

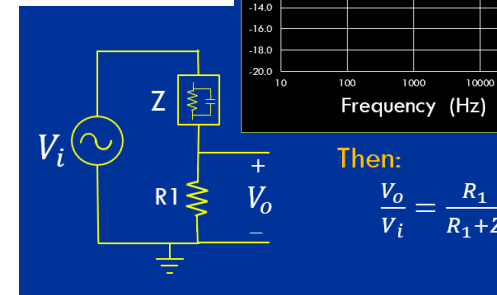
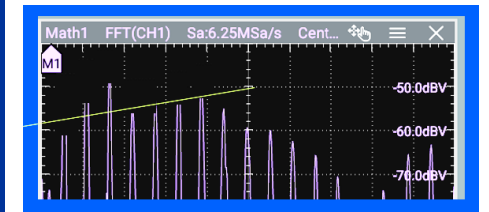
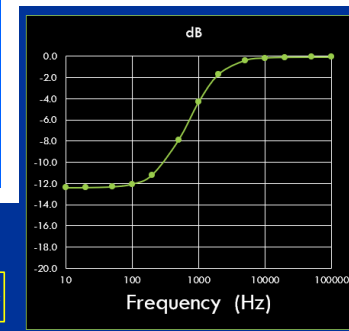
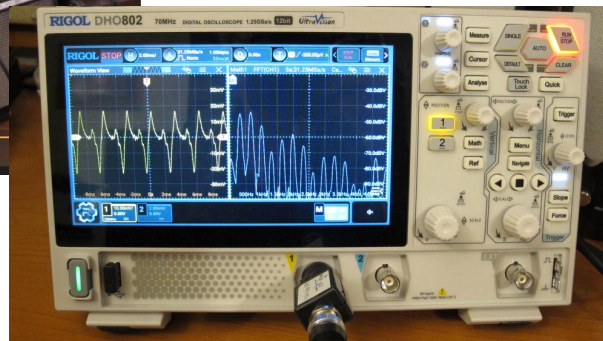
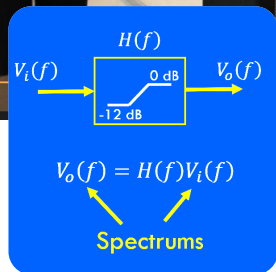
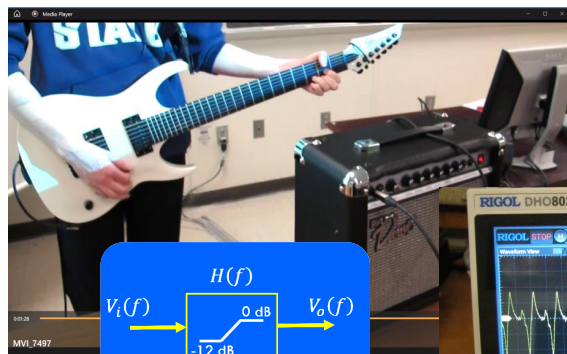
# ECE Topic #8 – Fourier and FFT Concepts in Circuit Design (Parts 1 and 2)

Slides downloaded from: <https://ecefiles.org/ece-topics/>

Companion videos at: <https://www.youtube.com/watch?v=ywnmV0EDDp8> (Part 1) and  
<https://www.youtube.com/watch?v=tZ8pwX-eFVk> (Part 2)

This material is **provided by ecefiles.org for educational use only.**

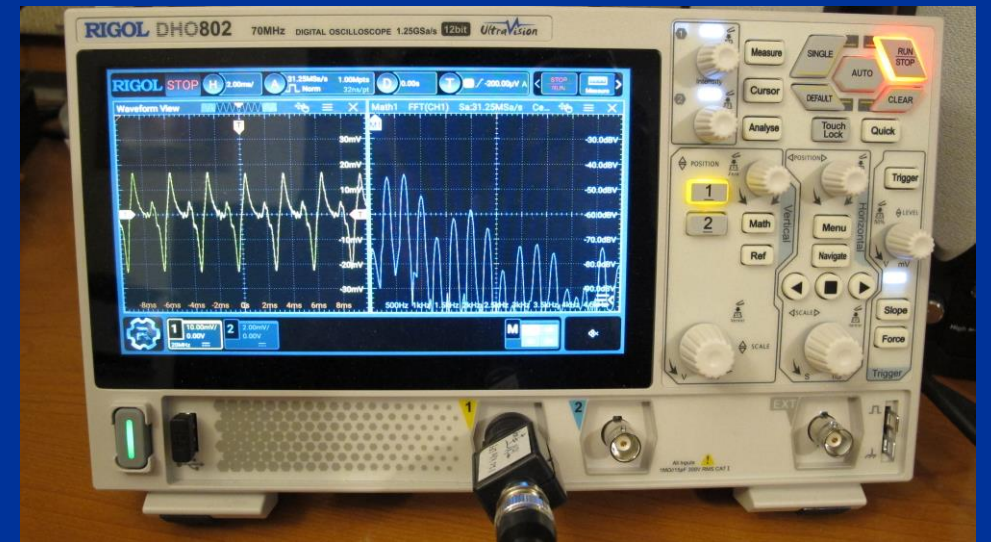
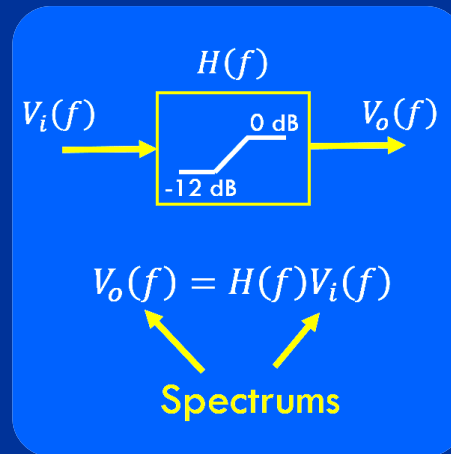
Fourier Series and Fast Fourier Transform (FFT) concepts with a focus on applications. Covers time and frequency domain using guitar sounds, but extension to application in wireless communications is also touched on. A Rigol DHO 800 series scope is used to show waveforms and spectrums and interpretation of the FFT display is presented in some depth Part 1 introduces these concepts and part 2 focuses on circuits and how designers use these concepts to achieve system level goals.



$$|V_o(f)|_{\text{dB}} = |H(f)|_{\text{dB}} + |V_i(f)|_{\text{dB}}$$

# Topics in ECE #8

## Fourier and FFT Concepts in Circuit Design



# Some Existing Fourier, FFT Videos on YouTube

YouTube interface showing search results for "Intro to Fourier and the FFT in Circuit Analysis".

**Fourier Series And Fourier Transform**  
 ALL ABOUT ELECTRONICS · Playlist  
 Introduction to Fourier Series | Trigonometric Fourier Series Explained · 18:59  
 Exponential Fourier Series Explained | Concept of Negative Frequency E... · 17:51  
 VIEW FULL PLAYLIST

**FOURIER ANALYSIS**  
 The Fourier Series and Fourier Transform Demystified  
 772K views · 1 year ago  
 Up and Atom  
 \*Follow me\* @upndatom Up and Atom on Twitter: <https://twitter.com/upndatom>  
 CC  
 The Fourier Series of a Sawtooth Wave |... 8 moments

**Overview | FFT: Fun with Fourier Transforms | Adafruit Learning System**  
 Learn How to Make Cool Stuff. Browse Our Project Tutorials  
 Sponsored · <https://learn.adafruit.com/>

**FFT in Data Analysis (Fast Fourier Transform)**  
 43K views · 5 years ago  
 MadgeTech, Inc.  
 General overview of what FFT is and how FFT is used in data analysis. Titan  
 SB: ...

YouTube interface showing search results for "Intro to Fourier and the FFT in Circuit Analysis".

**Fourier Analysis-Introduction (Edited)**  
 16K views · 11 years ago  
 Darryl Morrell  
 Introduction to some applications and concepts associated with frequency domain (Fourier) analysis. More instructional ...

**Circuit Analysis Using Fourier Series**  
 CAN Education · Playlist  
 Circuit Analysis Using Fourier Series | RL Circuit Response | Nonsinusoidal Wavefor... · 15:33  
 Circuit Analysis Using Fourier Series | RC Circuit Response | Nonsinusoidal Wavefo... · 12:16  
 VIEW FULL PLAYLIST

**39: Introduction to Signal Processing with Fourier Analysis (Engineering Circuit)**  
 152 views · 3 years ago  
 Arash Karimpour  
 Book: Hambley, A. R., 2016. Electrical Engineering: Principles & Applications. Pearson, Seventh Edition.

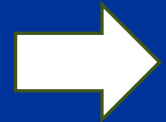
**Intro to FOURIER SERIES: The Big Idea**  
 232K views · 3 years ago  
 Dr. Trefor Bazett  
 Welcome to my new playlist on Fourier Series. In this first video we explore the big idea of ...  
 Periodic Functions | The Big Idea | Qualitative Features |... 4 chapters

# What Are We Hoping to Add ?

- An intuitive understanding with minimal math(s) prerequisites
- Real-world examples of finding Fourier series / transforms
- Real-world examples of use in circuit analysis and circuit understanding

The screenshot shows a YouTube playlist page for 'ECE Topics' by MegawattKS. The playlist is titled 'ECE Topics' and contains 8 videos. The first video is 'Voltage, Current, Resistance, and Power - ECE Topics #1' with 922 views. The second video is 'Power, Energy, and Electric Vehicles - ECE Topics #2' with 446 views. The third video is 'Circuit Analysis - From Theory to Applications - ECE Topics #3' with 1K views. The fourth video is 'Understanding Circuits - ECE topics #4 (part 1)' with 934 views. The fifth video is 'Understanding Circuits - Part 2 - ECE Topics #4A' with 657 views. The sixth video is 'Oscilloscopes, Microphones, and Noise - ECE Topics #5' with 657 views. The seventh video is 'Complex Numbers, Phasors, Impedances, and Frequency Response' with 910 views. The eighth video is 'Frequencies, Amplitudes, Log Scales, dB and dBm - ECE Topics #7' with 727 views.

# Today's Topics

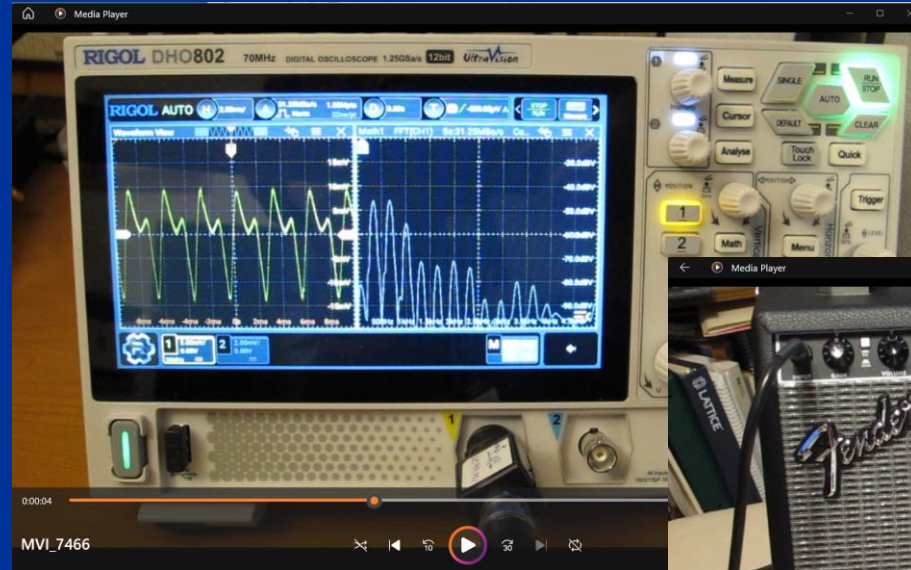


- Time and Frequency domains
- Fourier – the Bridge between domains
- Circuits: from Phasor Analysis to Signal Processing

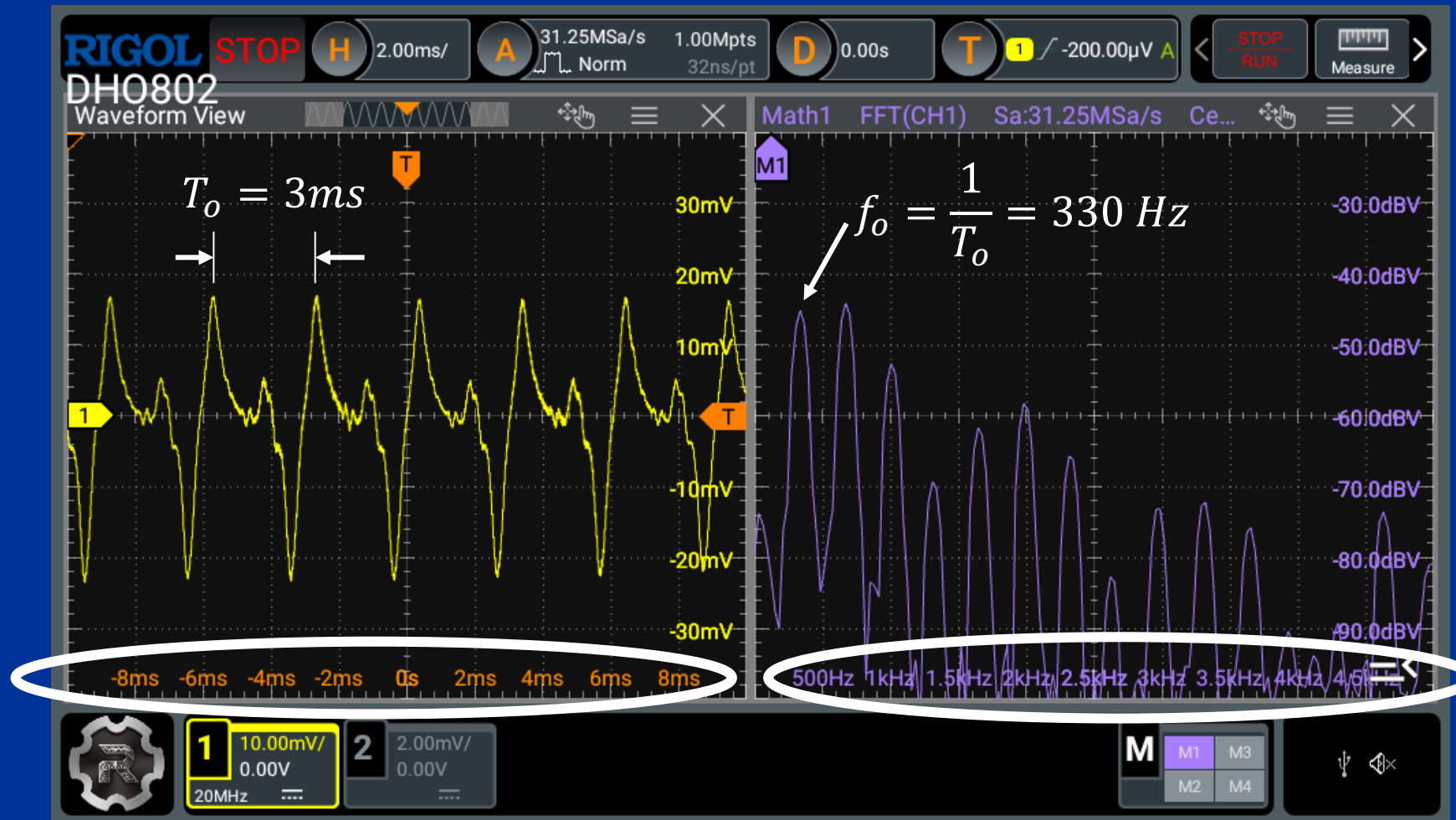
# Guitar Waveforms and Spectrums



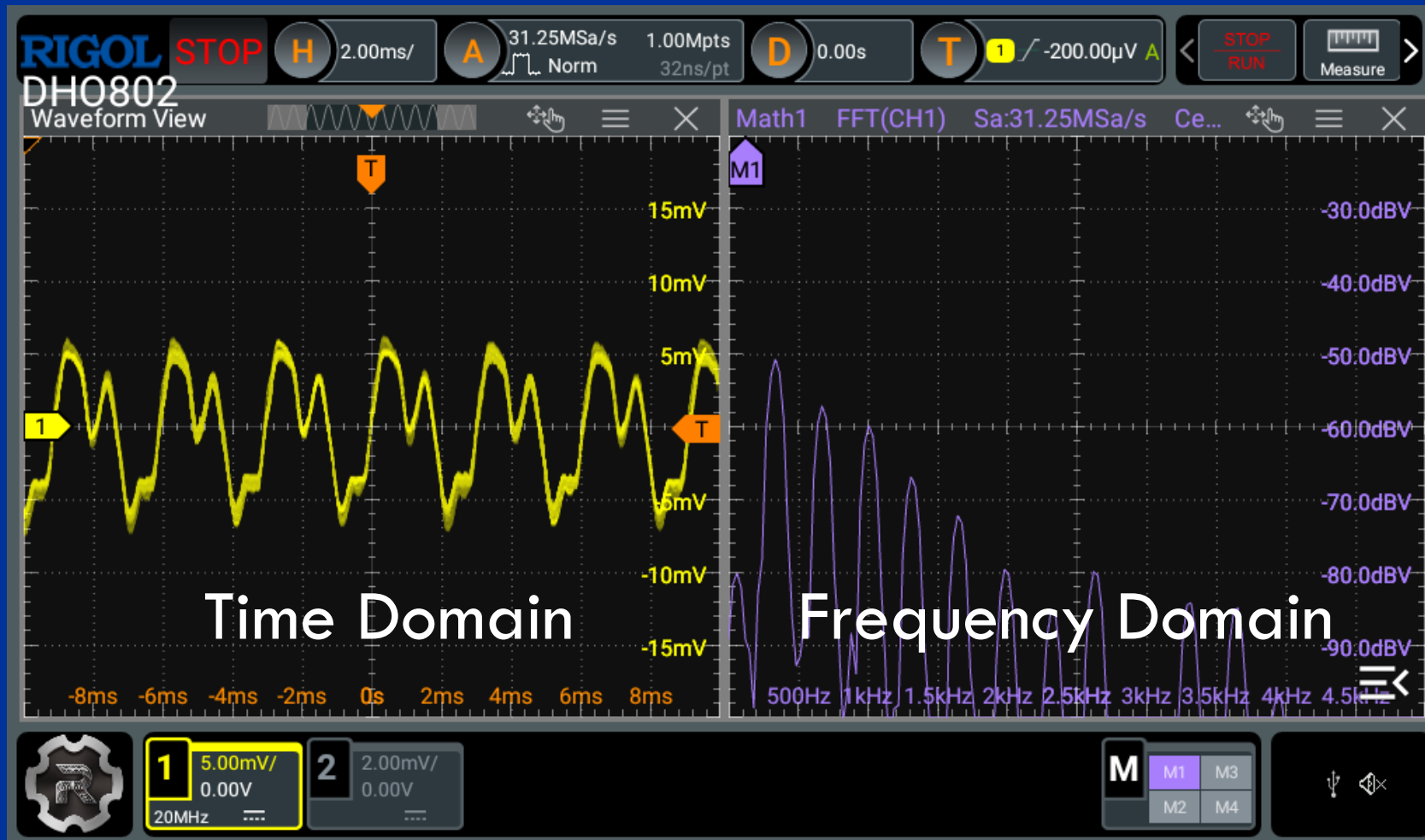
Tuning up new  
Stratocaster guitar 😊



# Guitar Waveforms and Spectrums



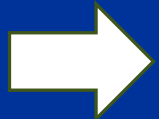
# Time and Frequency Domains





# Today's Topics

- Time and Frequency domains



- Fourier – the Bridge between domains
- Circuits: from Phasor Analysis to Signal Processing

# ECE Topics vs University Courses

## Freshman year

### Fall semester (16 credit hours)

- CHM 210 - Chemistry I **Credits: (4)**
- COMM 105 - Public Speaking IA **Credits: (2)**
- ECE 015 - New Student Assembly **Credits: (0)**
- ECE 210 - Introduction to Electrical Engineering **Credits: (3)**
- ENGL 100 - Expository Writing I **Credits: (3)**
- MATH 220 - Analytic Geometry and Calculus I **Credits: (4)**

### Spring semester (17 credit hours)

- BIOL 198 - Principles of Biology **Credits: (4)**  
or
- CHM 230 - Chemistry II **Credits: (4)**
- ECE 115 - New Student Design Project **Credits: (1)**
- ECON 110 - Principles of Macroeconomics **Credits: (3)**
- MATH 221 - Analytic Geometry and Calculus II **Credits: (4)**
- PHYS 213 - Engineering Physics I **Credits: (5)**

## Sophomore year

### Fall semester (17 credit hours)

- CHE 354 - Basic Concepts in Materials Science and Engineering **Credits: (1)**
- CHE 356 - Fundamentals of Electrical Properties **Credits: (1)**
- ECE 241 - Introduction to Computer Engineering **Credits: (3)**
- ECE 410 - Circuit Theory I **Credits: (3)**
- MATH 240 - Elementary Differential Equations **Credits: (4)**
- PHYS 214 - Engineering Physics II **Credits: (5)**

### Spring semester (16 credit hours)

- CIS 209 - C Programming for Engineers **Credits: (3)**
- ECE 511 - Circuit Theory II **Credits: (3)**
- ECE 525 - Electronics I **Credits: (3)**
- MATH 222 - Analytic Geometry and Calculus III **Credits: (4)**
- STAT 510 - Introductory Probability and Statistics I **Credits: (3)**

## Junior year

### Fall semester (16 credit hours)

- \*\*Humanities/Social Science Elective **Credits: (3)**
- ECE 431 - Microcontrollers **Credits: (3)**
- ECE 526 - Electronics II **Credits: (3)**
- ECE 540 - Applied Scientific Computing for Engineers **Credits: (3)**
- ECE 557 - Electromagnetic Theory I **Credits: (4)**

### Spring semester (17 credit hours)

- \*\*Humanities/Social Science Elective **Credits: (3)**
- ECE Technical Electives **Credits: (3)**
- ECE 502 - Electronics Laboratory **Credits: (2)**
- ECE 512 - Linear Systems **Credits: (3)**
- ECE 581 - Energy Conversion I **Credits: (3)**
- ENGL 415 - Written Communication for Engineers **Credits: (3)**

## Senior year

### Fall semester (15 credit hours)

- \*\*\*Technical electives **Credits: (6)**
- CE 530 - Statics and Dynamics **Credits: (3)**
- ECE 530 - Control Systems Design **Credits: (3)**
- ECE 590 - Senior Design Experience **Credits: (3)**

### Spring semester (15 credit hours)

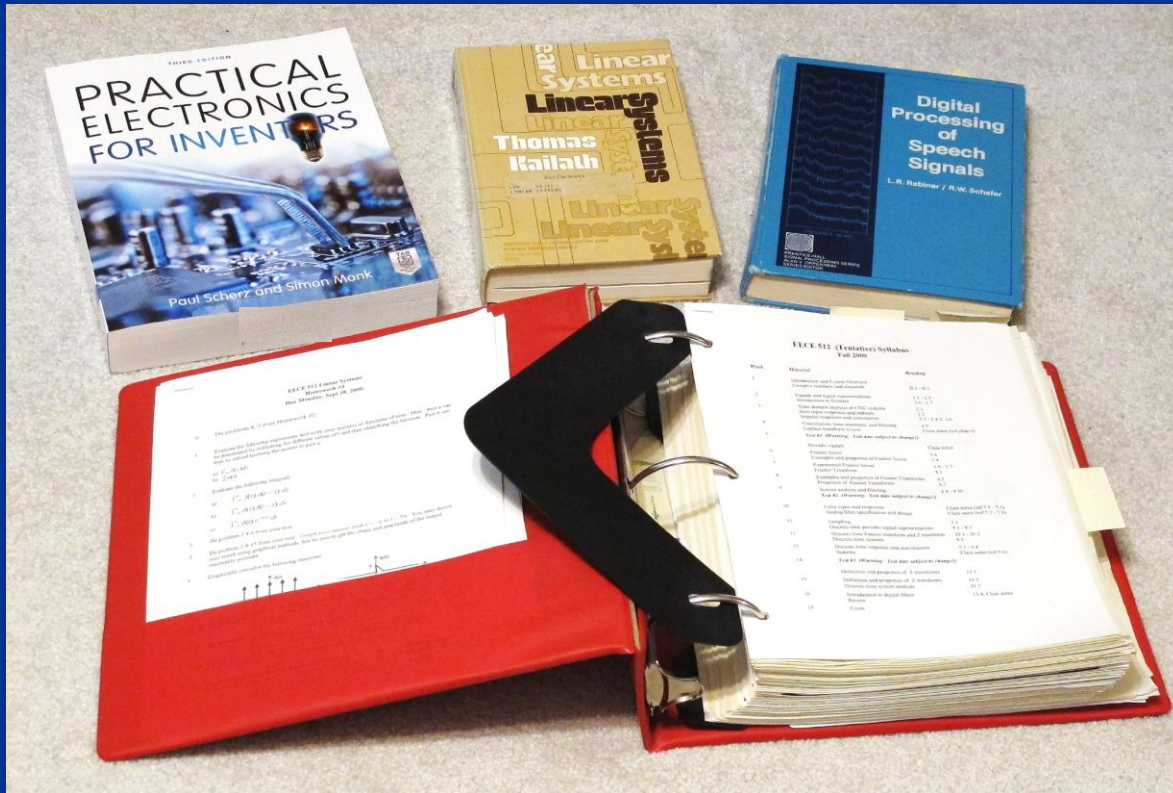
- \*\*\*Technical electives **Credits: (9)**
- \*\*Humanities/Social Science Elective **Credits: (3)**
- ME 513 - Thermodynamics I **Credits: (3)**

## Electrical engineering options

### General option

Fourier theory covered (mainly) in Junior year

# Textbooks and Lectures ...



## ECE 512 Linear Systems Fall 2000

**Office Hours:** TU 2:30 - 5:30  
Others by appointment

**Text:** B. P. Lathi, *Signal Processing and Linear Systems*, Berkeley-Cambridge Press, Carmichael, CA.

**References:** B. W. Kernighan and D. M. Richie, *The C Programming Language*, 2nd Edition, Prentice-Hall (or equivalent).

### Course Description:

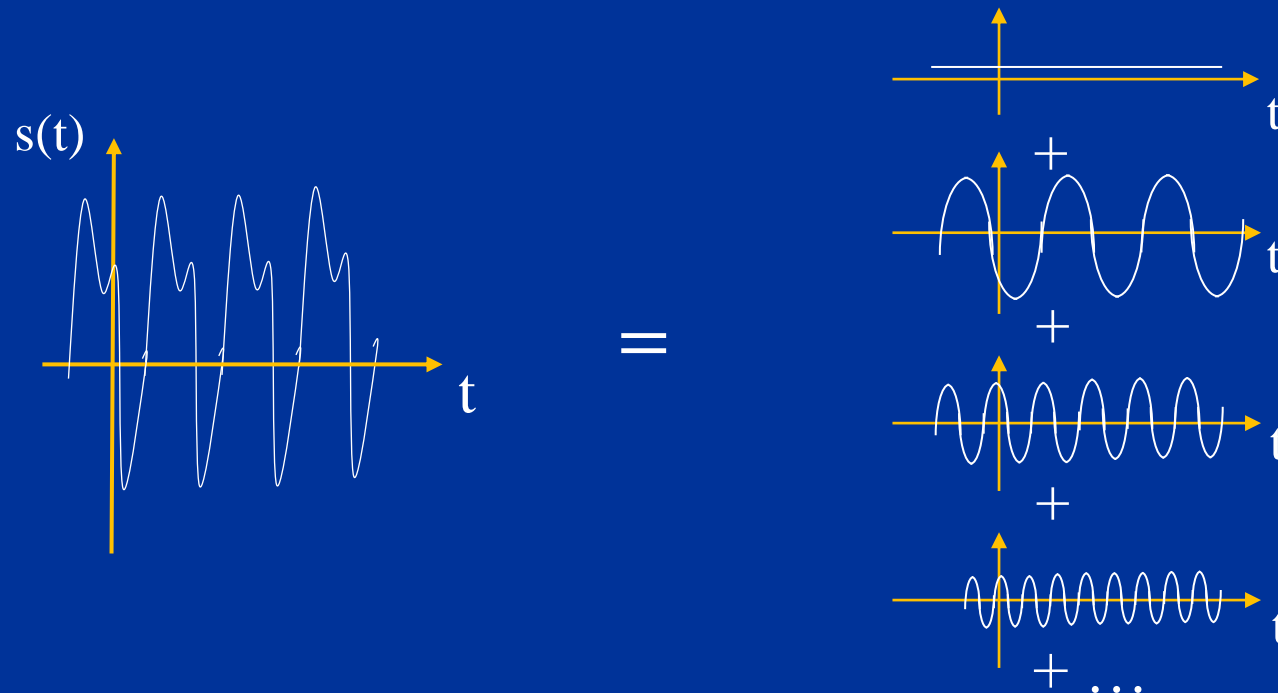
This course introduces the mathematical tools essential to the analysis of complex dynamic circuits and systems. The course builds on material studied in Math 240 (Differential Equations) and ECE511 (Circuits II), providing a foundation for a wide range of subjects within the discipline of Electrical and Computer Engineering, including analog and digital signal processing, terrestrial and radio telecommunications, electronic circuit design, and analog/digital controls.

Topics covered will include:

- ◆ Classification and representation of signals and systems,
- ◆ Review of time-domain and Laplace transform analysis techniques,
- ◆ Representation of arbitrary signals as sums of simpler, sinusoidal signals,
- ◆ The use of these representations to understand the behavior of systems,
- ◆ Sampling of analog signals to create digital signals, and
- ◆ Design of analog and digital frequency selective filters.

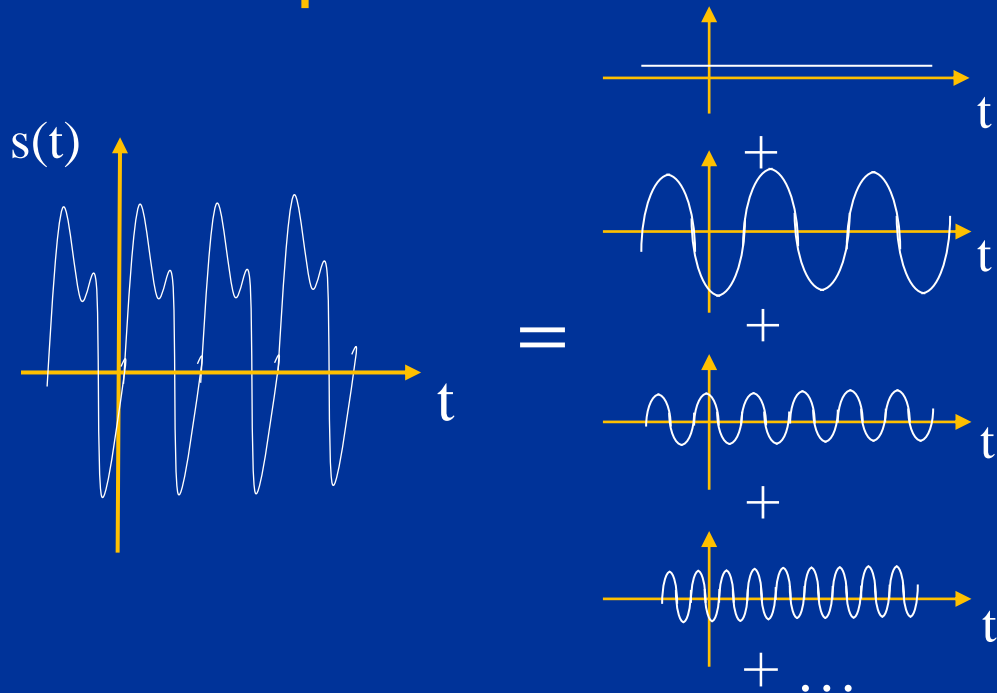
# Fourier Series – The Basic Concept

Any periodic waveform can be decomposed into a sum of sinusoids with harmonically related frequencies.



# In the Language of Math(s)

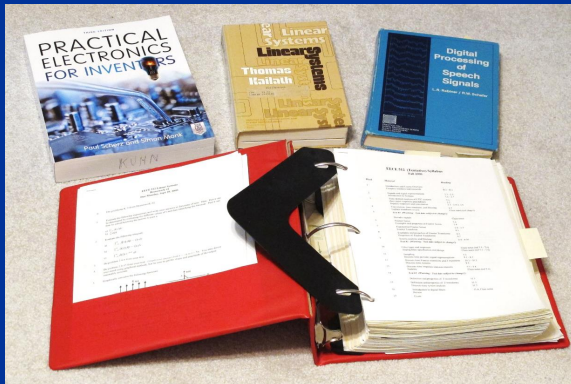
Time Domain Waveform  
Decomposition



Trigonometric Fourier Series

$$\begin{aligned} &C_0 \\ &+ \\ &C_1 \cos(2\pi f_0 t + \theta_1) \\ &+ \\ &C_2 \cos(2\pi(2f_0)t + \theta_2) \\ &+ \\ &C_3 \cos(2\pi(3f_0)t + \theta_3) \\ &+ \dots \end{aligned} = \boxed{\sum_{n=0}^{\infty} C_n \cos(2\pi(nf_0)t + \theta_n)}$$

# Finding / Plotting Spectrum (of a Square-wave)



Summary

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t)$$

where  $a_0 = \frac{1}{T_0} \int_{T_0} f(t) dt$  (DC or average value)

Recall Property 3

$$a_n = \frac{2}{T_0} \int_{T_0} f(t) \cos(n\omega t) dt$$

$$b_n = \frac{2}{T_0} \int_{T_0} f(t) \sin(n\omega t) dt$$

Called "Trigonometric Fourier Series"

Can also write as

$$f(t) = c_0 + \sum_{n=1}^{\infty} c_n \cos(n\omega t + \theta_n)$$

$$c_0 = a_0$$

$$c_n = (a_n^2 + b_n^2)^{1/2}$$

$$\theta_n = \tan^{-1}\left(\frac{-b_n}{a_n}\right)$$

Called "Compact Trigonometric F-S"

Example Fourier Series

Example 3 Square wave

$$S(t) = a_0 + \sum_{n=1}^{\infty} \{a_n \cos(n\omega t) + b_n \sin(n\omega t)\}$$

$$a_0 = \frac{1}{T} \int_{-T/2}^{T/2} S(t) dt = 0 \quad (S(t) \text{ is odd})$$

or by symmetry, avg. value is zero.

$$a_n = \frac{2}{T} \int_{-T/2}^{T/2} S(t) \cos(n\omega t) dt = 0$$

(odd x even) = odd

$$b_n = \frac{2}{T} \int_{-T/2}^{T/2} S(t) \sin(n\omega t) dt$$

$$= 2 \int_0^{T/2} S(t) \sin(n\omega t) dt$$

$$= \frac{4}{T} \int_0^{T/2} \sin(n\omega t) dt$$

$$= \frac{4}{T} \left[ \frac{-1}{n\omega} \cos(n\omega t) \right]_0^{T/2}$$

$$= \frac{4}{T} \frac{1}{n\omega} [\cos(n\omega \frac{T}{2}) - 1]$$

$$= \frac{-2}{n\pi} [\cos(n\pi) - 1]$$

$$= \begin{cases} 0 & n = 2, 4, 6, \dots \\ \frac{4}{\pi} \frac{1}{n} & n = 1, 3, 5, \dots \end{cases}$$

So

$$S(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin(n\omega t)$$

or

$$S(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{2n-1} \sin((2n-1)\omega t)$$

Compact Trigonometric F-S

$$S(t) = c_0 + \sum_{n=1}^{\infty} c_n \cos(n\omega t + \theta_n)$$

$$c_0 = a_0 = 0$$

$$c_n = (a_n^2 + b_n^2)^{1/2} = b_n$$

$$\theta_n = \tan^{-1}\left(\frac{-b_n}{a_n}\right) = \begin{cases} \text{undefined} & n = 2, 4, 6, \dots \\ -90^\circ & n = 1, 3, 5, \dots \end{cases}$$

$$\Rightarrow S(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \cos(n\omega t - 90^\circ)$$

Plot

Amplitude Spectrum  $c_n = \sqrt{a_n^2 + b_n^2}$

Phase

Not shown for n=2

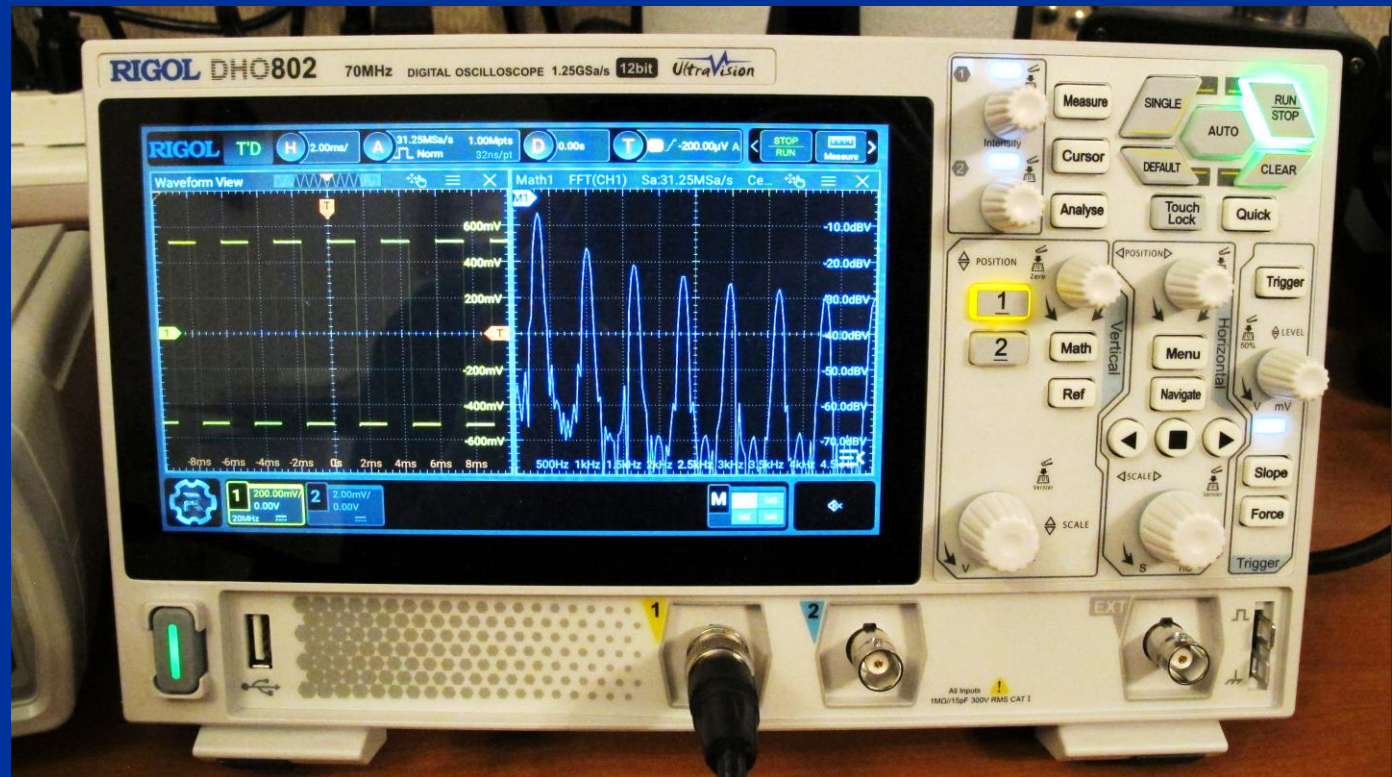
Together with  $\omega_0$ , provides a complete description of waveform!

# Finding Spectrums in Practice ...

## Use Fast Fourier Transform (FFT)



330 Hz, 1Vpp Square-wave  
with 50% duty cycle

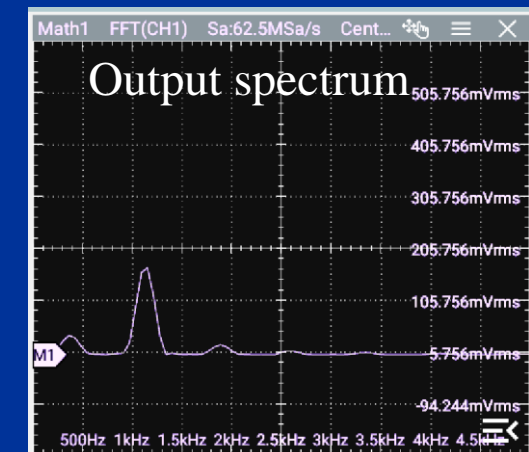
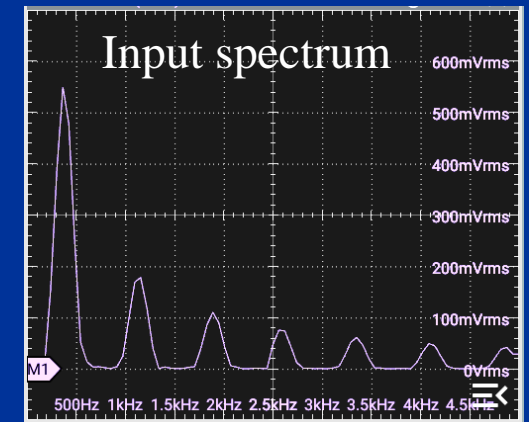
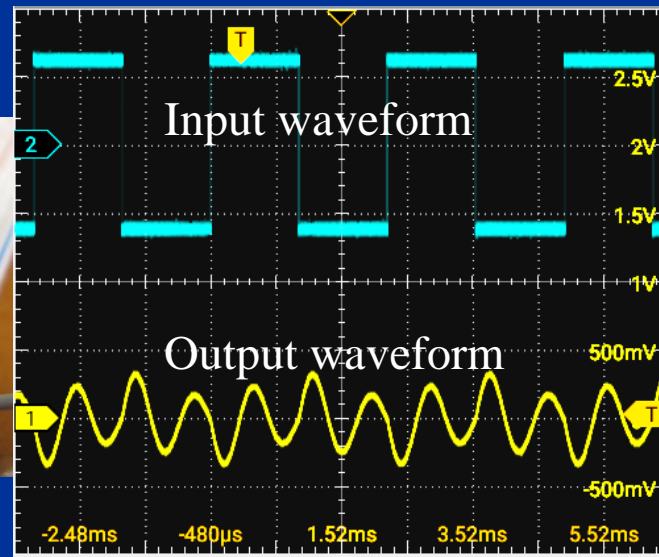
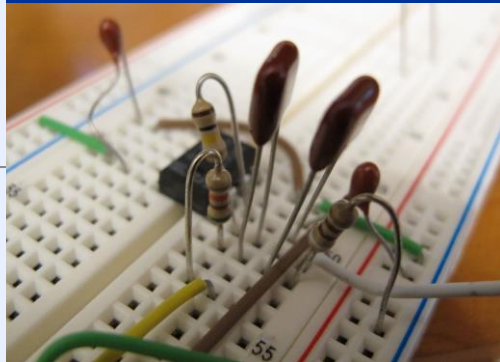
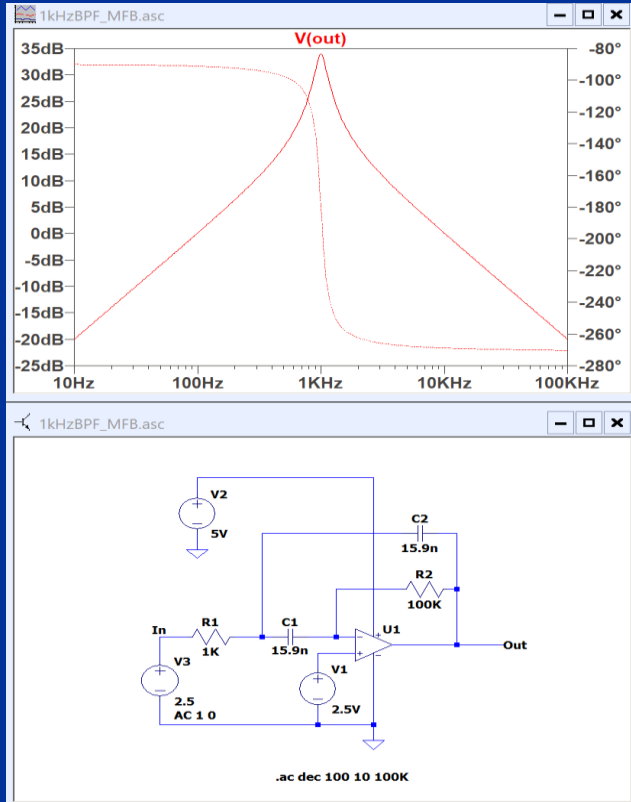


NOTE: We often just look at the amplitude spectrum. Why?

# An Interesting Experiment

Proving a square-wave has sinewaves in it 😊

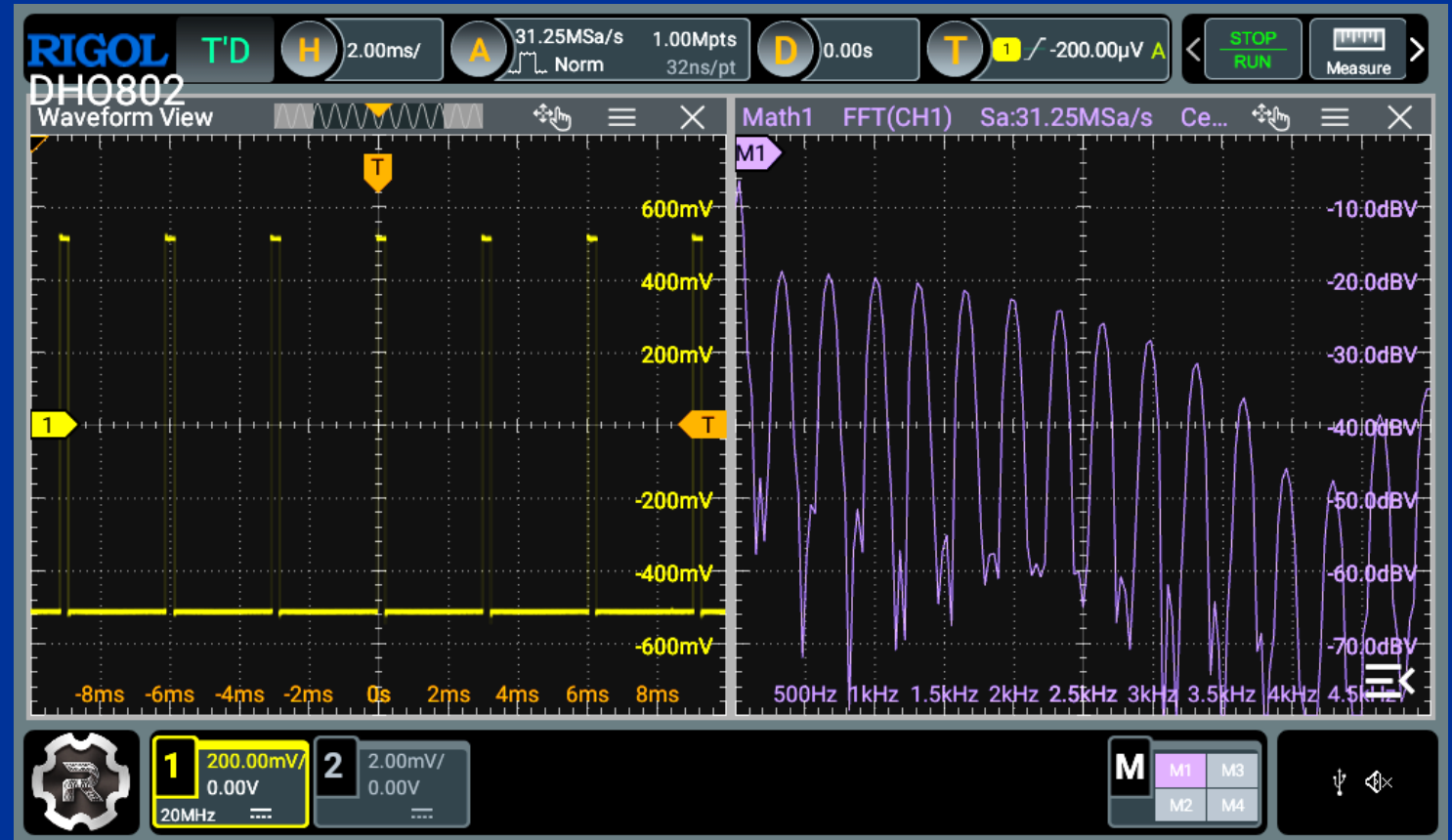
High-Q MFB Bandpass filter





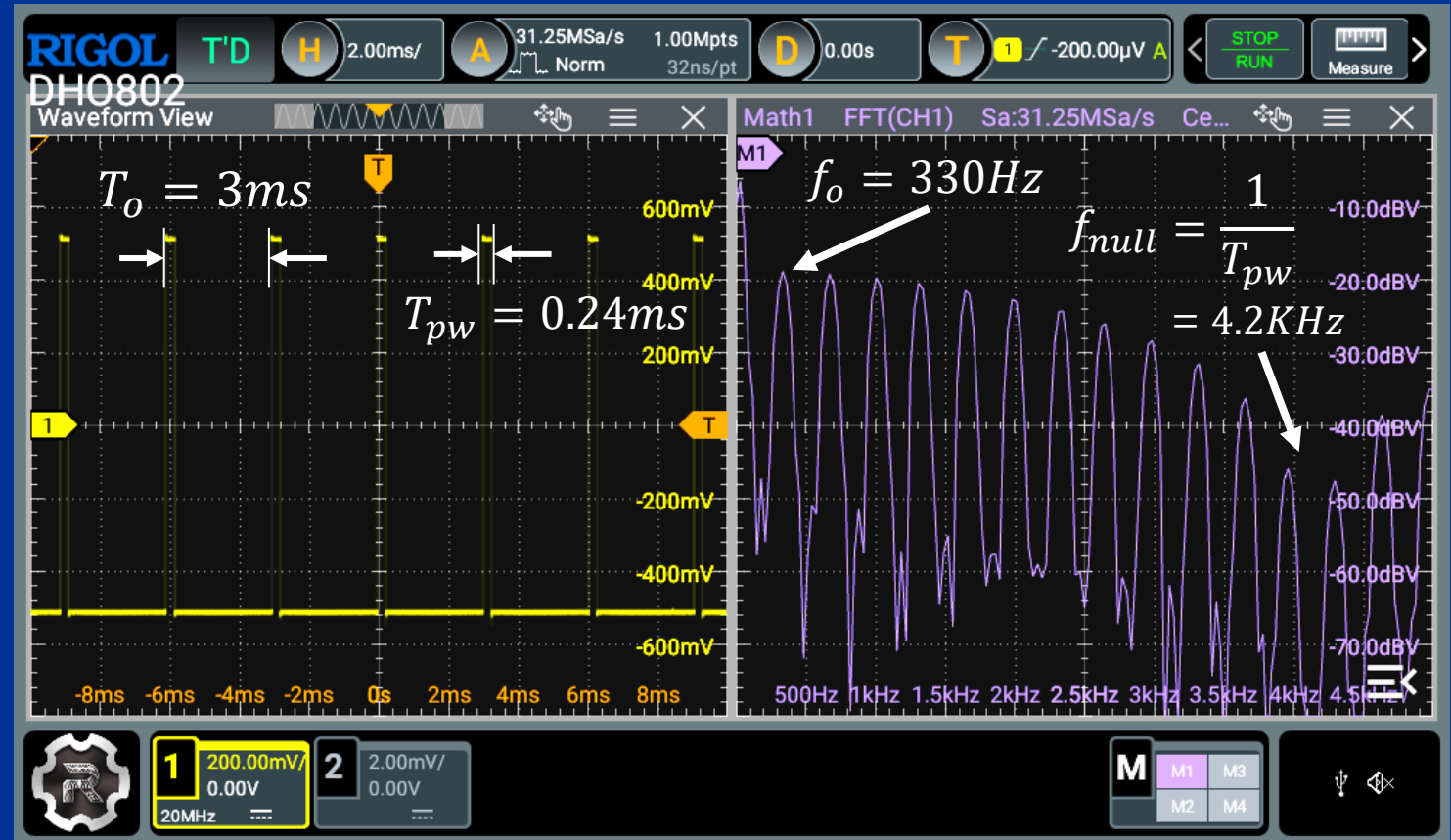
# Spectrum of a Pulse Train

330 Hz, 1Vpp “Square-wave”  
with 8% duty cycle



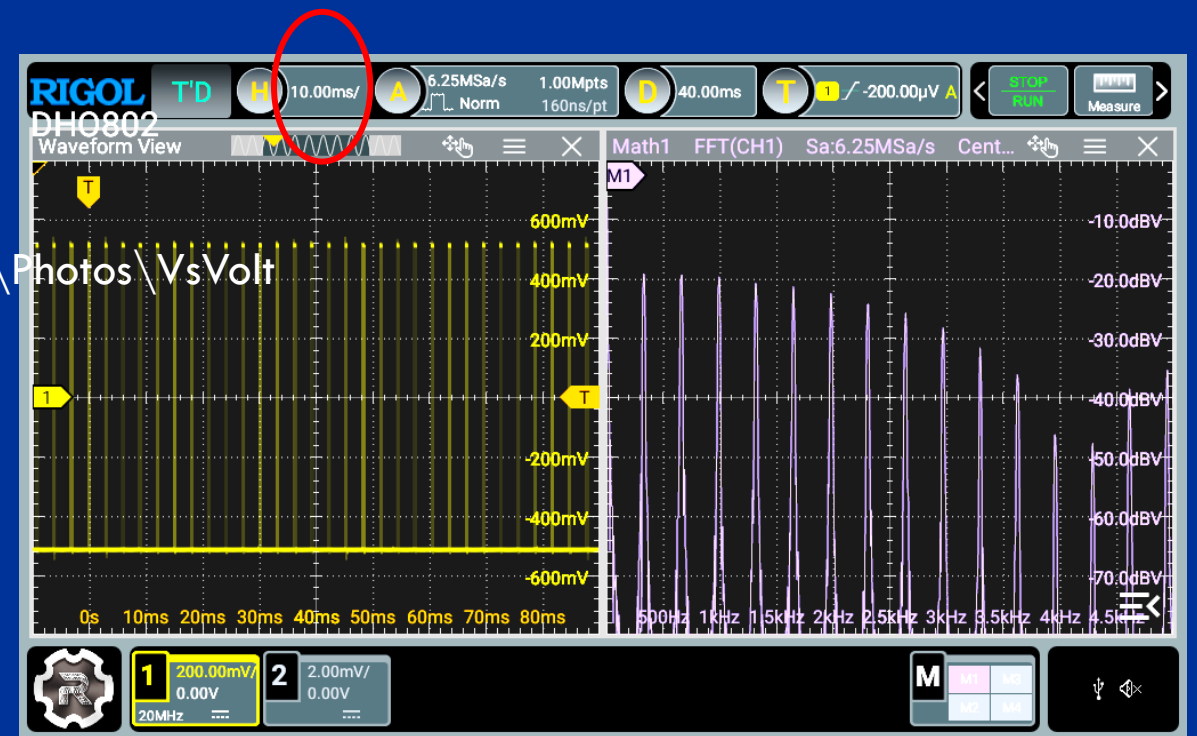
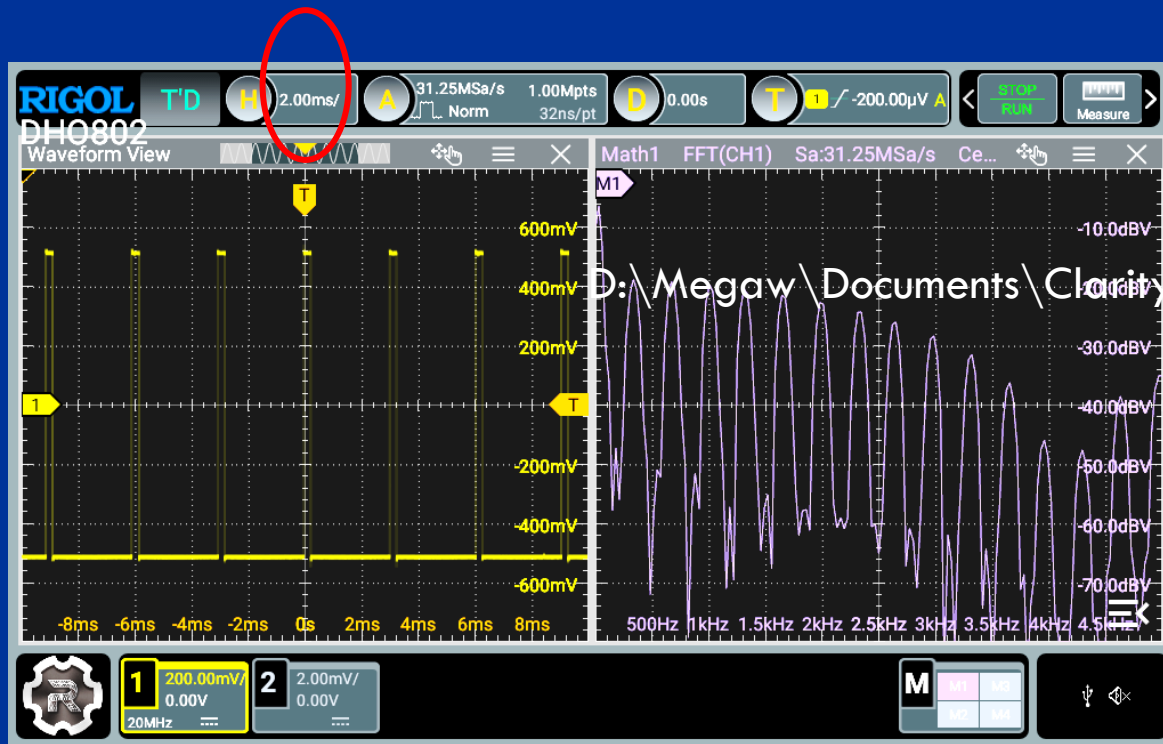
# Spectrum of a Pulse Train

330 Hz, 1Vpp “Square-wave”  
with 8% duty cycle



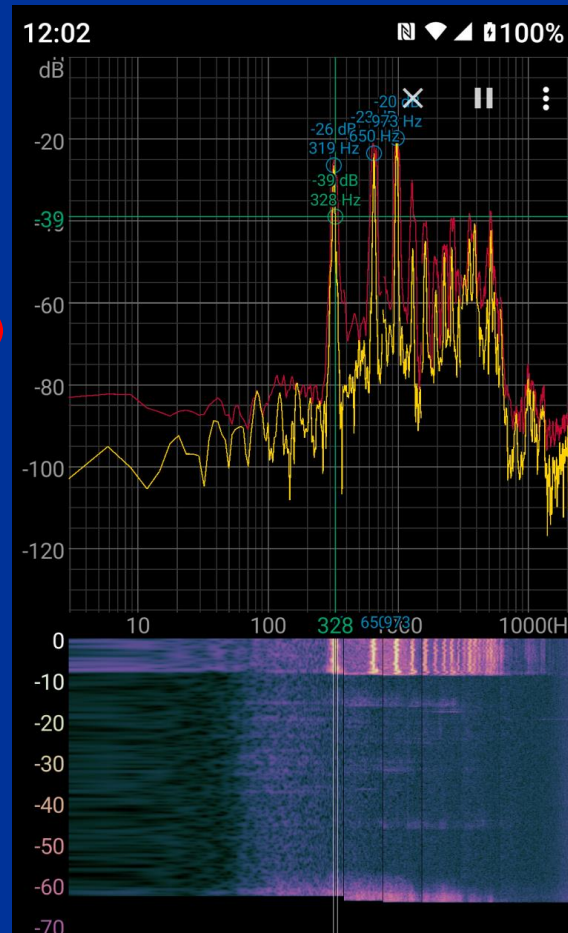
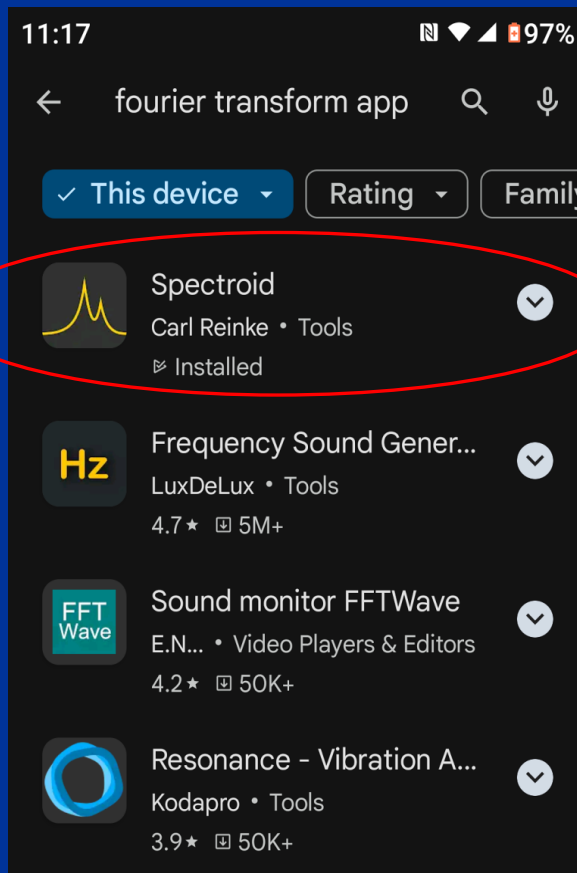
- Narrow pulses have lots of Harmonics !
- And use lots of bandwidth ...

# Effect of Scope's Sweep Time-base on FFT Spectrum Resolution

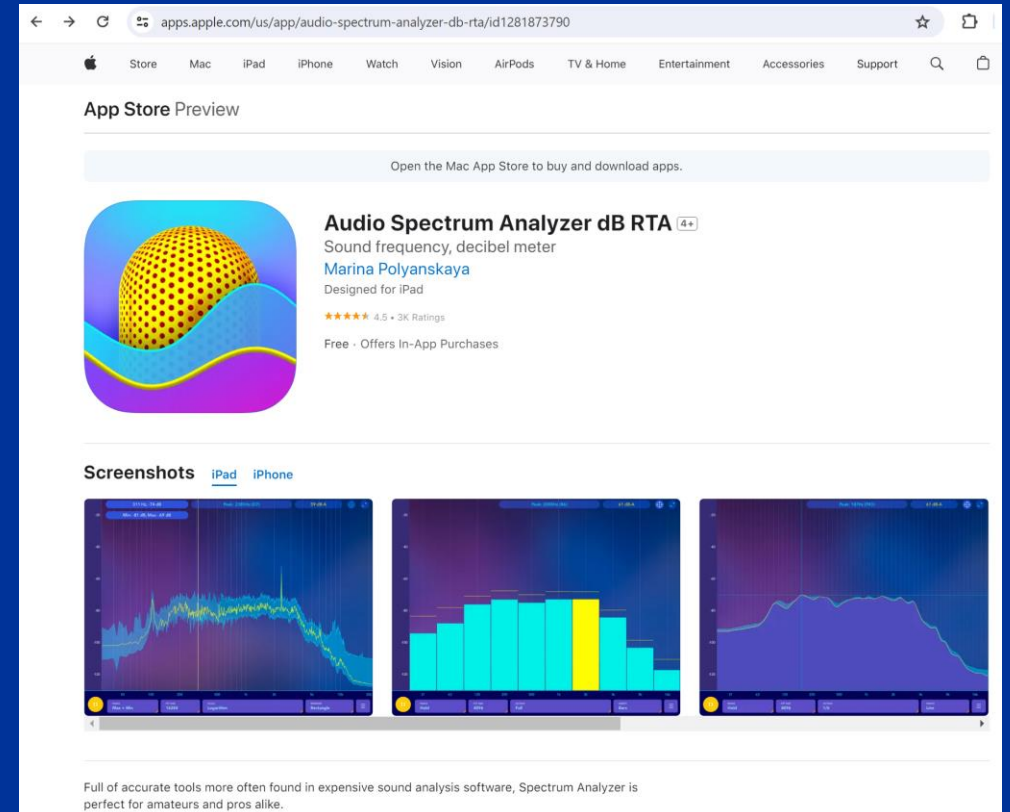


# Some FFT Cell Phone Apps ☺

## Android

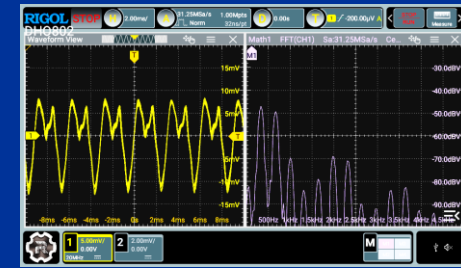


## Apple

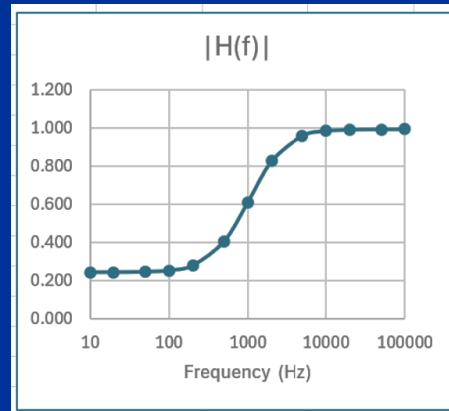
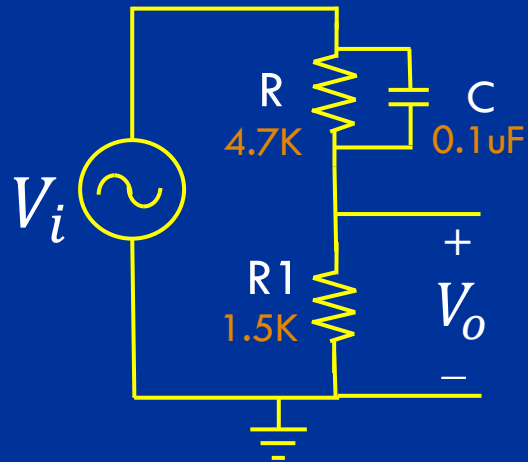




# Topics in ECE #8A

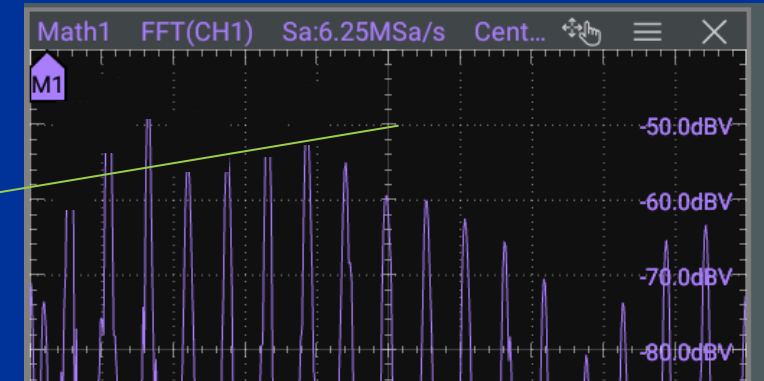


## Fourier and FFT Concepts in Circuit Design (Part 2)



$$V_o(f) = H(f)V_i(f)$$

Spectrums



$$|V_o(f)|_{\text{dBV}} = |H(f)|_{\text{dB}} + |V_i(f)|_{\text{dBV}}$$

# Today's Topics

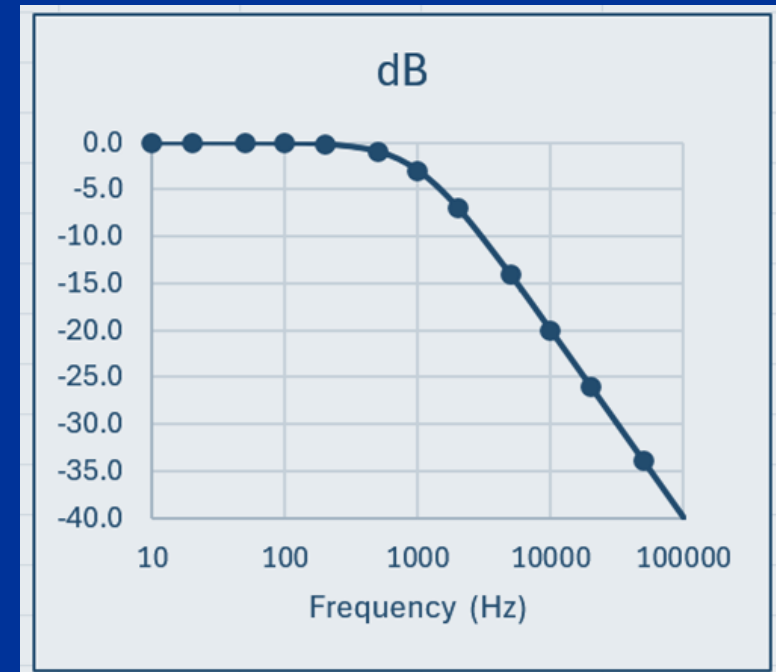
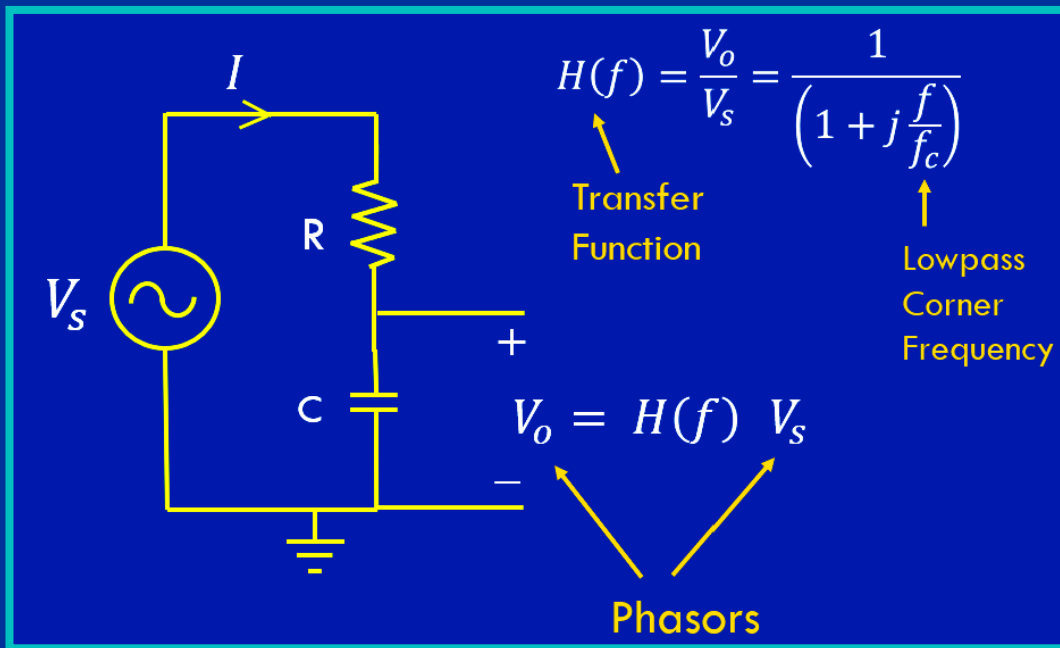
Part 1

- Time and Frequency domains
  - Fourier – the Bridge between domains
- ➔
- Circuits: from Phasor Analysis to Signal Processing (and Filtering)



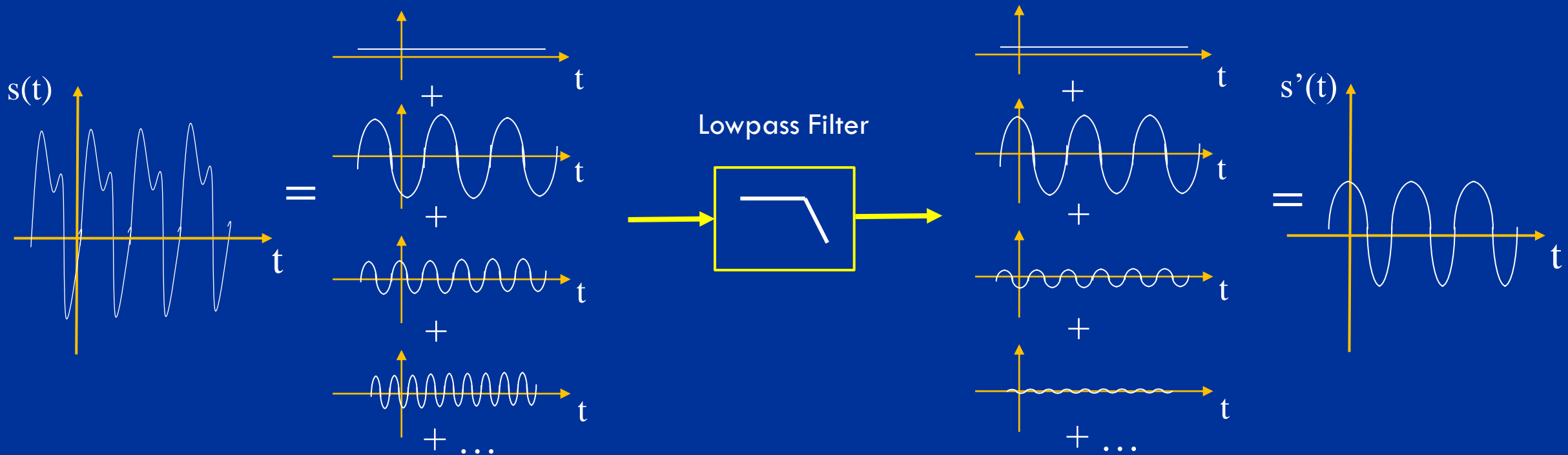
# Lowpass Filter (One-pole)

(from Episodes 6 and 7)



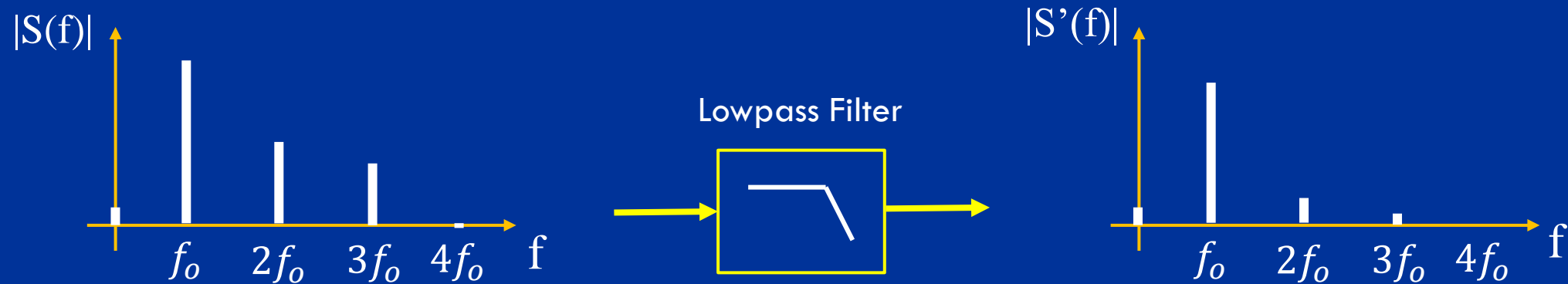
# Applying Fourier in (Linear) Circuits and Systems

## Time-domain View





# Frequency Domain View



## NOTE:

- Magnitude-only plots shown
- Phase is important too, *if* waveshape matters ...

# What do we hear ?

medrxiv.org/content/10.1101/2023.04.13.23288518v2

medRxiv THE PREPRINT SERVER FOR HEALTH SCIENCES

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## Place Coding in the Human Cochlea

Posted May 22, 2023.

Amit Walia, Amanda J. Ortmann, Shannon Lefler, Timothy A. Holden, Sidharth V. Puram, Jacques A. Herzog, Craig A. Buchman

doi: <https://doi.org/10.1101/2023.04.13.23288518>

This article is a preprint and has not been peer-reviewed [what does this mean?]. It reports new medical research that has yet to be evaluated and so should not be used to guide clinical practice.

Download PDF | Email | Print/Save Options | Author Declarations | Supplementary Material | Data/Code | Citation Tools | Get QR code

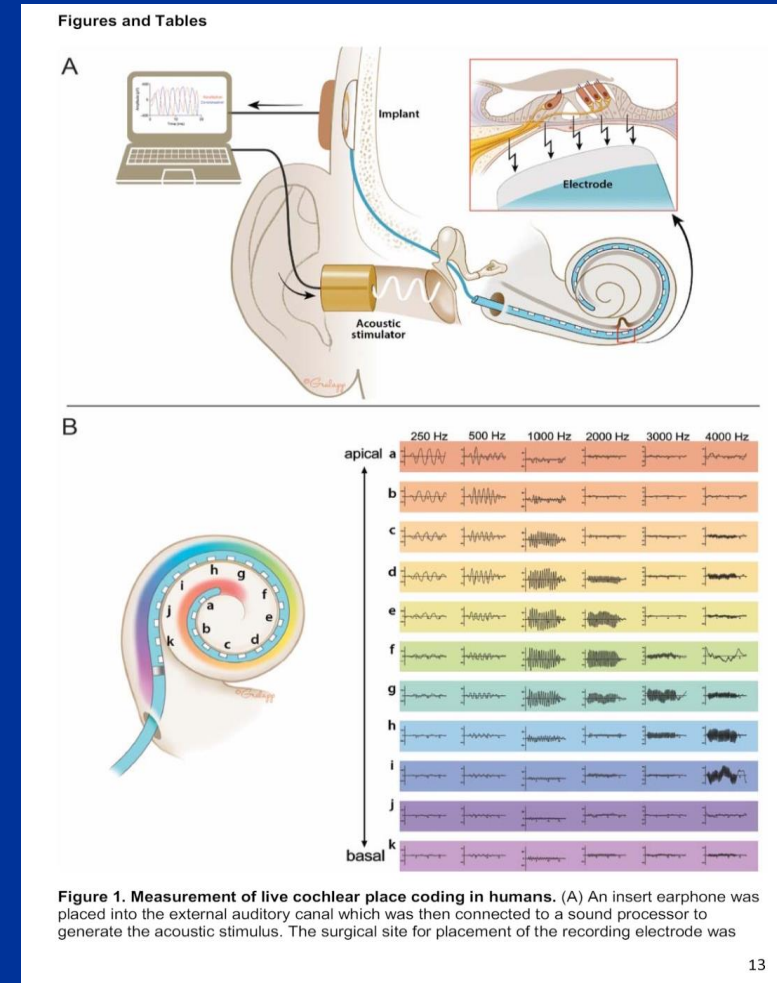
Abstract Full Text Metrics

Abstract

The cochlea's capacity to decode sound frequencies is enhanced by a unique structural arrangement along its longitudinal axis, a feature termed 'tonotopy' or place coding. Auditory hair cells at the cochlea's base are activated by high-frequency sounds, while those at the apex respond to lower frequencies.

COVID-19 SARS-CoV-2 preprints from medRxiv and bioRxiv

Subject Area Otolaryngology



**PREPRINT** - Accessed 05 June 2024 at

<https://www.medrxiv.org/content/10.1101/2023.04.13.23288518v2.full.pdf>

# Demo Video

The screenshot shows a YouTube video player. The main video is an oscilloscope display showing a square wave (black) and a distorted sine wave (green). The oscilloscope interface includes a menu on the right with 'Agilent' and '2.000MHz' settings, and a bottom status bar with 'Scale: 80.0mV', 'Offset: 150.00mV', and 'FFT Resolution: 18 1Hz'. The video player interface includes a search bar, a play button, and a progress bar at 2:20 / 2:22. Below the video, the title is 'Waveforms and Sounds (Part 2 of 2)' by 'MegawattKS' (8.04K subscribers). The video has 382 views and was posted 9 years ago. The description asks why some signals sound the same despite different wave-shapes and hints at phase response in audio signal processing. To the right of the video player is a list of recommended videos:

- Antenna Briefs #7 - Radio Wave Reflections in Propagation an... (23:36)
- Arduino Reverb (15:09)
- Radio noise (EMF) from high-efficiency fluorescent lights (4... (1:31)
- Understanding Circuits - ECE topics #4 (part 1) (26:05)
- Oscilloscopes, Microphones, and Noise - ECE Topics #5 (14:05)

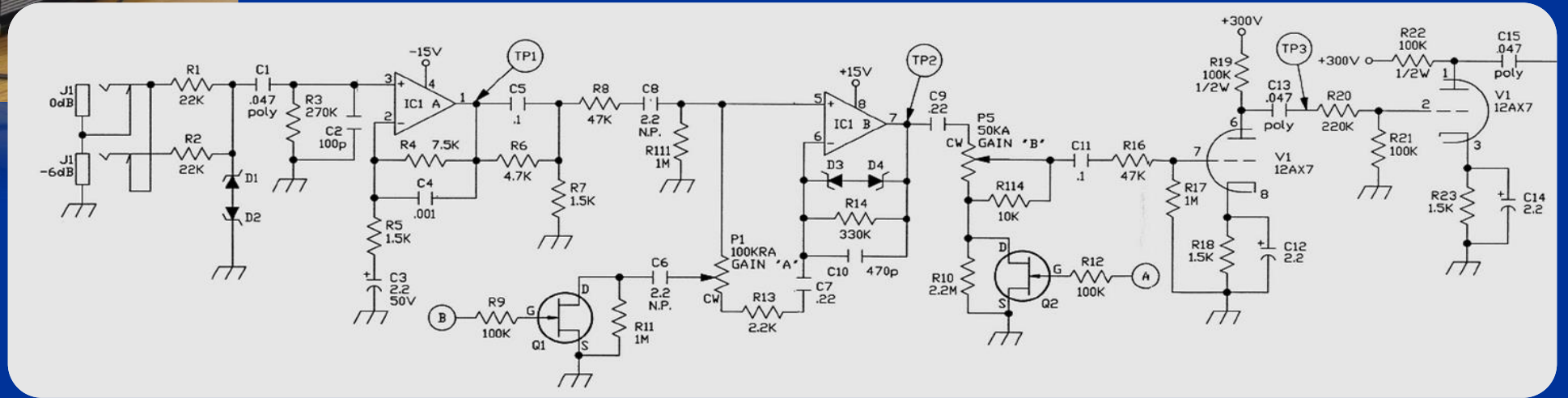
<https://www.youtube.com/watch?v=VF78yEnNUhw>

# Real World Signals and Circuits

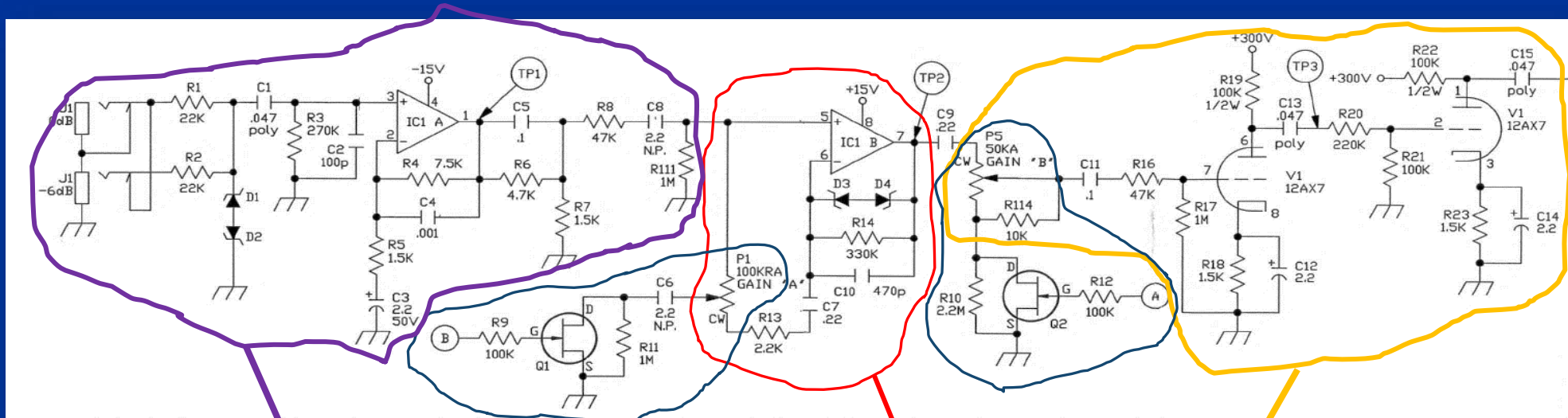
## (from Episodes 3 and 4)



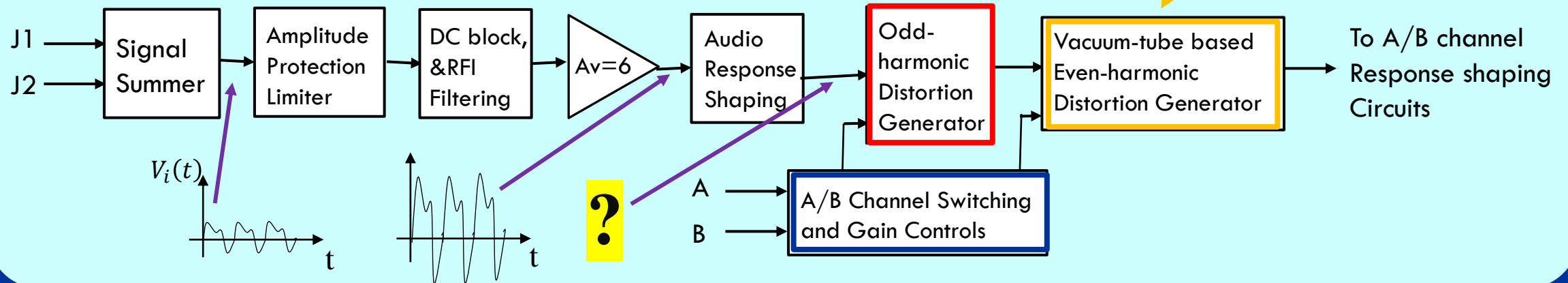
<http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf>



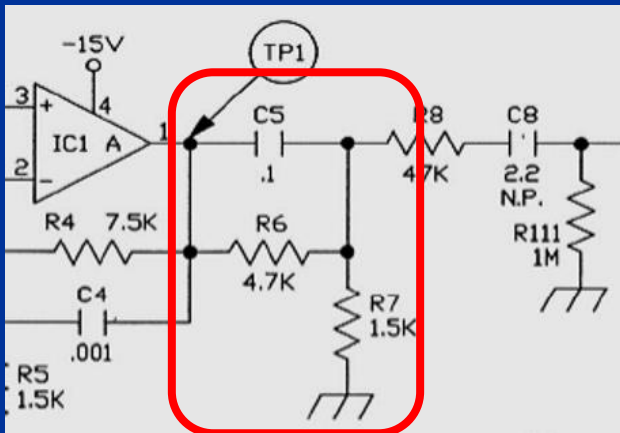
# Parsing Schematic into Block Diagram



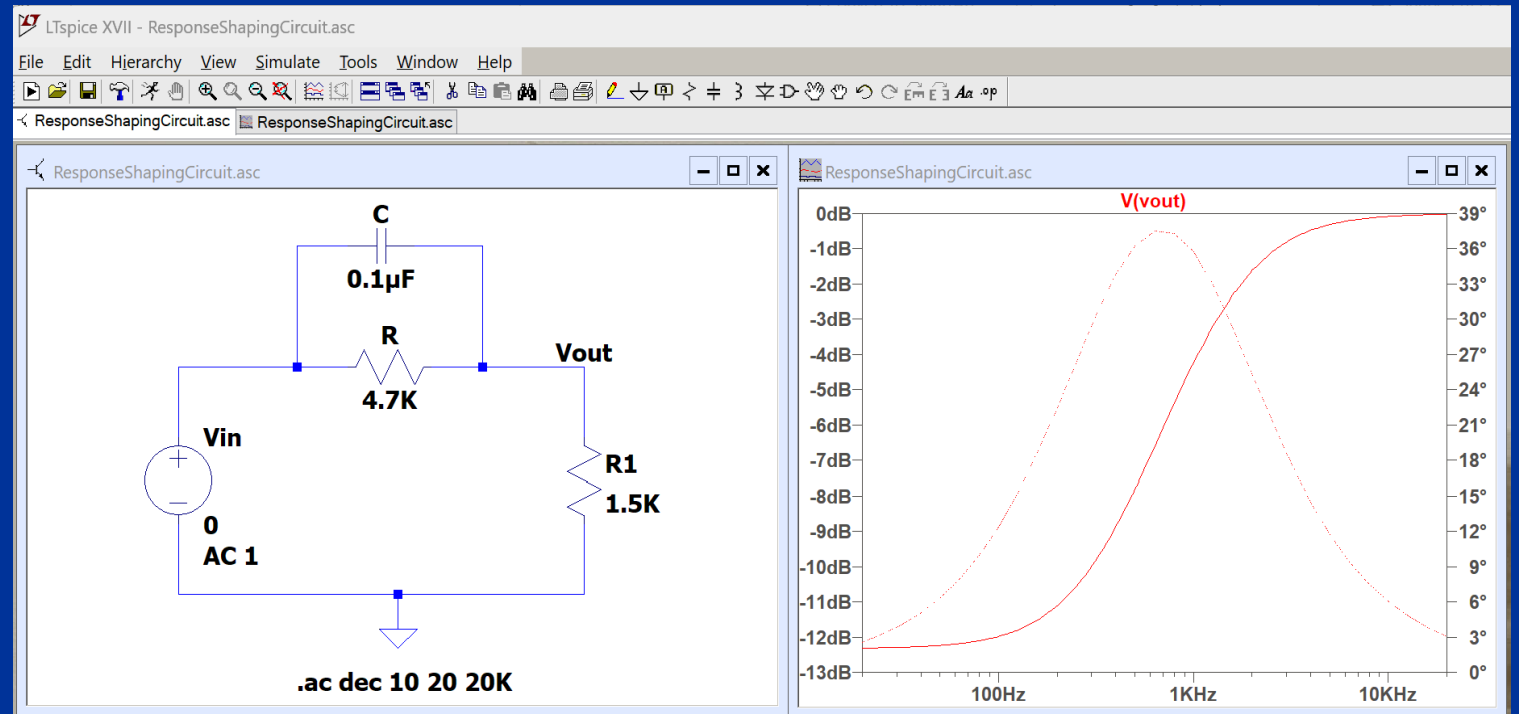
<http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf>



# Circuit Simulation



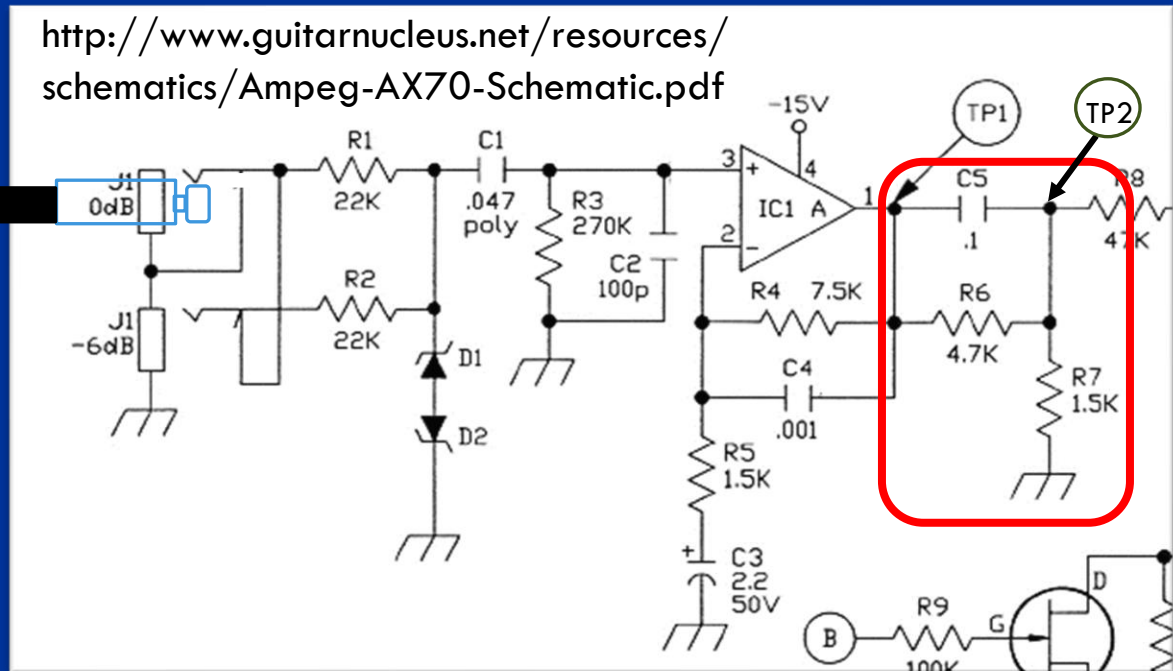
<http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf>



# Circuit Analysis/Understanding

## (from Episode 4)

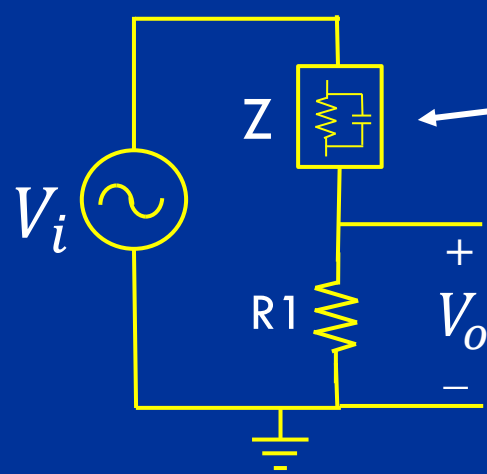
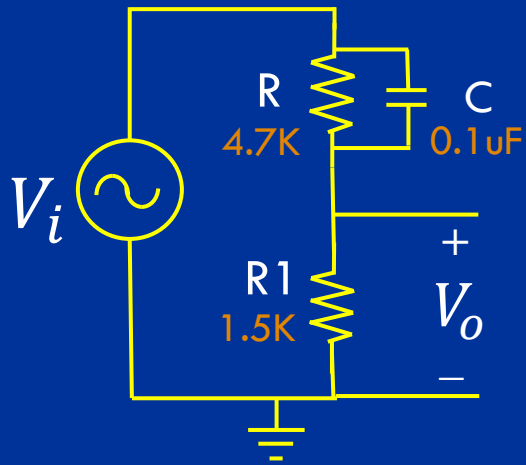
<http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf>



- R6, C5, R7 create a frequency-dependent voltage divider
- At low-frequency ( $\ll 340$  Hz),  $X_{C5} \gg R6$ , so division is approx  $R7 / (R7 + R6) = 0.24$
- At high-frequency ( $\gg 1.4$  kHz),  $X_{C5} \ll R7$ , so not much voltage division. C5 just couples signal to next stage
- Response is 12 dB **bass-cut, treble-boost**

Need complex math and voltage divider equation for full solution ...

# Circuit Design



First:

$$Z = R || Z_c \quad \text{where} \quad Z_c = \frac{1}{j2\pi f C} = \frac{1}{j\omega C} = \frac{1}{sC}$$

Then:

$$\frac{V_o}{V_i} = \frac{R_1}{R_1 + Z} = \frac{R_1}{R_1 + \left( \frac{R \frac{1}{sC}}{R + \frac{1}{sC}} \right)} = \frac{R_1}{R_1 + \left( \frac{R}{1 + sCR} \right)}$$

So ...

$$\frac{V_o}{V_i} = \frac{R_1}{R_1 + \left( \frac{R}{1 + sCR} \right)}$$

*where  $s = j\omega = j2\pi f$*

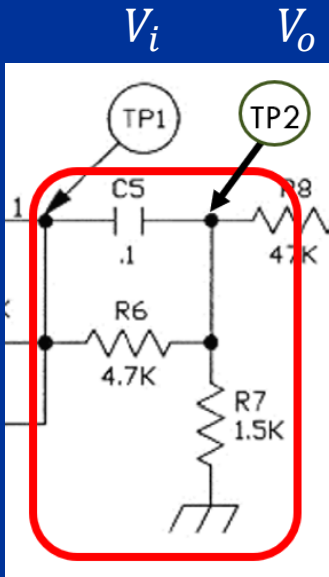
Checking:

As  $s \rightarrow 0$  :  $\frac{V_o}{V_i} = \frac{R_1}{R_1 + R} = \frac{1.5K}{1.5K + 4.7K} = 0.24$

As  $s \rightarrow \infty$  :  $\frac{V_o}{V_i} = \frac{R_1}{R_1 + 0} = 1$



# Putting Transfer Function into Standard Form



$$\begin{aligned} \frac{V_o}{V_i} &= \frac{R_1}{R_1 + \left(\frac{R}{1+sCR}\right)} = \frac{R_1(1+sCR)}{R_1(1+sCR)+R} = \frac{R_1(1+sCR)}{R_1+R+sCRR_1\frac{R_1+R}{R_1+R}} = \left(\frac{R_1}{R_1+R}\right) \frac{1+sCR}{1+sC\frac{R_1R}{R_1+R}} \\ &= \left(\frac{R_1}{R_1+R}\right) \frac{1+s/\omega_z}{1+s/\omega_p} \end{aligned}$$

Where:

$$\omega_z = \frac{1}{RC}$$

$$\omega_p = \frac{1}{(R||R_1)C}$$

Or, in terms of f:

$$f_z = \frac{1}{2\pi RC} = 339 \text{ Hz}$$

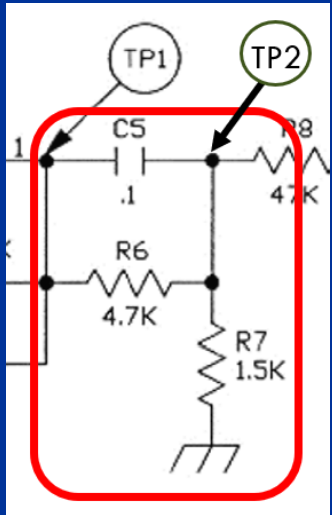
$$f_p = \frac{1}{2\pi(R||R_1)C} = 1.4 \text{ kHz}$$

$$H(f) = \frac{V_o}{V_i} = (0.24) \frac{1+jf/f_z}{1+jf/f_p}$$

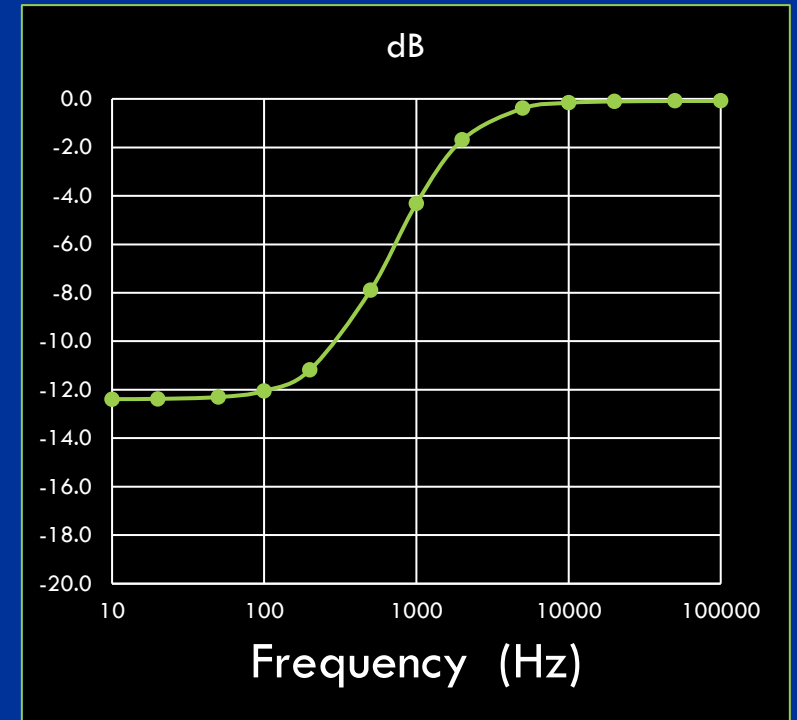
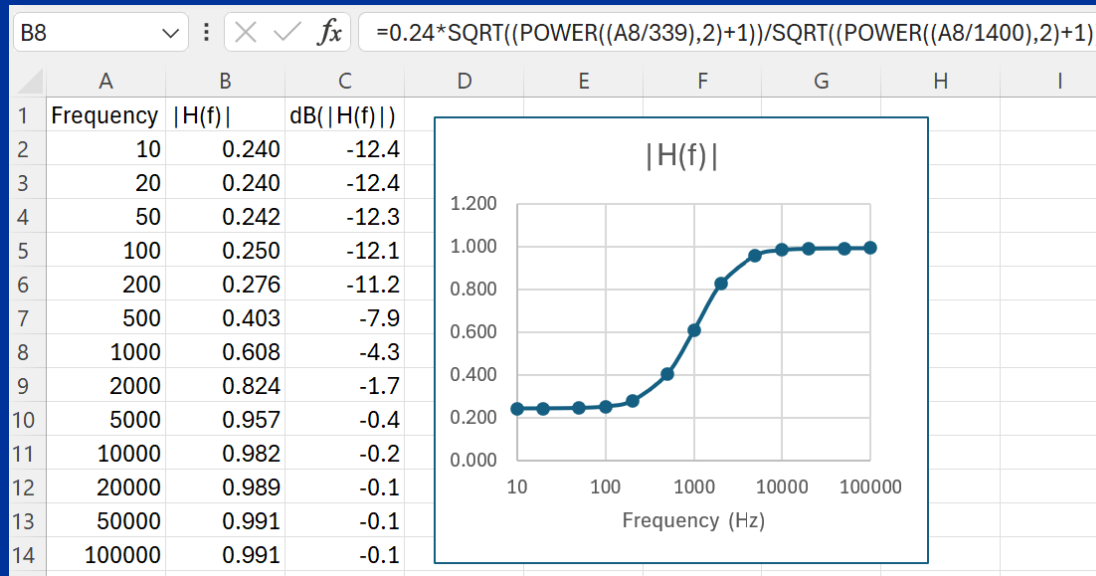
# $|H(f)|$ Evaluation with Excel

(Following Examples in Episodes 6, 7)

$V_i(f)$   $V_o(f)$



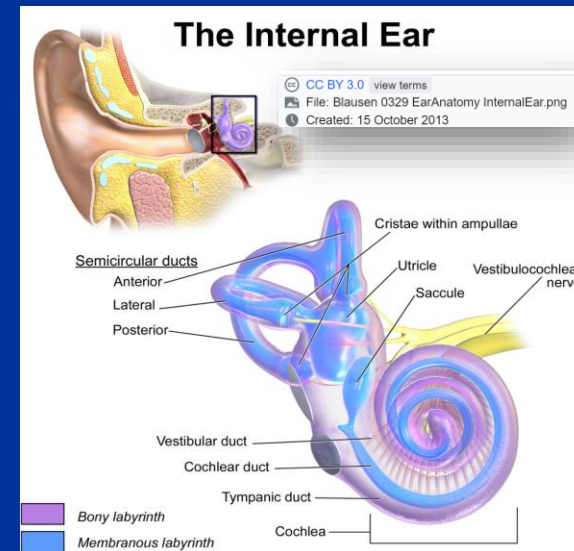
$$H(f) = \frac{V_o(f)}{V_i(f)} = 0.242 \frac{1 + j \frac{f}{339}}{1 + j \frac{f}{1400}}$$



# Amplitudes and dB in Audio

## (from Episode 7)

- Sound pressure level (SPL) is measured in Pascals (  $1 Pa = 1 \frac{N}{m^2}$  )
- In audio, SPL is often expressed in "dB"
- 10 dB increase in SPL is perceived to be "twice as loud"



# E on 4<sup>th</sup> String (330/2 Hz)

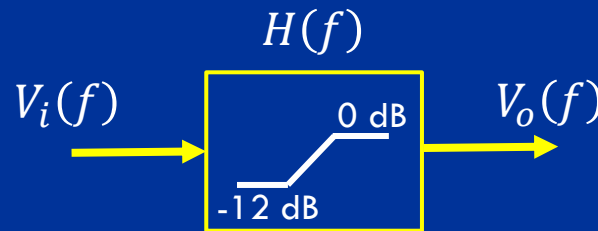
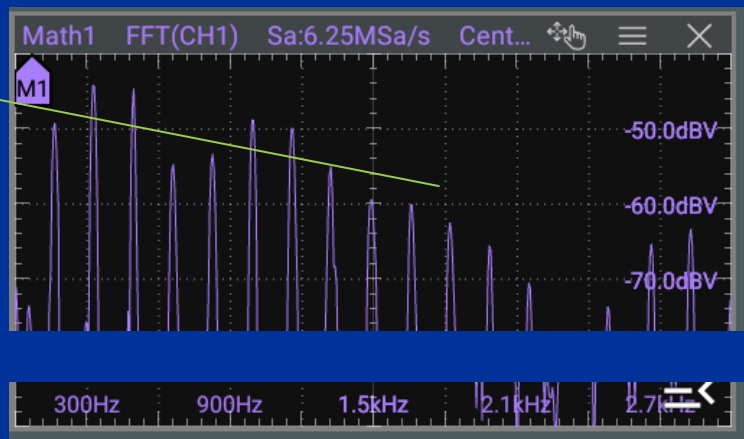


# Effect of Response Shaping On Spectrum

“Adding dB:” 😊

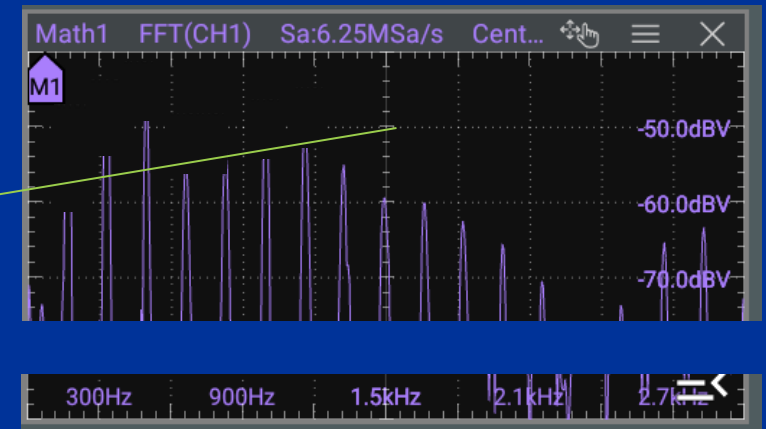
$$\begin{aligned} 20\log|V_o(f)| &= 20\log|H(f) V_i(f)| \\ &= 20\log|H(f)| + 20\log|V_i(f)| \end{aligned}$$

$$|V_o(f)|_{\text{dBV}} = |H(f)|_{\text{dB}} + |V_i(f)|_{\text{dBV}}$$



$$V_o(f) = H(f)V_i(f)$$

Spectrums



# Possible Future Videos?

- Analog and Digital Filter Design
- Fourier Transform pairs and properties, including radio modulation
- Using the FFT in practice
- Speech production, recognition, and data compression
- Applications beyond circuits and systems ...

# Filter Design Preview

OPAMPS  
Opamp  
Typical Application

Use as signal preamp/conditioning  
between transducer & Analog to Digital Converter (ADC)

Digital words (numbers)  
To digital signal processor (DSP)

Opamp based audio "preamp" and lowpass filtering

From DSP

Lowpass Smoothing Filter

Audio Power Amp

Simple Inverting Amp with High Frequency Noise Filtering

$$V_o = -\frac{Z}{R_1} V_i$$

where  $Z = R_2 \parallel \frac{1}{j\omega C}$

$$\Rightarrow \frac{V_o}{V_i} = -\frac{R_2 \parallel \frac{1}{j\omega C}}{R_1}$$

$$= -\frac{R_2}{R_1} \frac{1}{1 + j\omega R_2 C}$$

$$= -\frac{R_2}{R_1} \frac{1}{1 + j\omega/\omega_0} \quad \text{with } \omega_0 = \frac{1}{R_2 C}$$

dB

$20 \log \frac{R_2}{R_1}$

$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi R_2 C}$

$X_c > R_2$  here  $\Rightarrow Z \approx R_2$   
 $X_c = R_2$  here  $\Rightarrow Z = \frac{1}{\sqrt{2}} R_2 \angle -45^\circ$   
 $X_c < R_2$  here  $\Rightarrow Z \approx -j X_c = \frac{1}{j 2\pi f C}$

Application: General. often added to basic amplifier

Active Filters

Revised Simple 1 pole LP filter

dB

$3\text{dB}$

$-20\text{dB/decade}$   
 $-6\text{dB/octave}$

$f_0 = \frac{1}{2\pi R_2 C}$

Simple 2 pole LP filter

dB

$6\text{dB}$

$-40\text{dB/decade}$   
 $-12\text{dB/octave}$

Better 2 pole LP Filter (Sallen-Key)

dB

$40\text{dB/decade}$   
 $-12\text{dB/octave}$

(See steps 15 or book on filters for R1, C values)

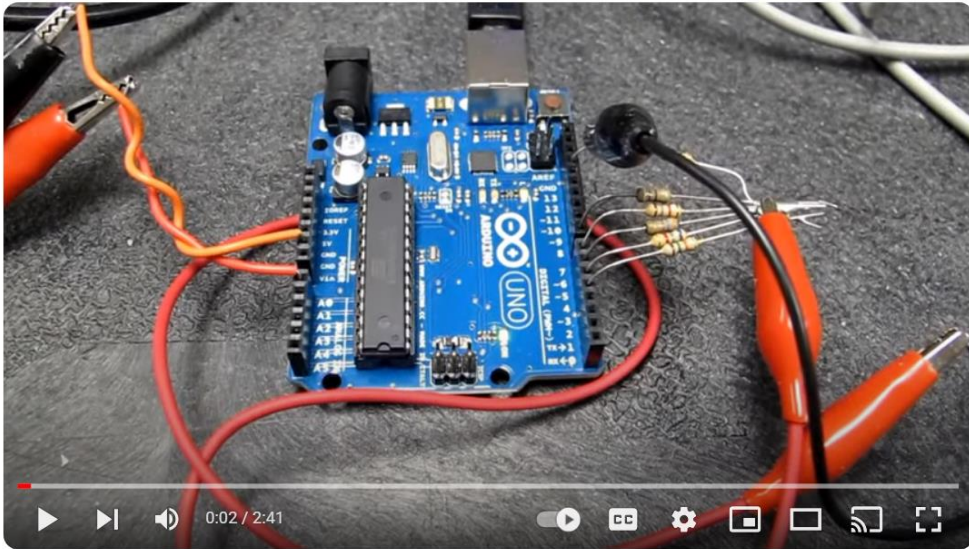
4 pole LP Filter

3-6 dB (depending on design) See book & ELEC 514

$-80\text{dB/decade}$   
 $-24\text{dB/octave}$

# Simple DSP Demo on Arduino

## One-pole IIR Digital Filter



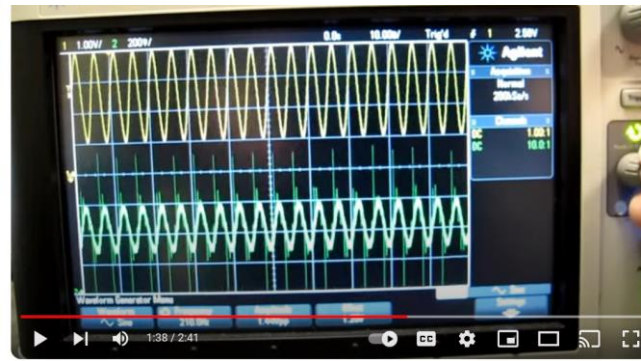
Arduino board digital signal processing demo

MegawattKS  
8.04K subscribers

20K views · 11 years ago

Demo of digital filter created on Arduino Uno board showing operation of a lowpass IIR response as well as basic ADC and DAC issues including quantization and aliasing. ...more

```
while(1) {  
  // Read the analog value on pin A0 and scale by 1/8  
  analogin = analogRead(A0) >> 3;  
  // Update DSP filter delay register and output value  
  // The filter is implemented as  $y(n) = x(n) + 0.875 y(n-1)$   
  new_analogout = analogin + (analogout - (analogout >> 3));  
  analogout = new_analogout;  
  // Write the value to the output pin, scaled back to 0 to 255
```



All From MegawattKS Electronic compone

Arduino Reverb  
MegawattKS  
23K views · 9 years ago

15:09

<https://www.youtube.com/watch?v=d-GvSgMQw-E>



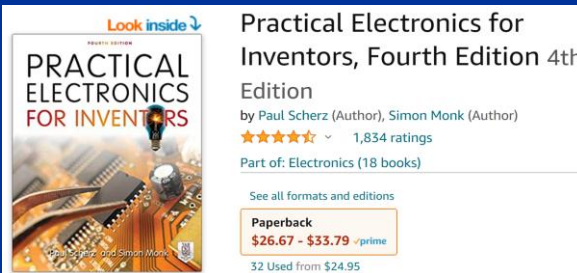
# Ways to Learn More

## Videos and Websites

- This Video's Playlist / Channel 😊
- Other Videos
- ECEfiles.org
- Other Websites

## Books

Circuits/filters for broad audience



**Practical Electronics for Inventors, Fourth Edition 4th Edition**  
by Paul Scherz (Author), Simon Monk (Author)  
★★★★★ 1,834 ratings  
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<https://www.amazon.com/Practical-Electronics-Inventors-Fourth-Scherz-dp-1259587541/dp/1259587541/>

College-level review



**Schaum's Outline of Signals and Systems, Fourth Edition (Schaum's Outlines) 4th Edition, Kindle Edition**  
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## University Courses

### Freshman year

#### Fall semester (16 credit hours)

- CHM 210 - Chemistry I **Credits:** (4)
- COMM 105 - Public Speaking IA **Credits:** (2)
- ECE 015 - New Student Assembly **Credits:** (0)
- ECE 210 - Introduction to Electrical Engineering **Credits:** (3)
- ENGL 100 - Expository Writing I **Credits:** (3)
- MATH 220 - Analytic Geometry and Calculus I **Credits:** (4)

#### Spring semester (17 credit hours)

- BIOL 198 - Principles of Biology **Credits:** (4)  
or
- CHM 230 - Chemistry II **Credits:** (4)
- ECE 115 - New Student Design Project **Credits:** (1)
- ECON 110 - Principles of Macroeconomics **Credits:** (3)
- MATH 221 - Analytic Geometry and Calculus II **Credits:** (4)
- PHYS 213 - Engineering Physics I **Credits:** (5)

### Sophomore year

#### Fall semester (17 credit hours)

- CHE 354 - Basic Concepts in Materials Science and Engineering **Credits:** (1)
- CHE 356 - Fundamentals of Electrical Properties **Credits:** (1)
- ECE 241 - Introduction to Computer Engineering **Credits:** (3)
- ECE 410 - Circuit Theory I **Credits:** (3)
- MATH 240 - Elementary Differential Equations **Credits:** (4)
- PHYS 214 - Engineering Physics II **Credits:** (5)

#### Spring semester (16 credit hours)

- CIS 209 - C Programming for Engineers **Credits:** (3)
- ECE 511 - Circuit Theory II **Credits:** (3)
- ECE 525 - Electronics I **Credits:** (3)
- MATH 222 - Analytic Geometry and Calculus III **Credits:** (4)
- STAT 510 - Introductory Probability and Statistics I **Credits:** (3)

### Junior year

#### Fall semester (16 credit hours)

- \*\*Humanities/Social Science Elective **Credits:** (3)
- ECE 431 - Microcontrollers **Credits:** (3)
- ECE 526 - Electronics II **Credits:** (3)
- ECE 540 - Applied Scientific Computing for Engineers **Credits:** (3)
- ECE 557 - Electromagnetic Theory I **Credits:** (4)

#### Spring semester (17 credit hours)

- \*\*Humanities/Social Science Elective **Credits:** (3)
- ECE Technical Electives **Credits:** (3)
- ECE 502 - Electronics Laboratory **Credits:** (2)
- ECE 512 - Linear Systems **Credits:** (3)
- ECE 581 - Energy Conversion I **Credits:** (3)
- ENGL 415 - Written Communication for Engineers **Credits:** (3)

### Senior year

#### Fall semester (15 credit hours)

- \*\*\*Technical electives **Credits:** (6)
- CE 530 - Statics and Dynamics **Credits:** (3)
- ECE 530 - Control Systems Design **Credits:** (3)
- ECE 590 - Senior Design Experience **Credits:** (3)

#### Spring semester (15 credit hours)

- \*\*\*Technical electives **Credits:** (9)
- \*\*Humanities/Social Science Elective **Credits:** (3)
- ME 513 - Thermodynamics I **Credits:** (3)

### Electrical engineering options

#### General option

THANKS FOR WATCHING !