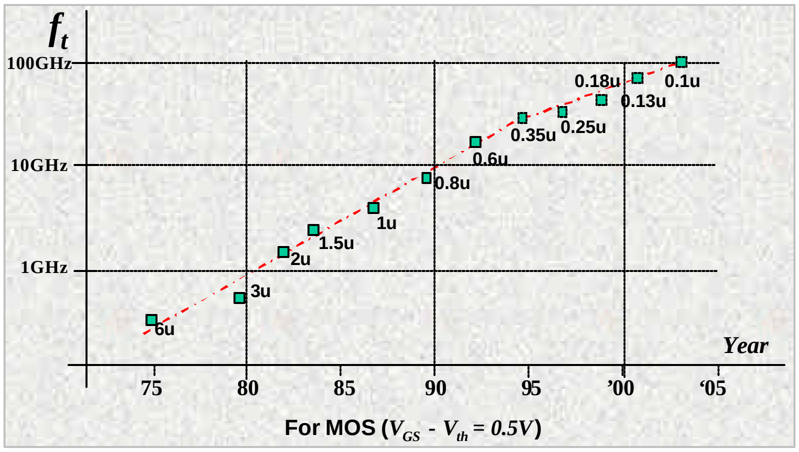
Analog-Digital Interface Circuits



- Naturally occurring signals are analog
  → Need Analog/Digital & Digital/Analog interface circuits

Question: Why not process the signal with analog circuits only & thus eliminate need for A/D & D/A?

MOSFET Maximum f_t v.s. Time



Ref: Paul R. Gray UCB EE290 course '95
International Technology Roadmap for Semiconductors, http://public.itrs.net

Digital Signal Processing Characteristics

- Direct benefit from the down scaling of VLSI technology
- Not sensitive to “analog” noise
- Enhanced functionality & flexibility
- Amenable to automated design & test
- “Arbitrary” precision
- Provides inexpensive storage capability

Analog Signal Processing Characteristics

- Has not fully benefited from the down scaling of VLSI technology
  - Supply voltages scale down accordingly
    → reduced voltage swings
  - Reduced voltage swings requires lowering of the circuit noise to keep a constant dynamic range
    → Higher power dissipation and chip area
- Sensitive to “analog” noise
- Not amenable to automated design
- Extra precision comes at a high price
- Availability of inexpensive digital capabilities on-chip enables automatic adjustments to compensate for analog circuit impairments
- Rapid progress in DSP has imposed higher demands on analog/digital interface circuitry
  → Plenty of room for innovations!

Cost/Function Comparison
DSP & Analog

- Digital circuitry: Fully benefited from CMOS device scaling
  - Cost/function decreases by ~29% each year
    →Cost/function 30X in 10 years*
- Analog circuitry: Not fully benefited from CMOS scaling
  - Device scaling mandates drop in supply voltages→ threaten analog feasibility
    →Cost/function for analog ckt almost constant or increase
- Rapid shift of functions from analog to digital signal processing & hence need for A/D & D/A interface circuitry

*Ref : International Technology Roadmap for Semiconductors, http://public.itrs.net

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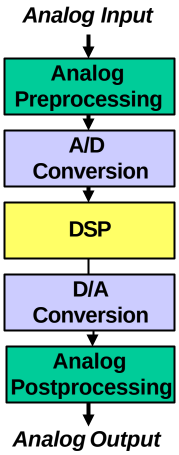
Example: Digital Audio

- Goal-Lossless archival and transmission of audio signals
- Circuit functions:
  - Preprocessing
    - Amplification
    - Anti-alias filtering
  - A/D Conversion
    - Resolution→16Bits
    - Sig. bandwidth→41kHz
  - DSP
    - Storage
    - Processing (e.g. recognition)
  - D/A Conversion
  - Postprocessing
    - Smoothing filter
    - Amplification



Example: Typical Cell Phone

Contains in integrated form:

- 4 Rx filters
- 4 Tx filters
- 4 Rx ADCs
- 4 Tx DACs

} Dual Standard, I/Q

- 3 Auxiliary ADCs
- 8 Auxiliary DACs

} Audio, Tx/Rx power control, Battery charge control, display, ...

Total: Filters → 8

ADCs → 7

DACs → 12

Areas Utilizing Analog/Digital Interface Circuitry

- **Communications**
  - Wireline communications
    - Telephone related (DSL, ISDN, CODEC)
    - Television circuitry (Cable modems, TV tuners…)
    - Ethernet (Gigabit, 10/100BaseT…)
  - Wireless
    - Cellular telephone (CDMA, Analog, GSM….)
    - Wireless LAN (Blue tooth, 802.11a/b/g…..)
    - Radio (analog & digital), Television
- **Computing & Control**
  - Storage media (disk drives, digital tape)
  - Imagers & displays
- **Instrumentation**
  - Test equipment
  - Physical sensors & actuators
- **Consumer Electronics**
  - Audio (CD, DAT)
  - Automotive control, appliances, toys

UCB Analog Courses
EECS 247 - 240 - 242

- EECS 247
  - Filters, ADCs, DACs, some system level
  - Signal processing fundamentals
  - Macro-models, large systems, some transistor level, constraints such as finite gain, supply voltage, noise, dynamic range considered
  - CAD Tools → Matlab, SPICE

- EECS 240
  - Transistor level, building blocks such as opamps, buffers, comparator….
  - Device and circuit fundamentals
  - CAD Tools → SPICE

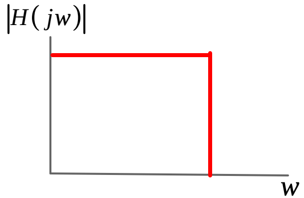
- EECS 242
  - RF amplification, mixing
  - Oscillators
  - Exotic technology devices
  - Nonlinear circuits

Material Covered in EE247

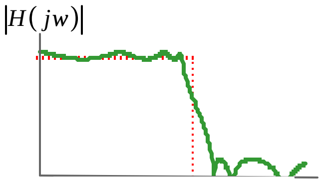
- Filters
  - Continuous-time filters
    - Biquads & ladder type filters
    - Opamp-RC, Opamp-MOSFET-C, gm-C filters
    - Automatic frequency tuning
  - Switched capacitor (SC) filters
- Data Converters
  - D/A converter architectures
  - A/D converter
    - Nyquist rate ADC- Flash, Pipeline ADCs,….
    - Oversampled converters
    - Self-calibration techniques
- Systems utilizing analog/digital interfaces
  - Wireline communication systems- ISDN, XDSL…
  - Wireless communication systems- Wireless LAN, Cellular telephone,…
  - Disk drive electronics
  - Fiber-optics systems

Introduction to Filters

- Filtering → Frequency-selective signal processing
  - It's the most common type of signal processing
  - Examples:
    - Extraction of desired signal from many (radio)
    - Separating signal and noise
    - Amplifier bandwidth limitations

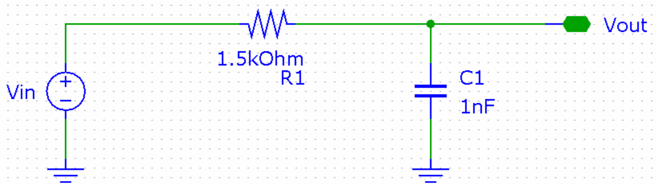


Ideal Low-Pass Brick Wall Filter



More Practical Filter

Simplest Filter
First-Order RC Filter (LPF1)



Steady-state frequency response:

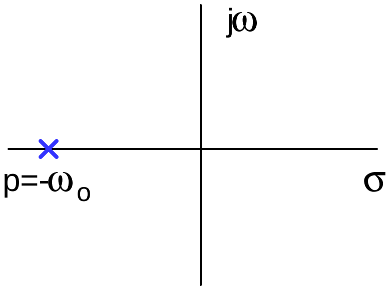
$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{1 + \frac{s}{\omega_o}}$$

with $$\omega_o = \frac{1}{RC} = 2\pi \times \underline{100kHz}$$

Poles and Zeros

$$H(s) = \frac{1}{1 + \frac{s}{w_o}}$$

s-plane (pzmap):



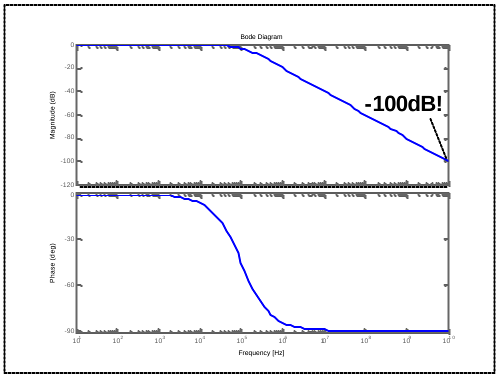
Pole : $p = -w_o$

Zero : $z \rightarrow \infty$

Filter Frequency Response
Bode Plot

$$\left| H(s = jw) \right|_{w=0} = 1$$

$$\left| H(s = jw) \right|_{w \rightarrow \infty} = 0$$



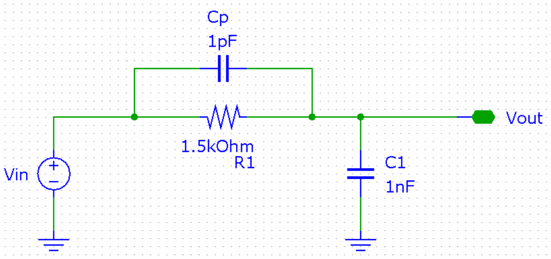
-100dB!

Asymptotes:

- 20 dB/dec magnitude rolloff
- 90 degrees phase shift per 2 decades

Question: can we really get 100dB attenuation at 10GHz?

First-Order RC Filter
Including Parasitics (LPF2)



$$H(s)=\frac{1+sRC_P}{1+sR\left(C+C_P\right)}$$

$$\text{Pole}:\quad p=-\frac{1}{R\left(C+C_P\right)}\approx-\frac{1}{RC}$$

$$\text{Zero}:\quad z=-\frac{1}{RC_P}$$

Filter Frequency Response

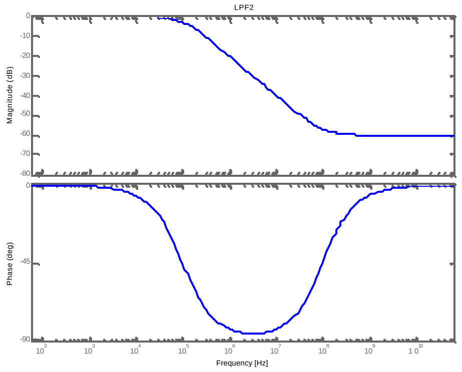
$$\left|H(jw)\right|_{w=0}=1$$

$$\left|H(jw)\right|_{w\to\infty}=\frac{C_P}{C+C_P}$$

$$\approx\frac{C_P}{C}$$

$$=10^{-3}$$

$$=-60dB$$



- Beware of other parasitics not included in this model …

Dynamic Range & Electronic Noise

- Dynamic range is defined as the ratio of maximum possible signal handled by a circuit to the minimum useful signal
  - Maximum signal handling capability usually limited by circuit non-linearity & maximum possible voltage swings which in turn is a function of supply voltage
  - Minimum signal handling capability is normally determined by electronic noise
    - Amplifier noise due to device thermal and flicker noise
    - Resistor thermal noise
- Dynamic range in analog ckts has direct implications for power dissipation

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Analog Dynamic Range

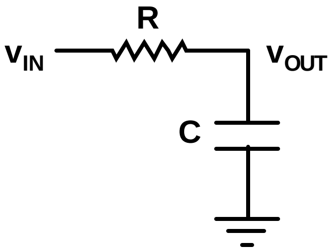
- Once the poles and zeroes of the analog filter transfer function are defined then special attention must be paid to the actual implementation

- Of the infinitely many ways to build a filter with a given transfer function, **each of those ways has a different output noise!**

- As an example noise and dynamic range for the 1st order lowpass filter will be derived

First Order Filter Noise

- Capacitors are noiseless
- Resistors have thermal noise
  - This noise is uniformly distributed from dc to infinity
  - Frequency-independent noise is called “white noise”



Resistor Noise

- Resistor noise characteristics
  - A mean value of zero
  - A mean-squared value

$$\overline{v_n^2} = 4k_B T_r R\Delta f$$

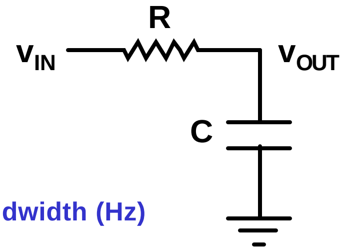
ohms

Volts^2

measurement bandwidth (Hz)

absolute temperature (°K)

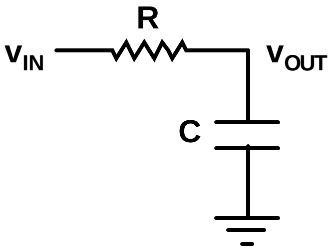
Boltzmann’s constant = 1.38e-23 J/°K



Resistor Noise

- Resistor rms noise voltage in a 10Hz band centered at 1kHz is the same as resistor rms noise in a 10Hz band centered at 1GHz
- Resistor noise spectral density, N_0, is the rms noise per √Hz of bandwidth:

$$N_0 = \sqrt{\frac{\overline{v_n^2}}{\Delta f}} = \sqrt{4k_B T_r R}$$



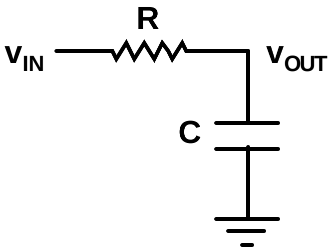
Resistor Noise

Good numbers to memorize:

- N_0 for a **1kW** resistor at room temperature is **4nV/ÖHz**
- Scaling R,
  - A 10MΩ resistor gives 400nV/√Hz
  - A 50Ω resistor gives 0.9nV/√Hz
- Or, remember

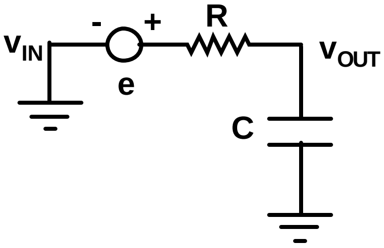
  $k_BT_r = 4\text{x}10^{-21}$ J (T$_r$ = 17 °C)
- Or, remember

  $k_BT_r/q = 26$mV (q = 1.6x10^{-19} C)



First Order Filter Noise

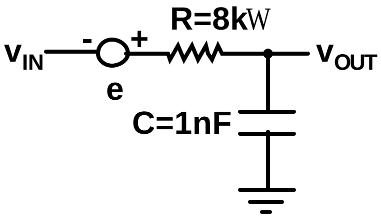
- Short circuit the input to ground.
- Resistor noise gives the filter a non-zero output when $v_{IN}=0$
- In this simple example, both the input signal and the resistor noise obviously have the same transfer functions to the output
- Since noise has random phase, we can use any polarity convention for a noise source (but we have to use it consistently)



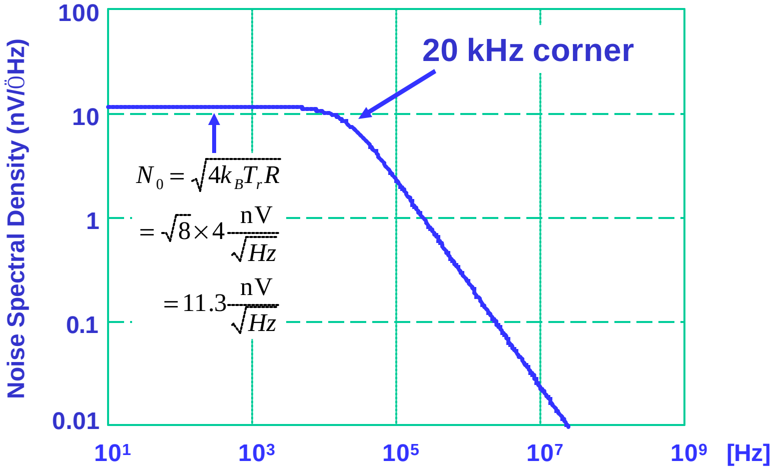
First Order Filter Noise

- What is the thermal noise of the RC filter?
- Let's ask SPICE!
  Netlist:

```
*Noise from RC LPF
vin vin 0 ac 1V
r1 vin vout 8kOhm
c1 vout 0 1nF
.ac dec 100 10Hz 1GHz
.noise V(vout) vin
.end
```



LPF1 Output Noise Density



$$N_0 = \sqrt{4k_B T_r R} = \sqrt{8} \times 4 \frac{\text{nV}}{\sqrt{Hz}} = 11.3 \frac{\text{nV}}{\sqrt{Hz}}$$

Total Noise

- Total noise is what the display on a volt-meter connected to v_o would show!
- Total noise is found by integrating the noise power spectral density with in the frequency band of interest
- Note that noise is integrated in the mean-squared domain, because noise in a bandwidth df around frequency f_1 is uncorrelated with noise in a bandwidth df around frequency f_2
  - Powers of uncorrelated random variables add
  - Squared transfer functions appear in the mean-squared integral

$$\overline{v_o^2} = \int_0^\infty 4k_B T R \left| H(2\pi jf) \right|^2 df$$

Total Noise

$$\overline{v_o^2} = \int_0^\infty 4k_BTR\left|H(2\pi jf)\right|^2 df$$

$$= \int_0^\infty 4k_BTR\left|\frac{1}{1+2\pi jfRC}\right|^2 df$$

$$\rightarrow \boxed{\overline{v_o^2} = \frac{k_BT}{C}}$$

- This interesting and somewhat counter intuitive result means that even though resistors provide the noise sources, total noise is determined by noiseless capacitors!
- For a given capacitance, as resistance goes up, the increase in noise density is balanced by a decrease in noise bandwidth

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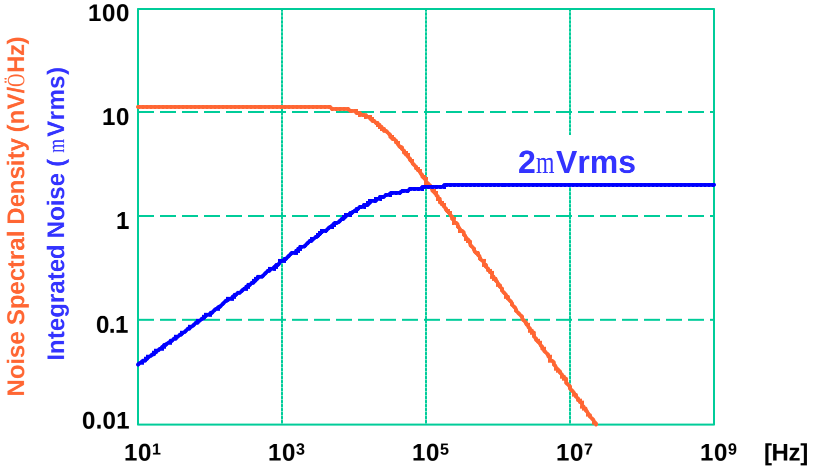
kT/C Noise

- kT/C noise is a fundamental analog circuit limitation
- The rms noise voltage of the simplest possible (first order) filter is $\sqrt{k_BT/C}$
- For 1pF capacitor, $\sqrt{k_BT/C}$ = 64 µV-rms (at 298°K)
- 1000pF gives 2 µV-rms
- The noise of a more complex & higher order filter is given by:

$$\sqrt{\alpha \times k_BT/C}$$

where α depends on implementation and features such as filter order

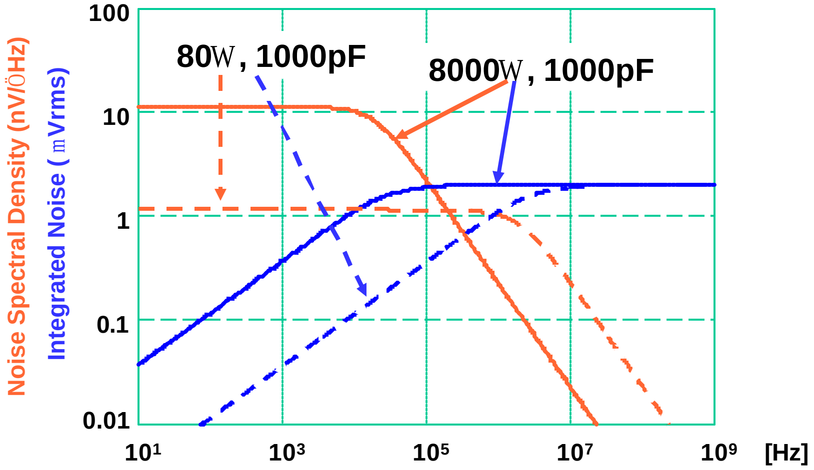
Low Pass Filter Total Output Noise (LPF1)



LPF1 Output Noise

- Note that the integrated noise essentially stops growing above 100kHz for this 20kHz lowpass filter
- Beware of faulty intuition which might tempt you to believe that an 80Ω, 1000pF filter has lower integrated noise compared to our 8000Ω, 1000pF filter…

LPF1 Output Noise



Analog Circuit Dynamic Range

- Maximum voltage swing for analog circuits can at most be equal to power supply voltage V_{DD} (normally is smaller)
- Assuming a sinusoid signal

$$V_{\max}(rms) = \frac{1}{\sqrt{2}}\frac{V_{DD}}{2}$$

- Noise for a filter:

$$V_n(rms) = \sqrt{\alpha \frac{k_B T}{C}}$$

$$DR = \frac{V_{\max}(rms)}{V_n(rms)} = \frac{V_{DD}\sqrt{C}}{\sqrt{8\alpha k_B T}} \qquad [V/V]$$

→ Dynamic range in dB is:

$$= 20\log_{10}\left(V_{DD}\sqrt{\frac{C}{\alpha}}\right) + 75 \qquad \text{[dB] with C in [pF]}$$

Analog Circuit Dynamic Range

- For integrated circuits built in modern CMOS processes, $V_{DD} < 3V$ and $C < 100pF$ ($\alpha = 1$)
  - DR < 104dB
- For PC board circuits built with "old-fashioned" 30V opamps and discrete capacitors of < 100nF
  - DR < 140dB
  - A 36dB advantage!

Dynamic Range versus Bits

- Bits and dB are related:

$$DR = 1.76 + 6.02N \quad [\mathrm{dB}]$$

  - see "quantization noise", later in the course
- Hence

104 dB	→	17 Bits
140 dB	→	23 Bits

Dynamic Range versus Power Dissipation

- Each extra bit corresponds to 6dB
- 6dB means cutting noise power by 4!
- This translates into 4x larger capacitors
- To drive these at the same speed, G_m must increase 4x
- Power is proportional to G_m (for fixed supply and V_{dsat})

In analog circuits with performance limited by thermal noise,
1 extra bit costs 4x power
E.g. 16Bit ADC at 200mW → 17Bit ADC at 800mW

Do not overdesign the dynamic range of analog circuits!

Noise Summary

- Thermal noise is a fundamental property of (electronic) circuits
- Noise is closely related to
  - Capacitor size
- In higher order filters, noise is proportional to C, filter order, Q, and depends on implementation
- Operational amplifiers can contribute significantly to overall filter noise
- Reducing noise in most analog circuits costs in terms of power dissipation and chip area