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)

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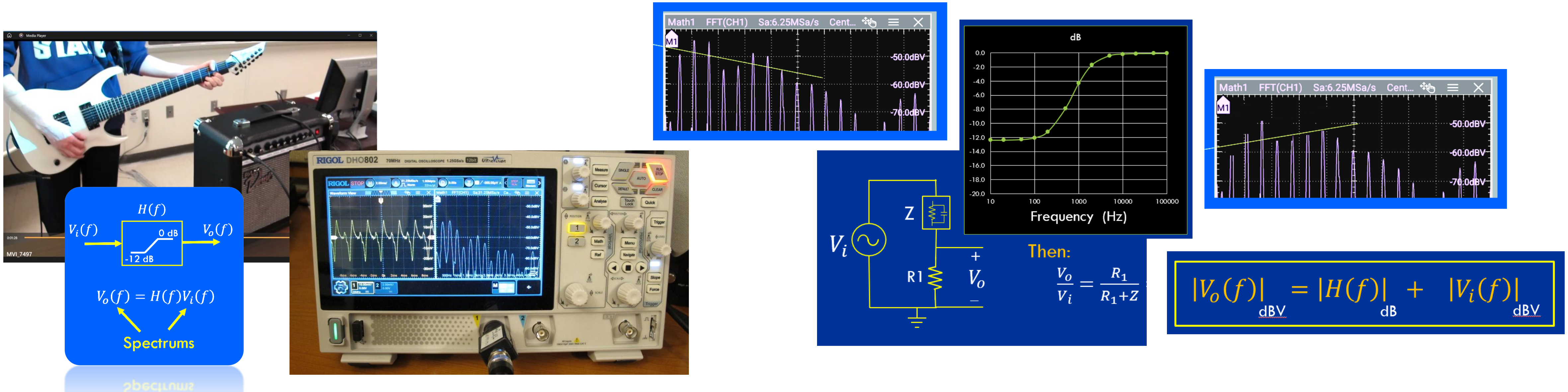
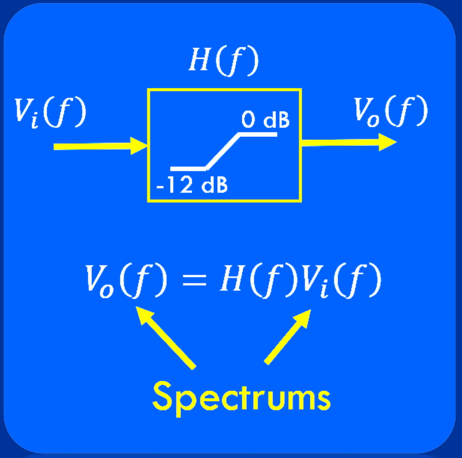
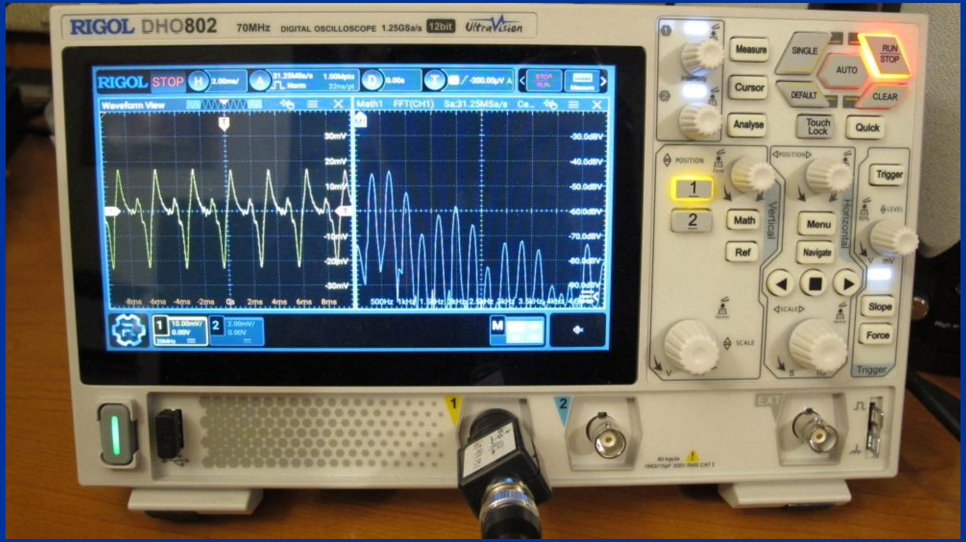
Fourier Series and Fast Fourier Transform (FFT) concepts with a focus on applications. Covers time and frequency domain using guitar sounds, but extension to application in wireless communications is also touched on. A Rigol DHO 800 series scope is used to show waveforms and spectrums and interpretation 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.



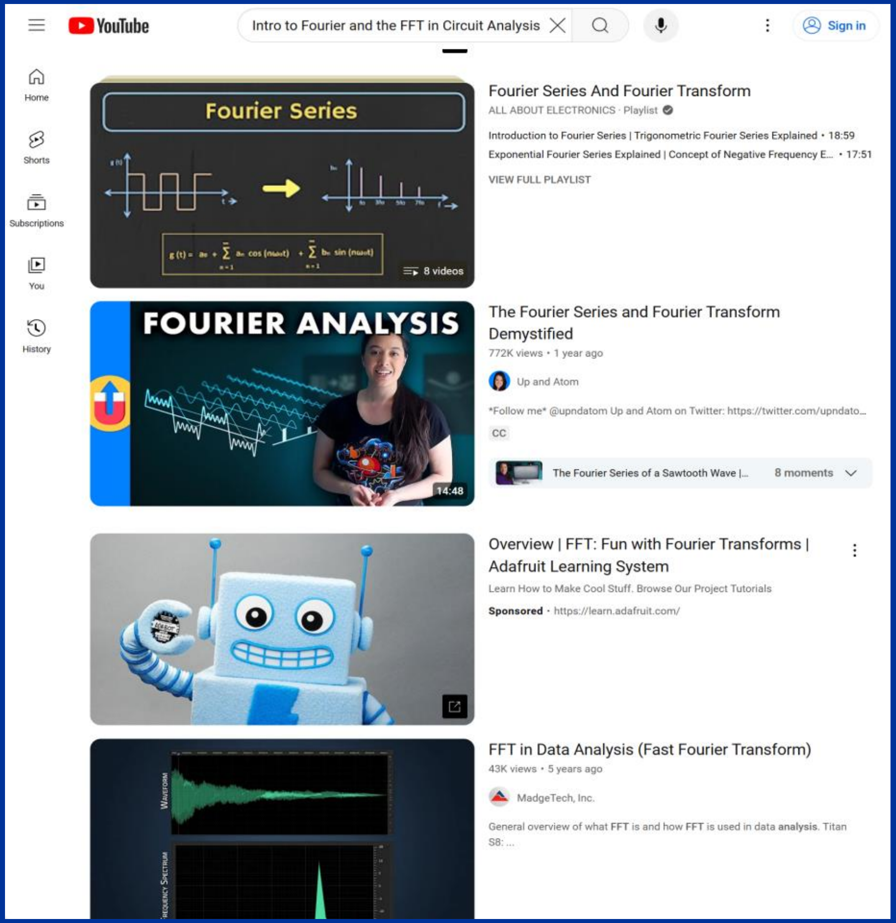
Topics in ECE #8

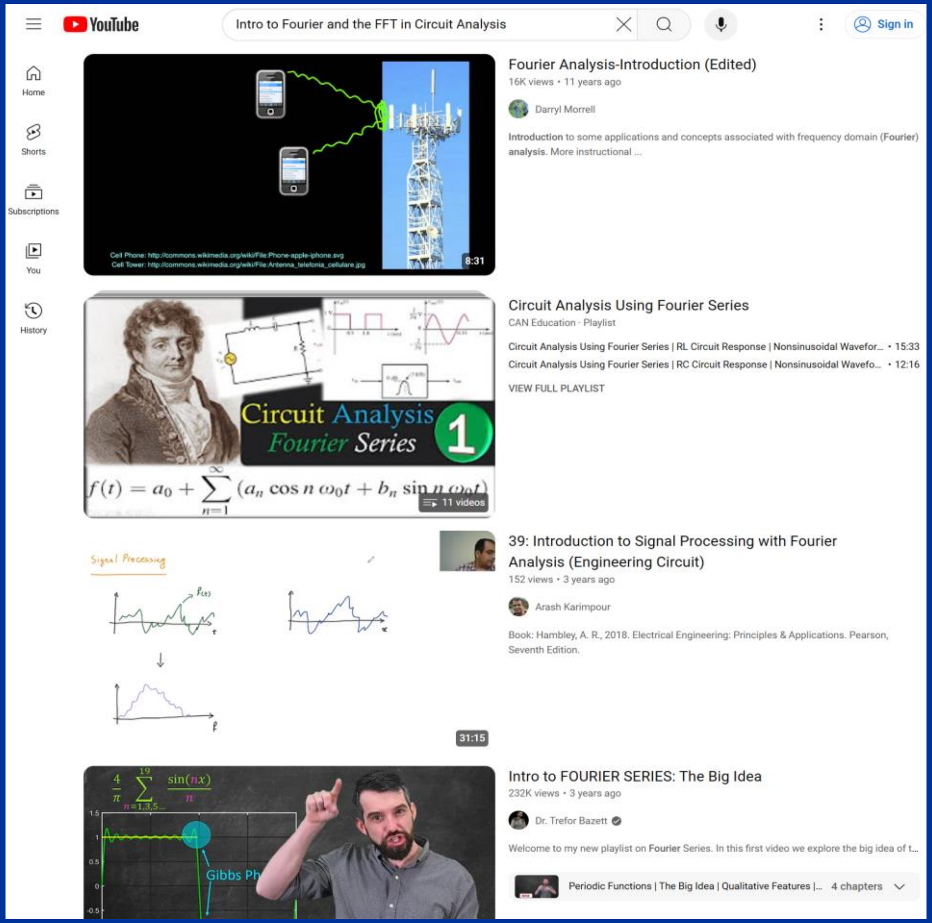
Fourier and FFT Concepts in Circuit Design





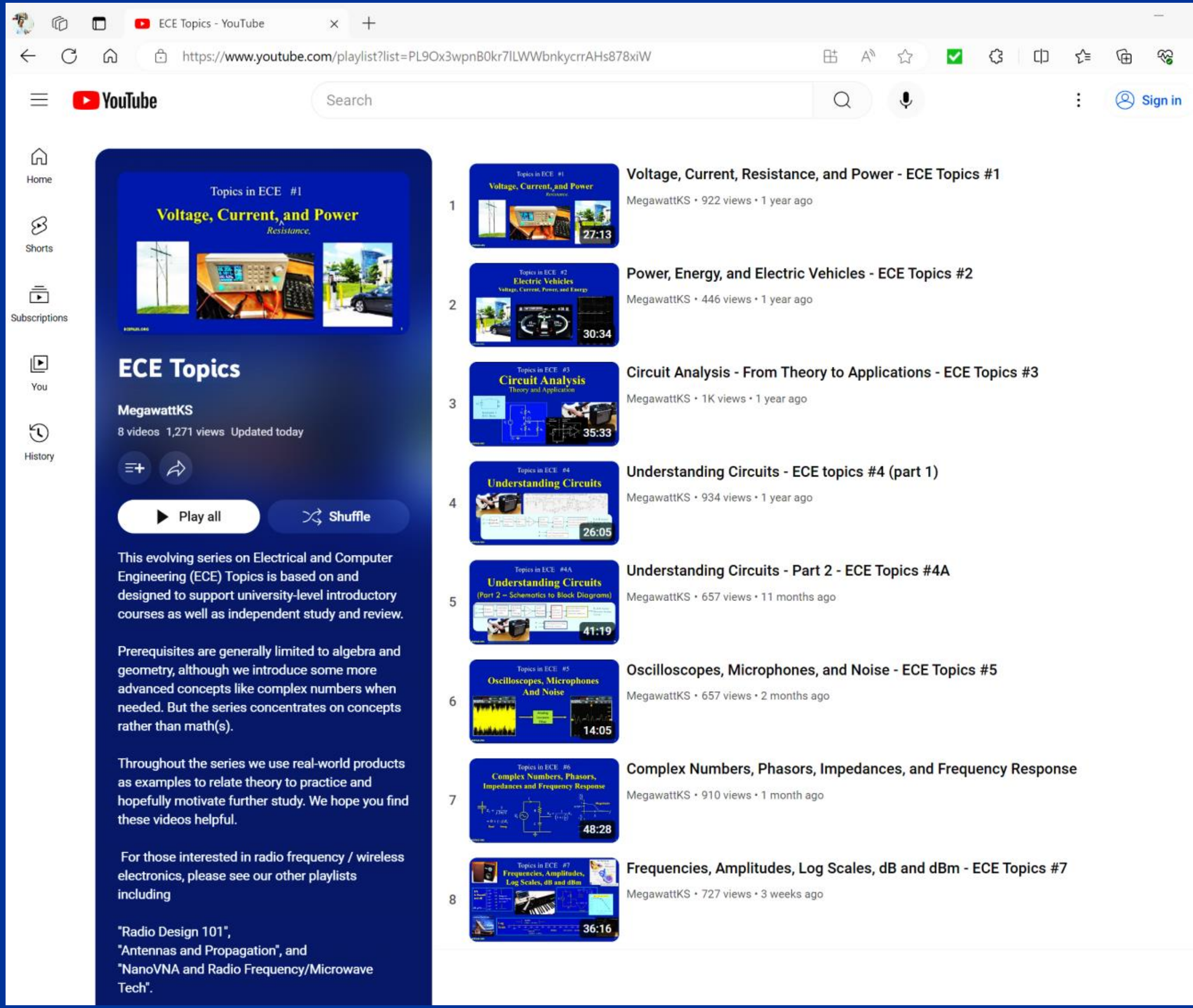
Some Existing Fourier, FFT Videos on YouTube





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

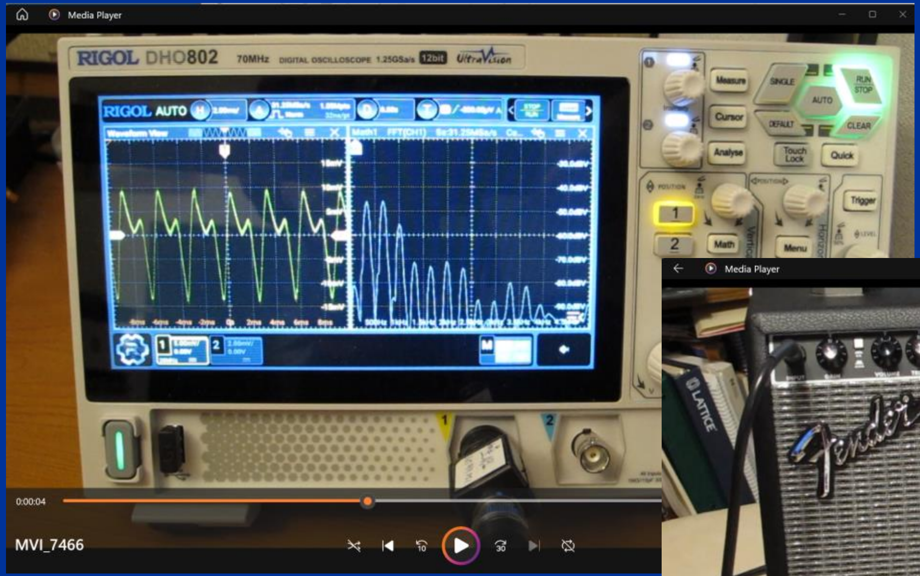


Today’s Topics

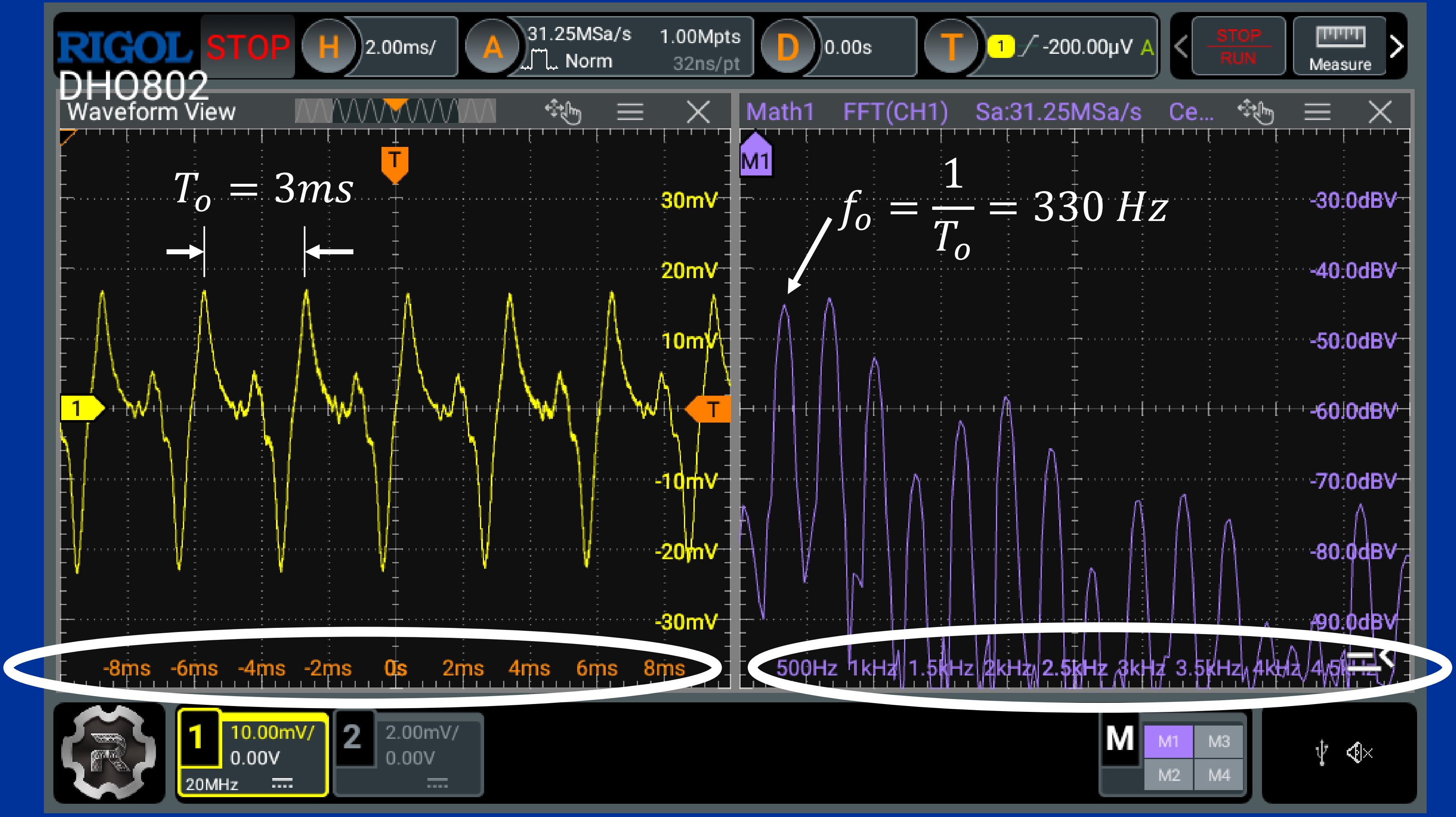
- Time and Frequency domains
- Fourier – the Bridge between domains
- Circuits: from Phasor Analysis to Signal Processing

Guitar Waveforms and Spectrums

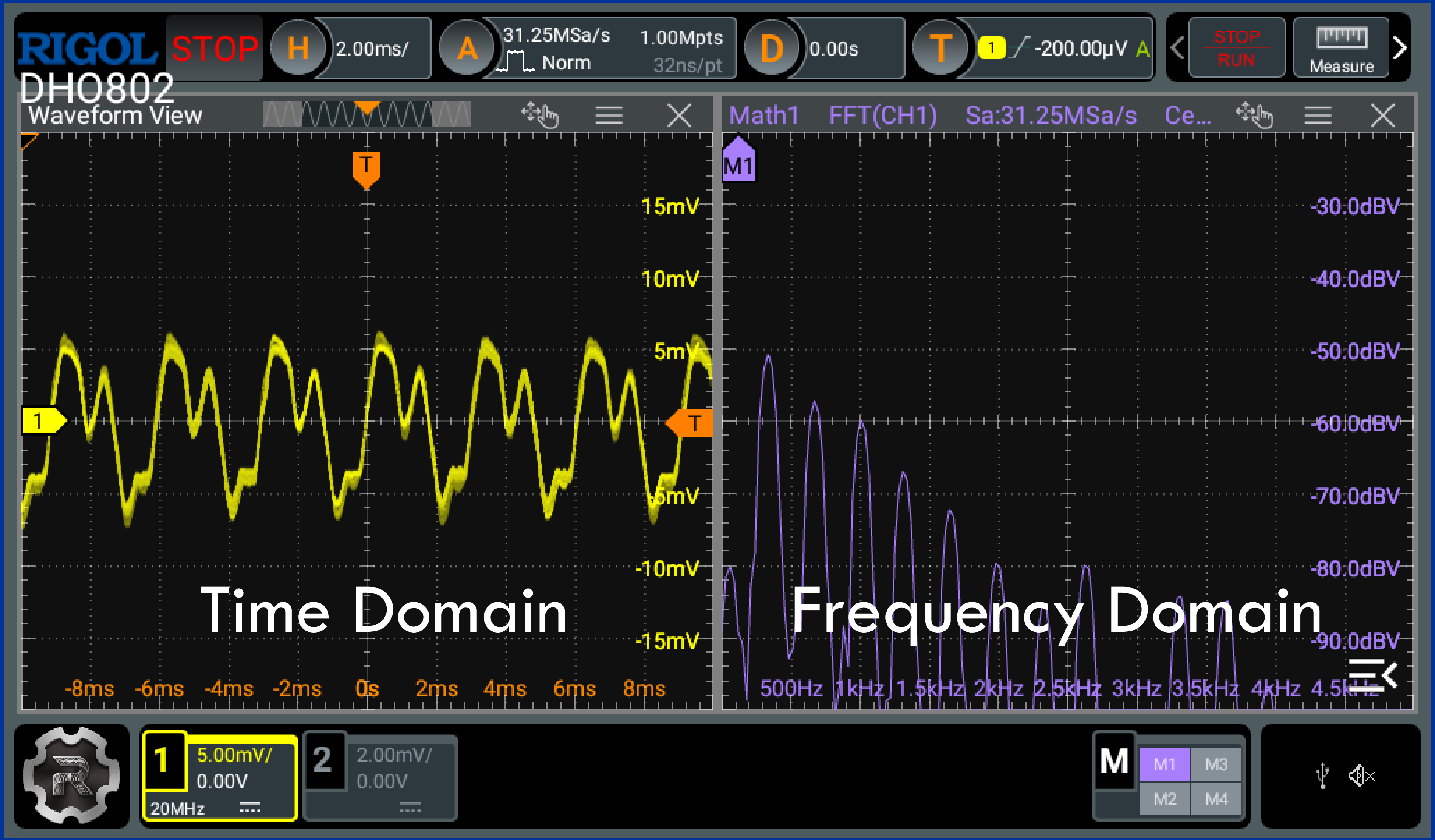
Tuning up new
Stratocaster guitar ☺



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)

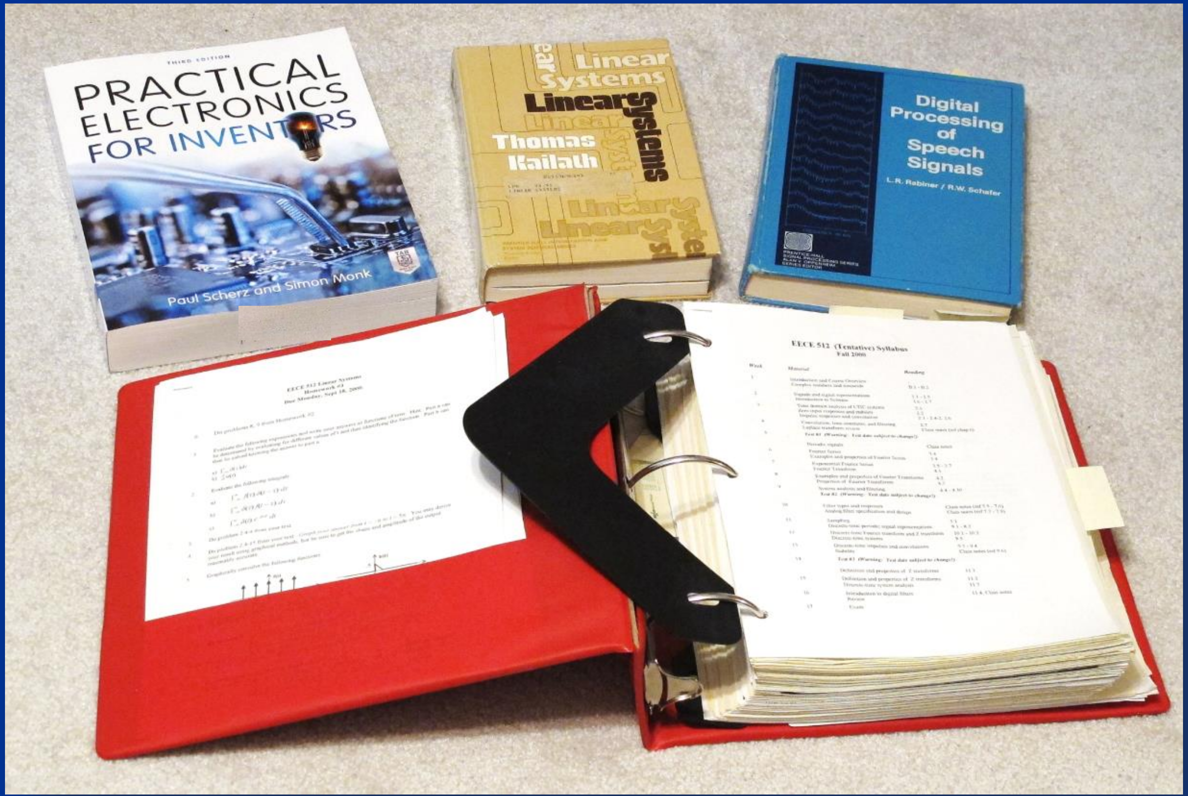
- ***Technical electives **Credits:** (9)
- **Humanities/Social Science Elective **Credits:** (3)
- ME 513 - Thermodynamics I **Credits:** (3)

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:

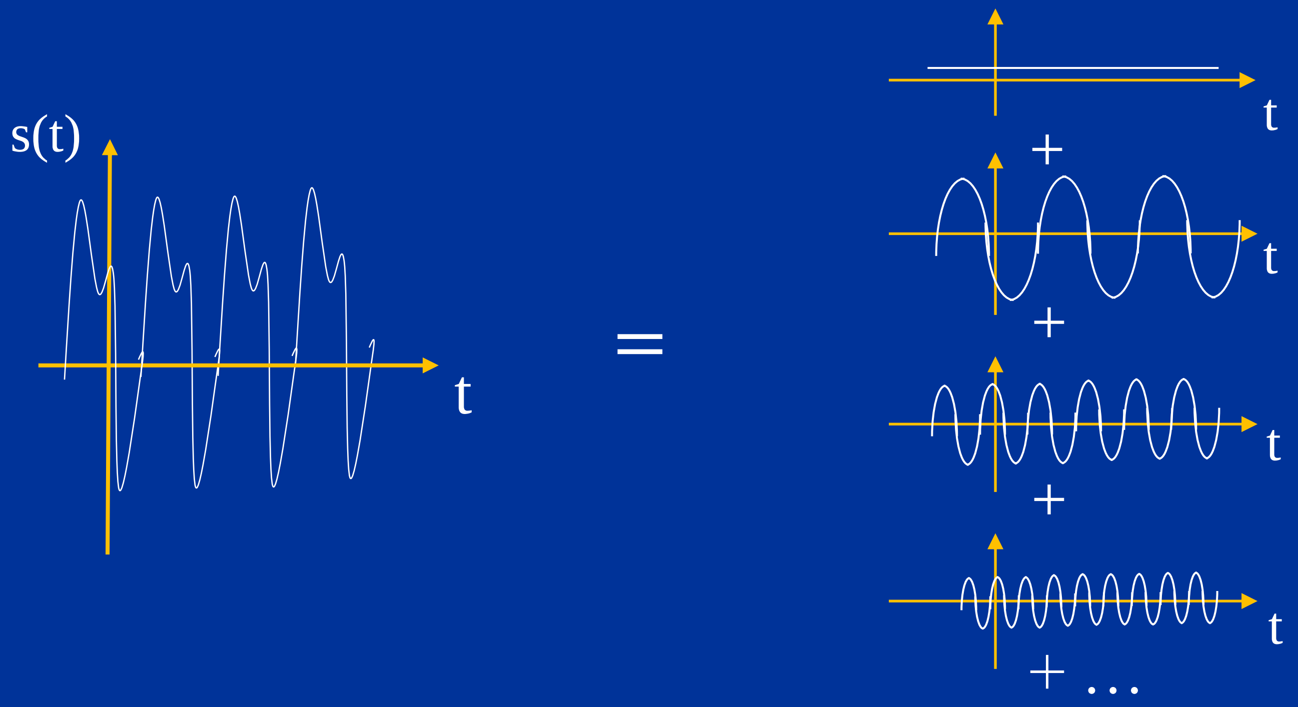
This course introduces the mathematical tools essential to the analysis of complex dynamic circuits and systems. The course builds on material studied in Math 240 (Differential Equations) and ECE511 (Circuits II), providing a foundation for a wide range of subjects within the discipline of Electrical 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.

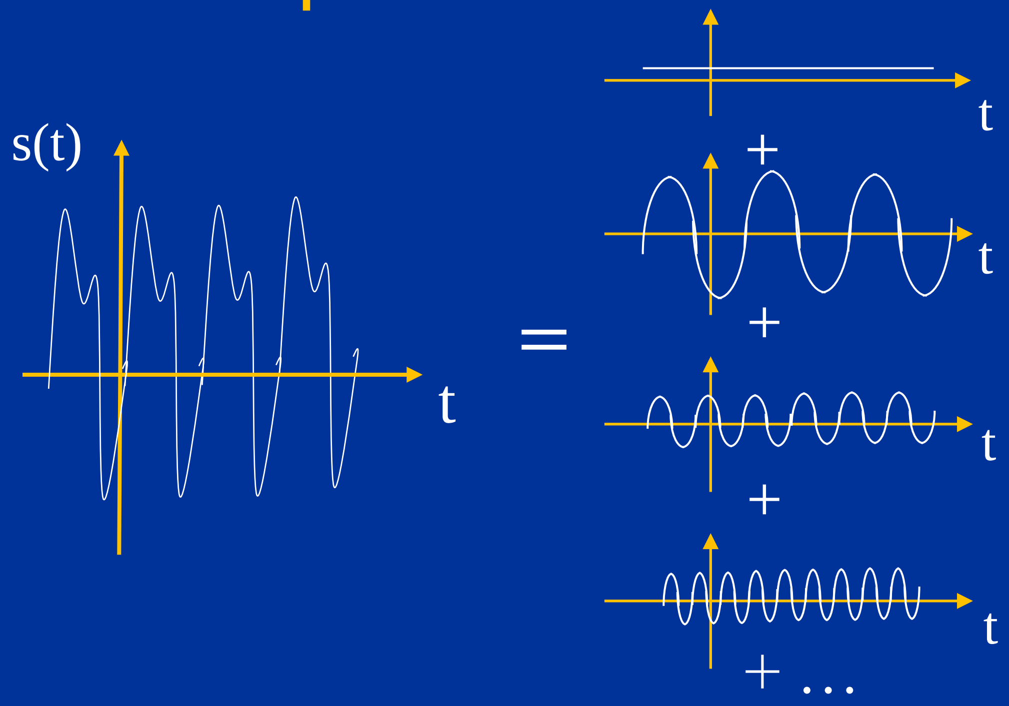
Fourier Series – The Basic Concept

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



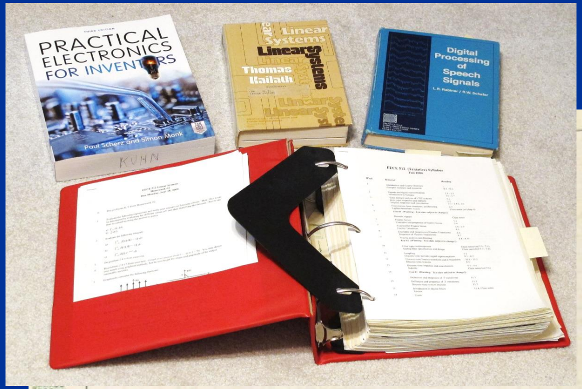
Trigonometric Fourier Series

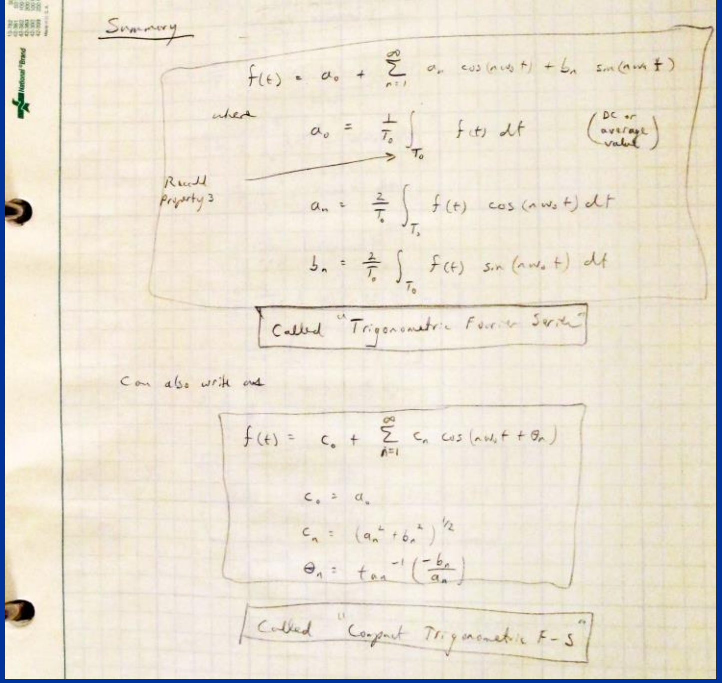
$$\equiv \; C_0 + C_1 cos(2\pi f_o t + \theta_1) + C_2 cos(2\pi(2f_o)t + \theta_2) + C_3 cos(2\pi(3f_o)t + \theta_3) + \ldots$$

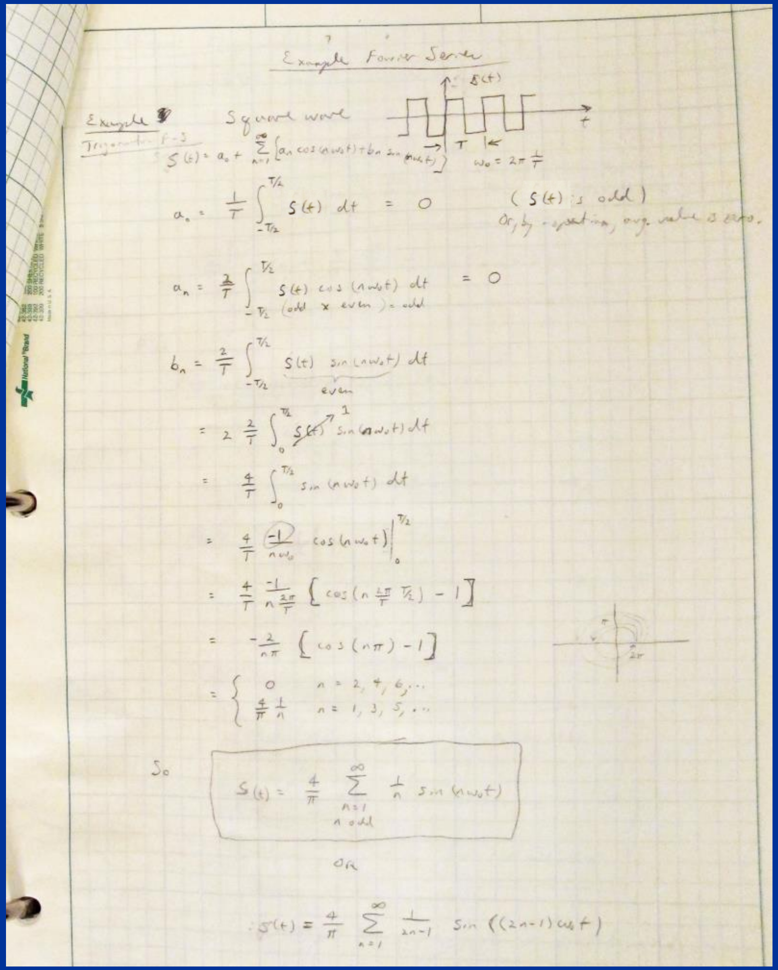
$$= \sum_{n=0}^{\infty} C_n cos(2\pi(nf_o)t + \theta_n)$$

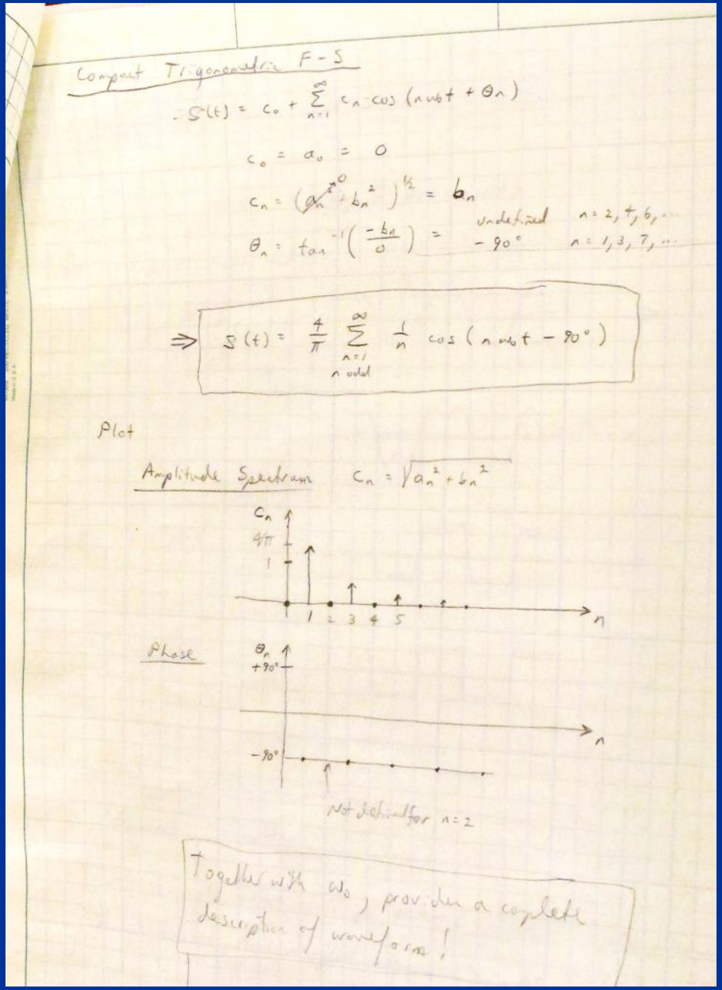
Finding / Plotting Spectrum

(of a Square-wave)





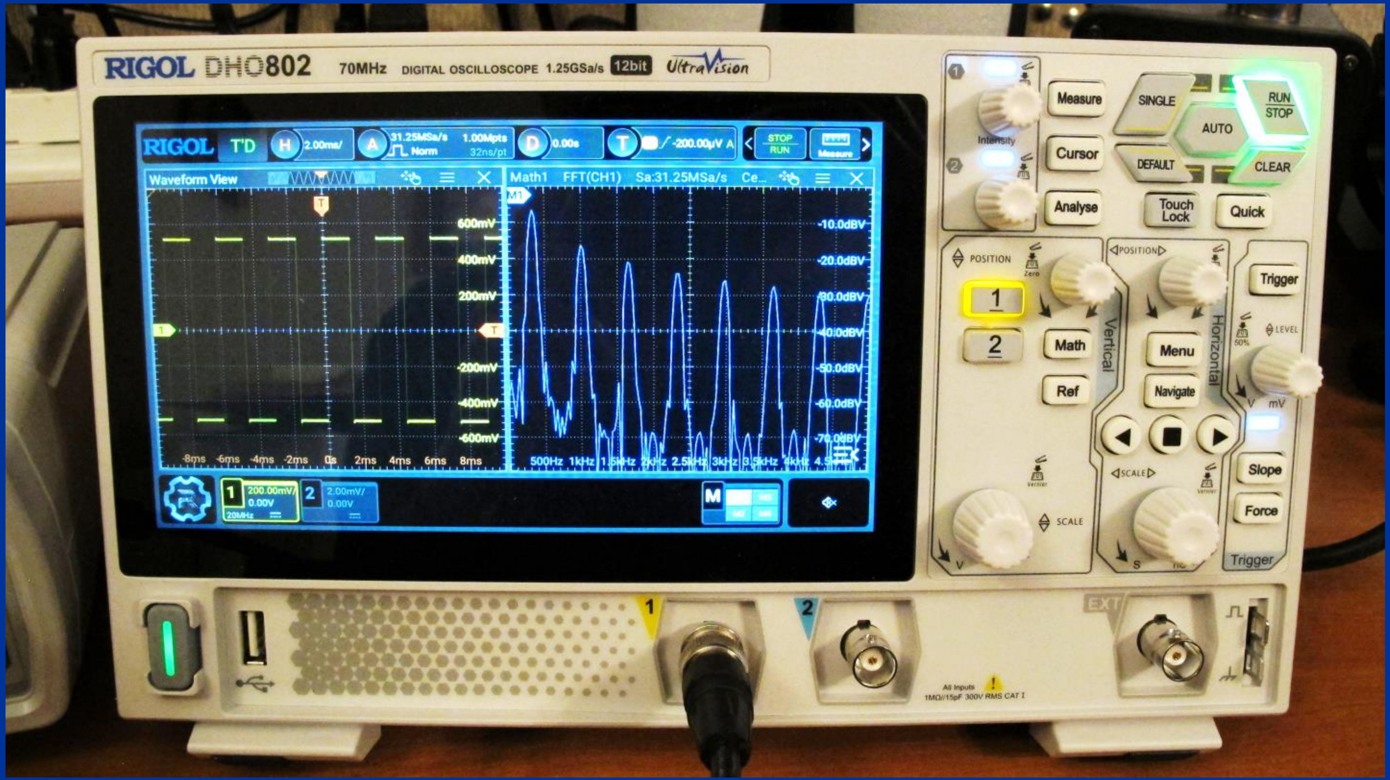




Finding Spectrums in Practice …

Use Fast Fourier Transform (FFT)

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

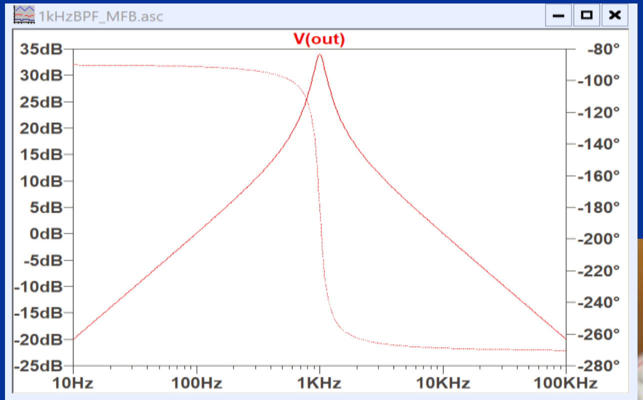


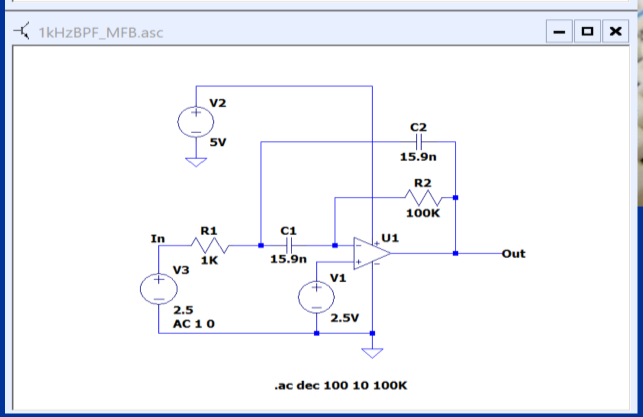
NOTE: We often just look at the amplitude spectrum. Why?

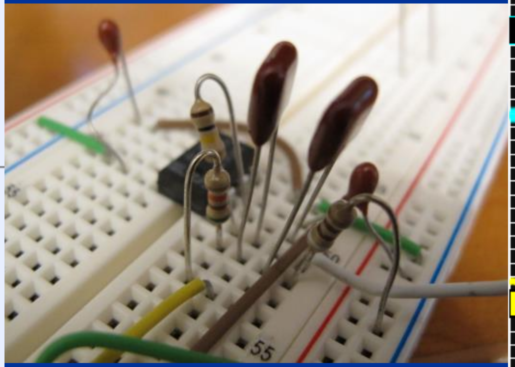
An Interesting Experiment

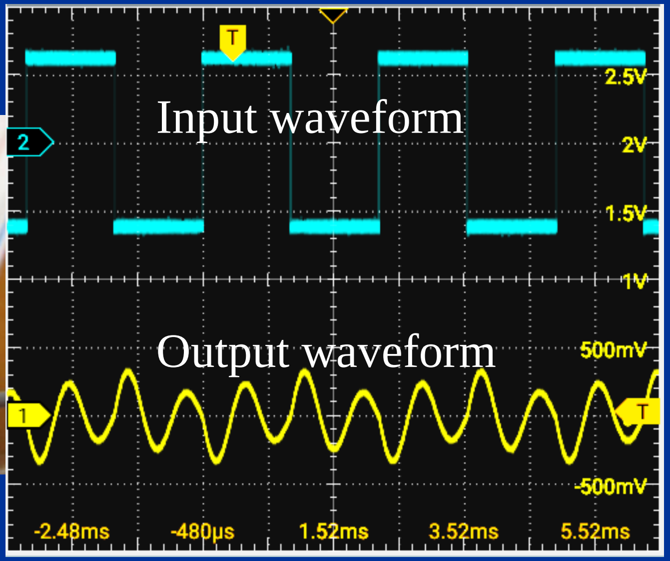
Proving a square-wave has sinewaves in it ☺

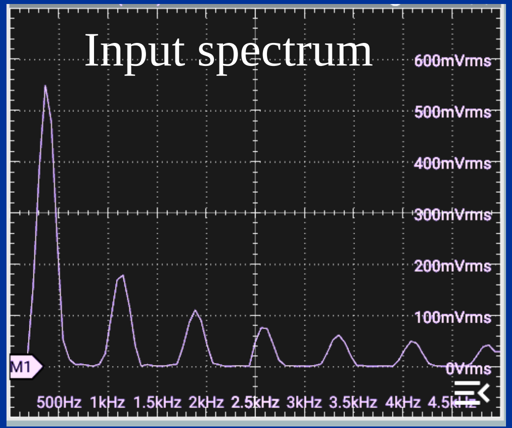
High-Q MFB Bandpass filter

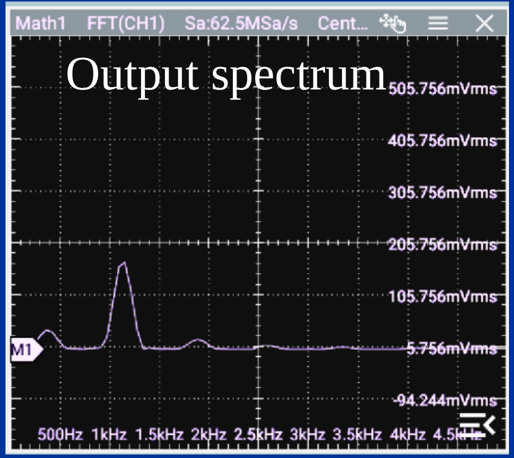






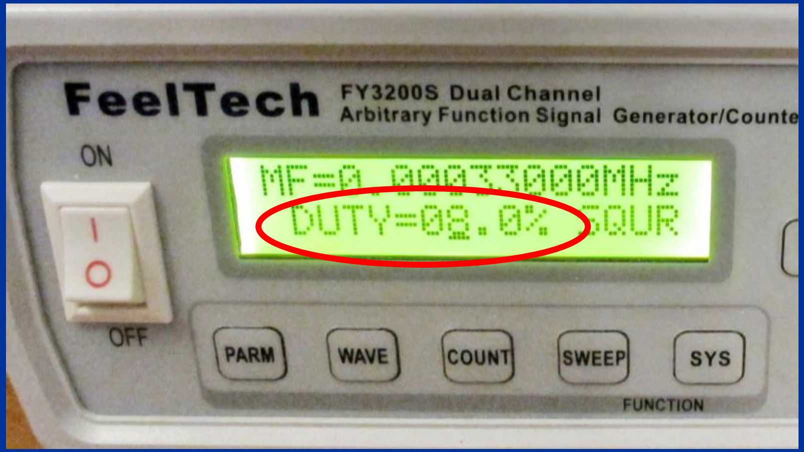


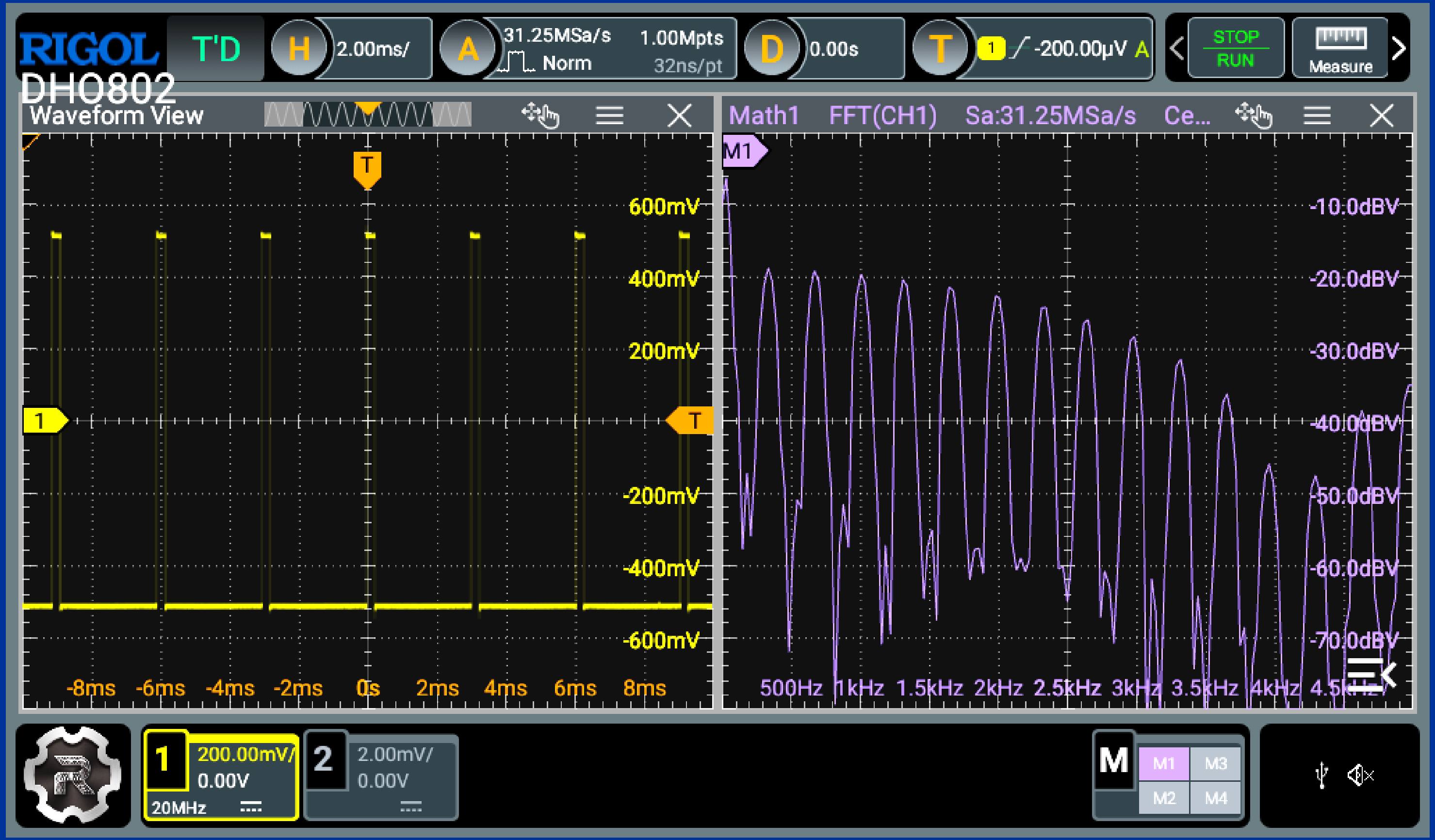




Spectrum of a Pulse Train

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





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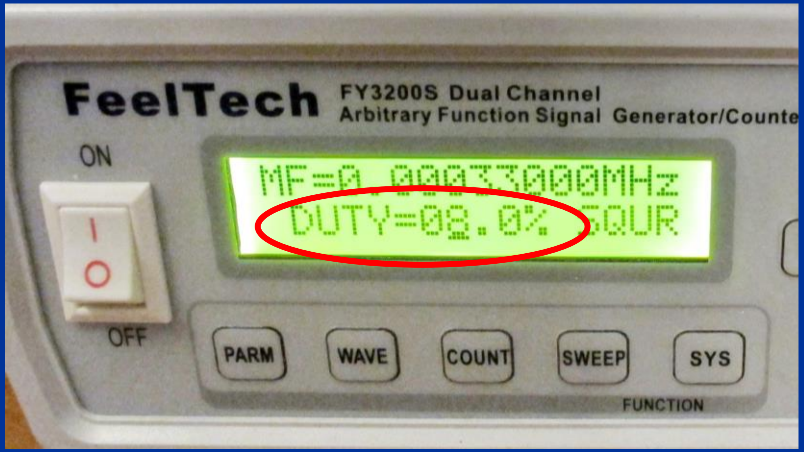
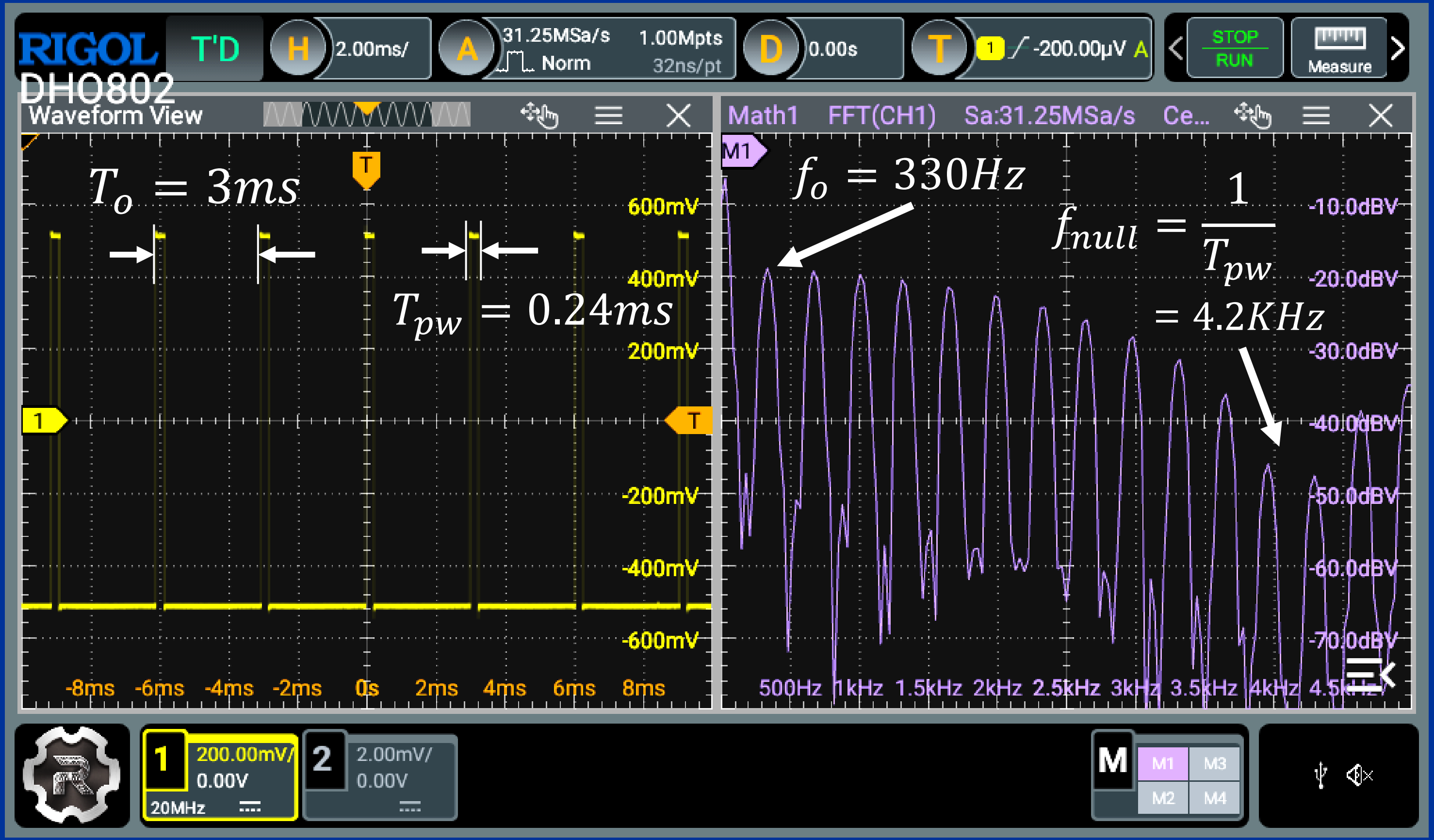
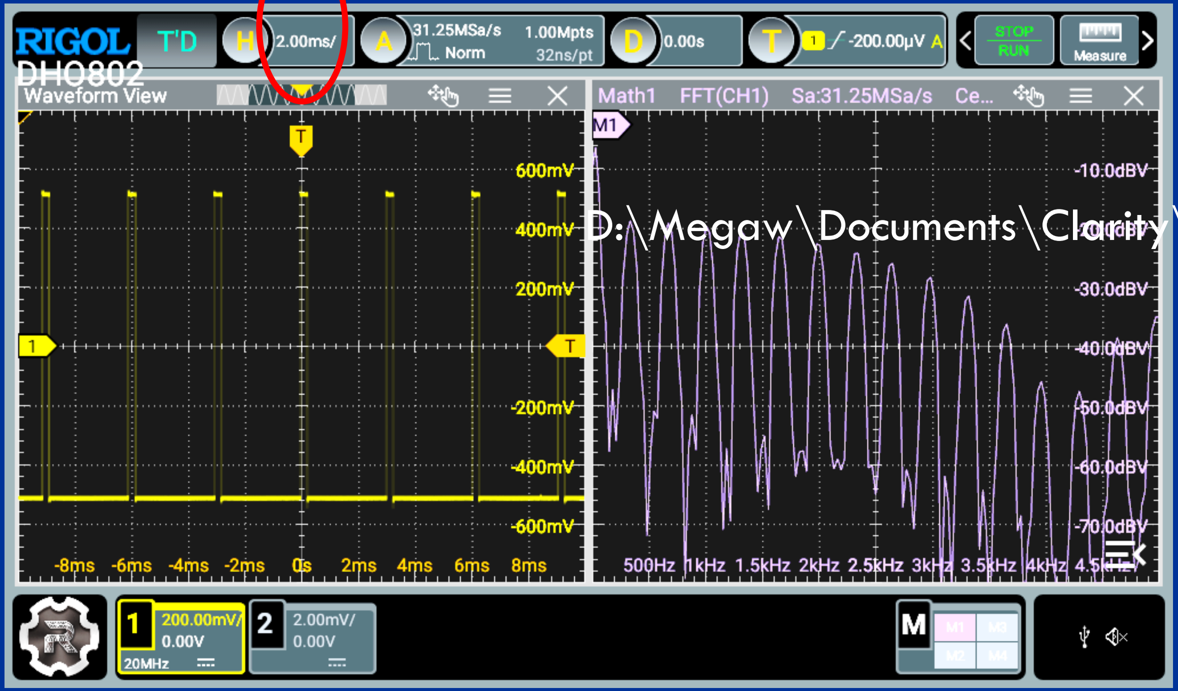


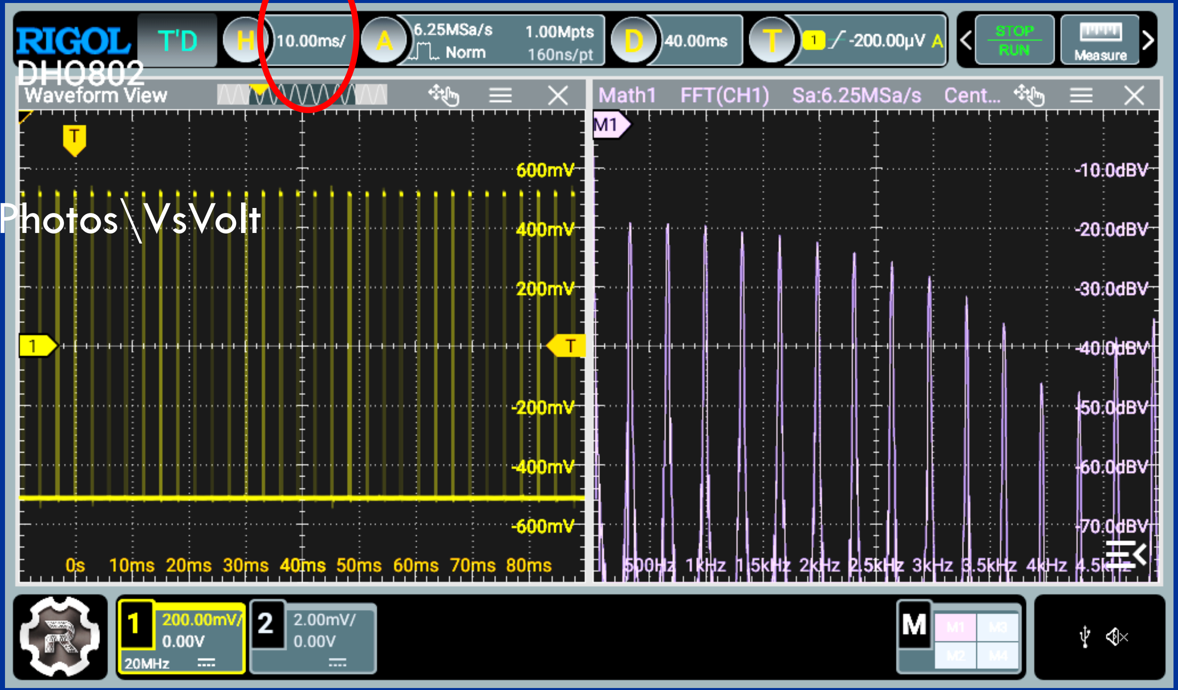


- Narrow pulses have lots of Harmonics !
- And use lots of bandwidth ...

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

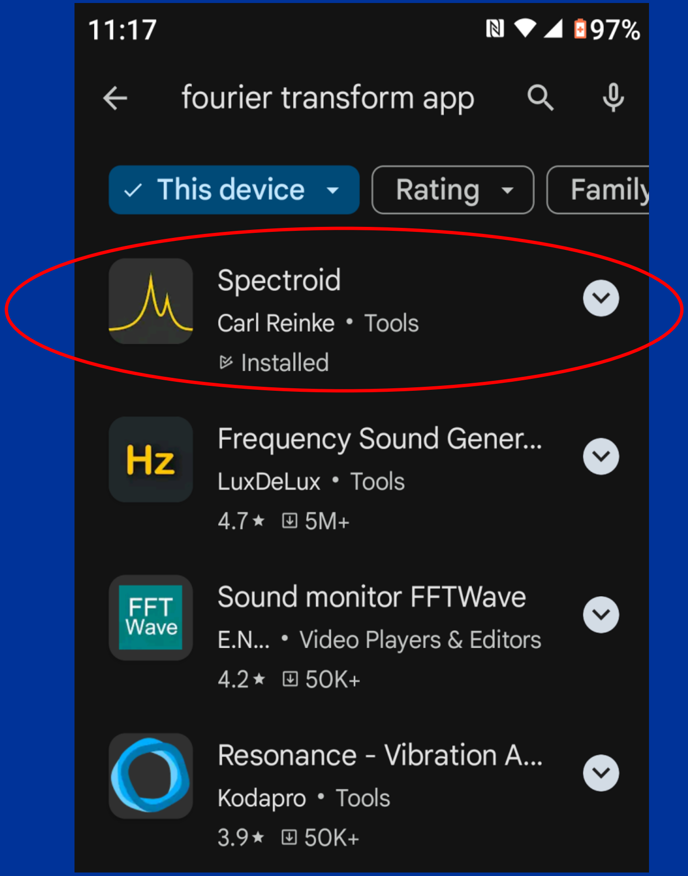


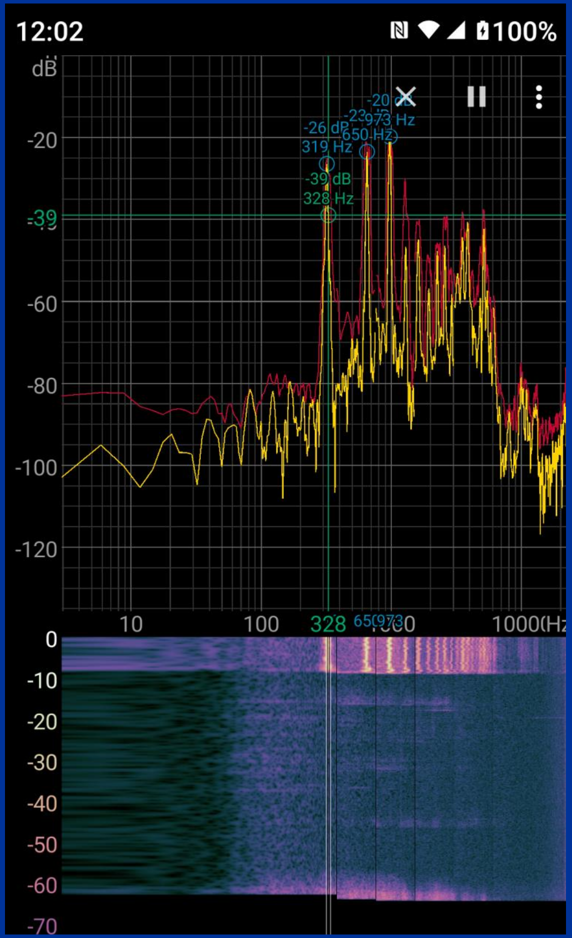
D:\Megaw\Documents\Clarity\Photos\VsVolt



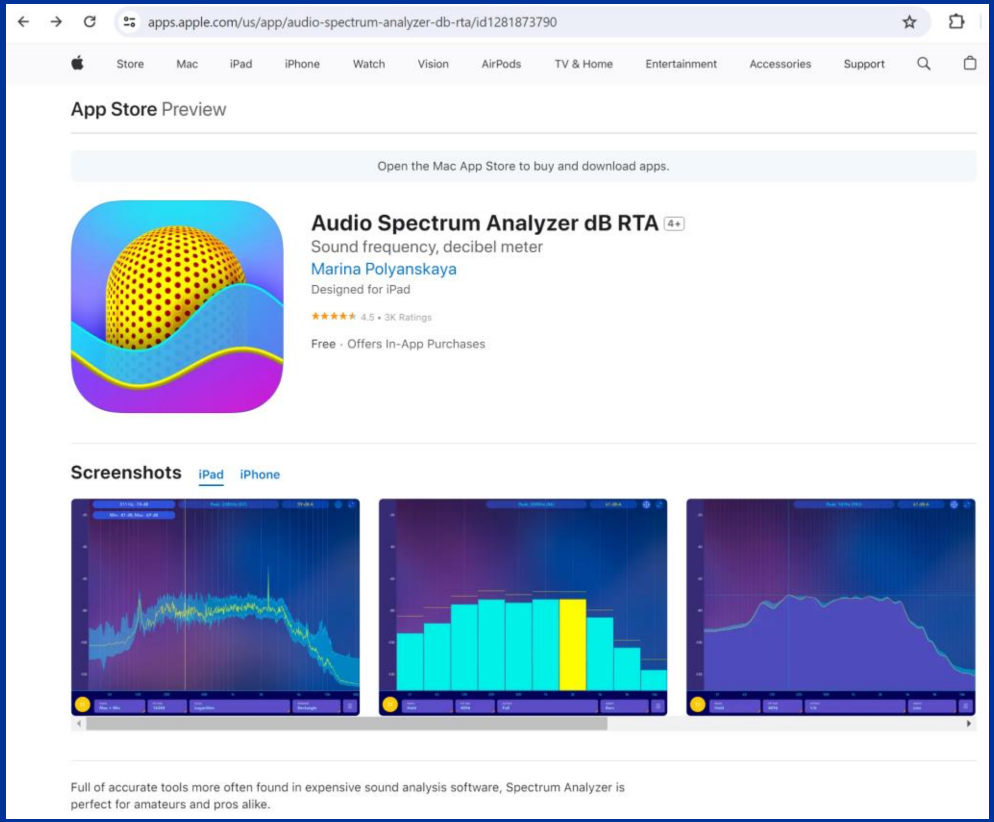
Some FFT Cell Phone Apps ☺

Android



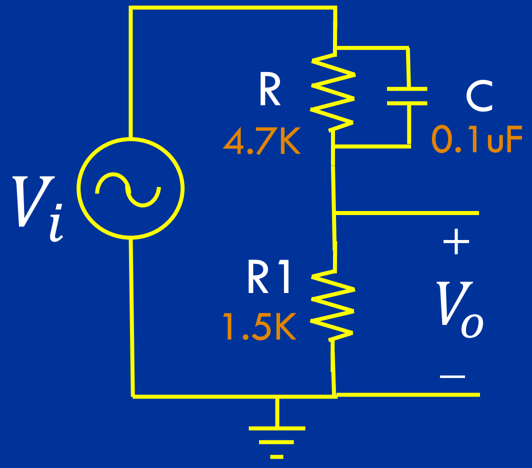


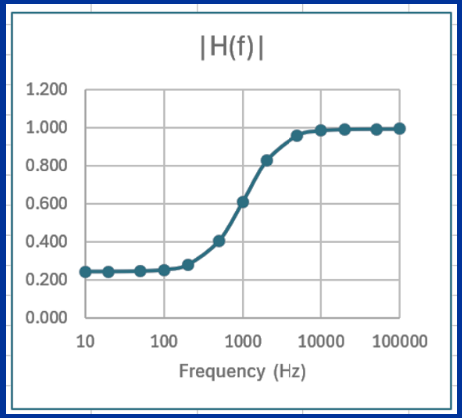
Apple



Topics in ECE #8A

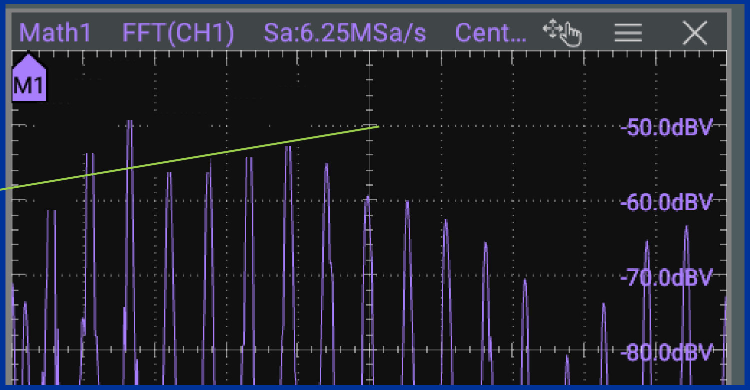
Fourier and FFT Concepts in Circuit Design (Part 2)





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

Spectrums



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

Today's Topics

Part 1

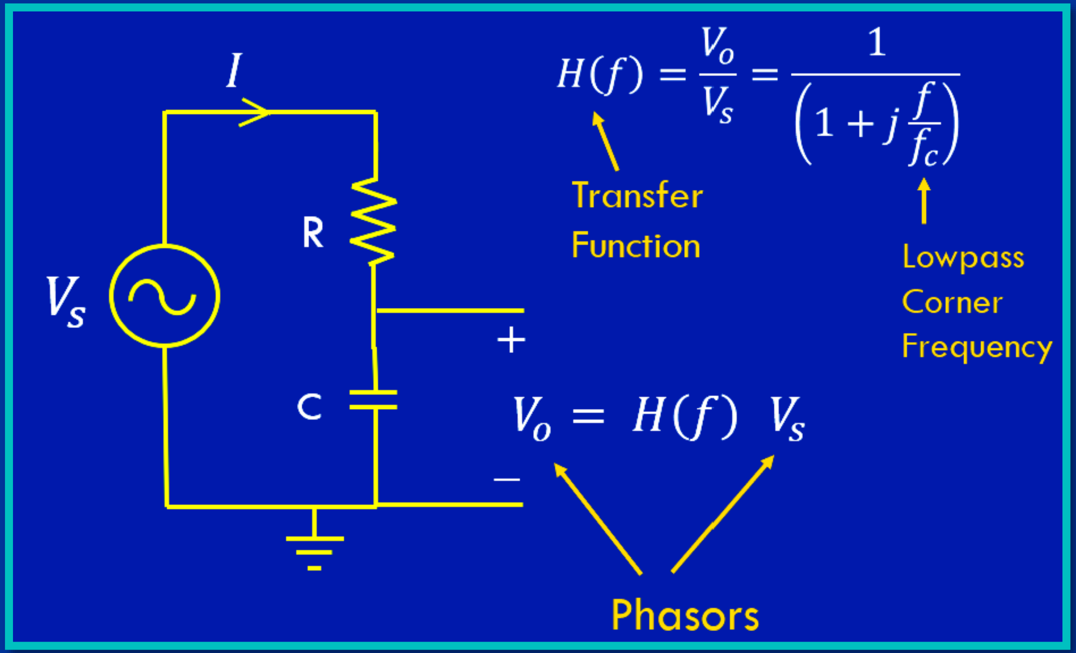
- Time and Frequency domains

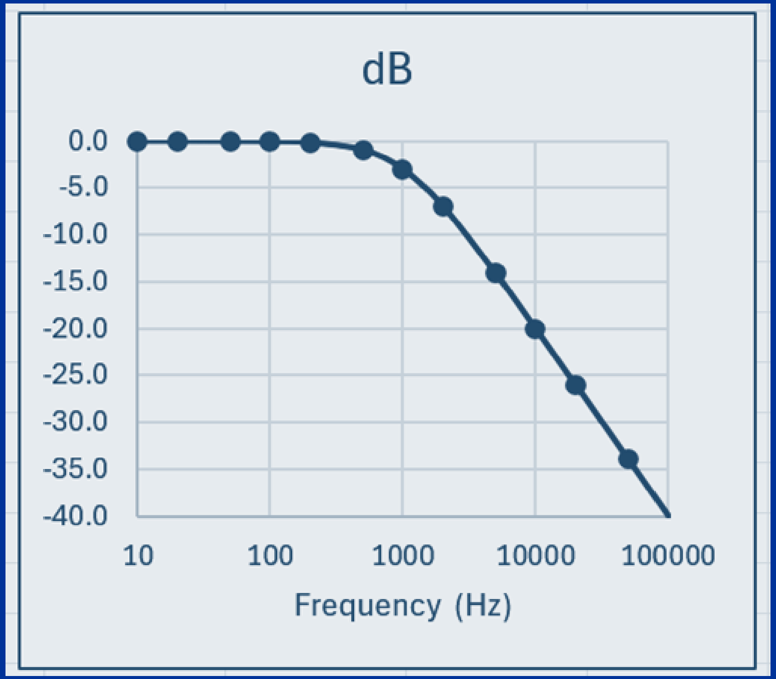
- Fourier – the Bridge between domains

➡

- Circuits: from Phasor Analysis to Signal Processing (and Filtering)

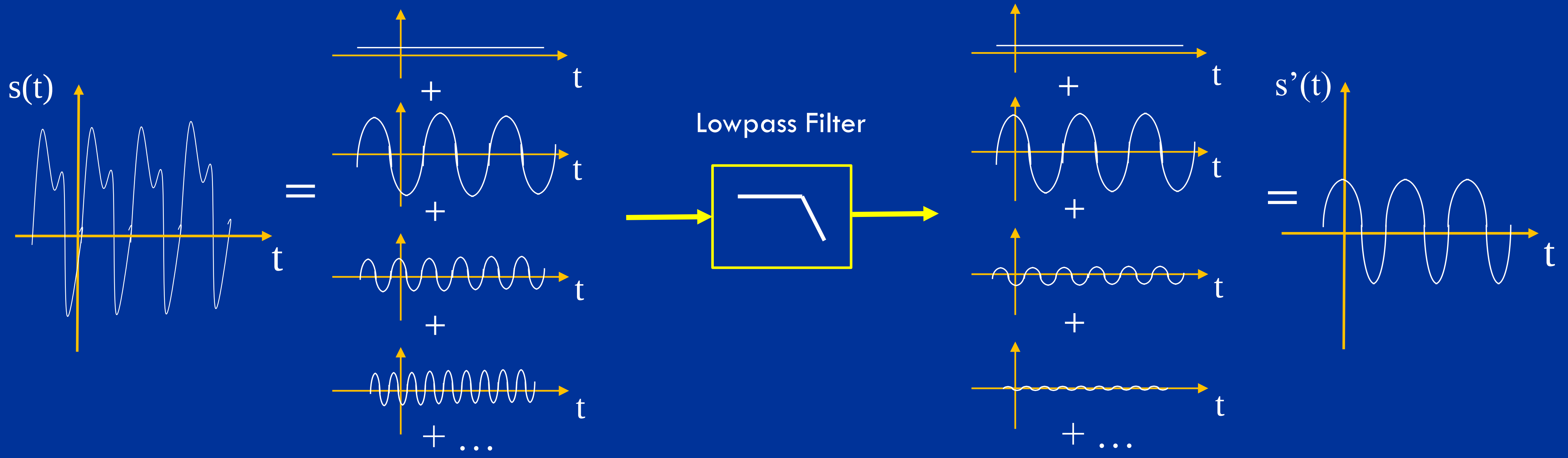
Lowpass Filter (One-pole)
(from Episodes 6 and 7)



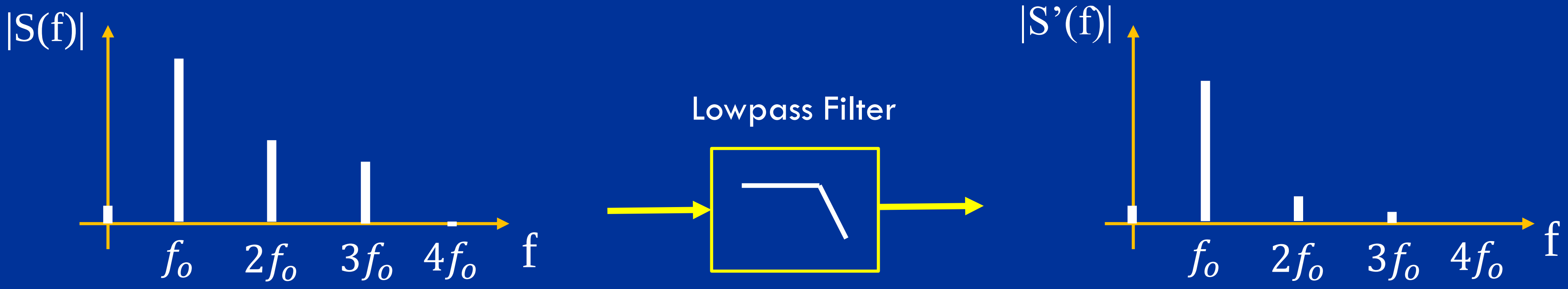


Applying Fourier in (Linear) Circuits and Systems

Time-domain View



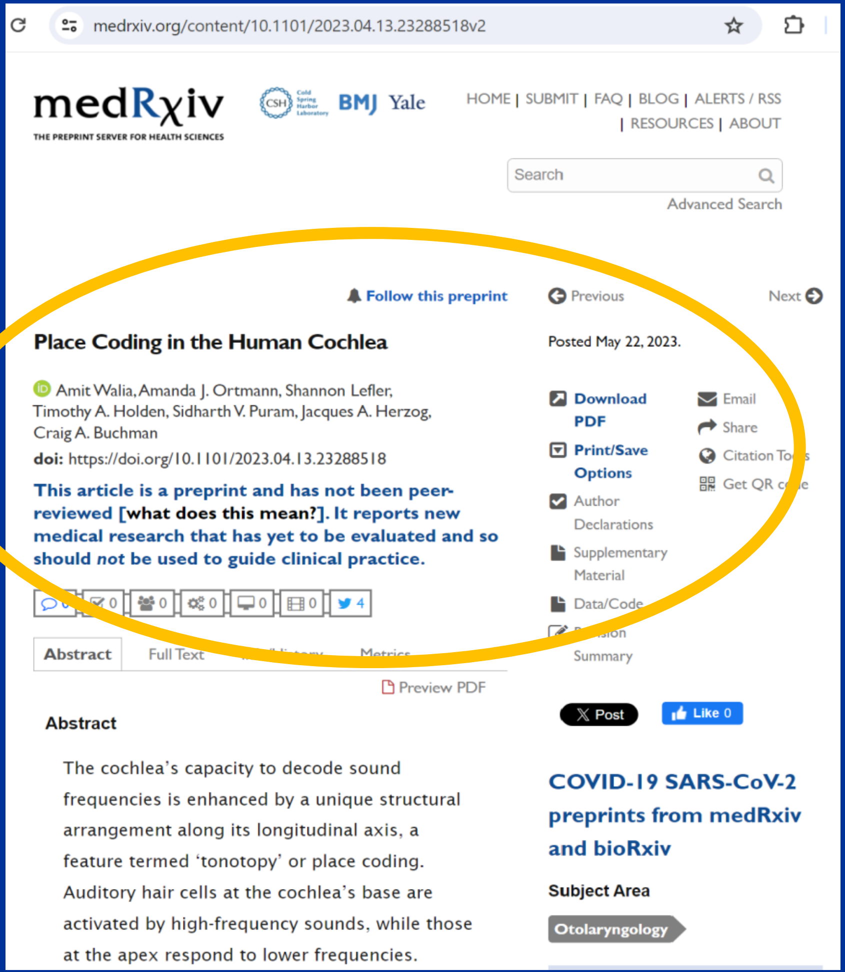
Frequency Domain View



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

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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.

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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.

X Post | Like 0

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

Subject Area

Otolaryngology

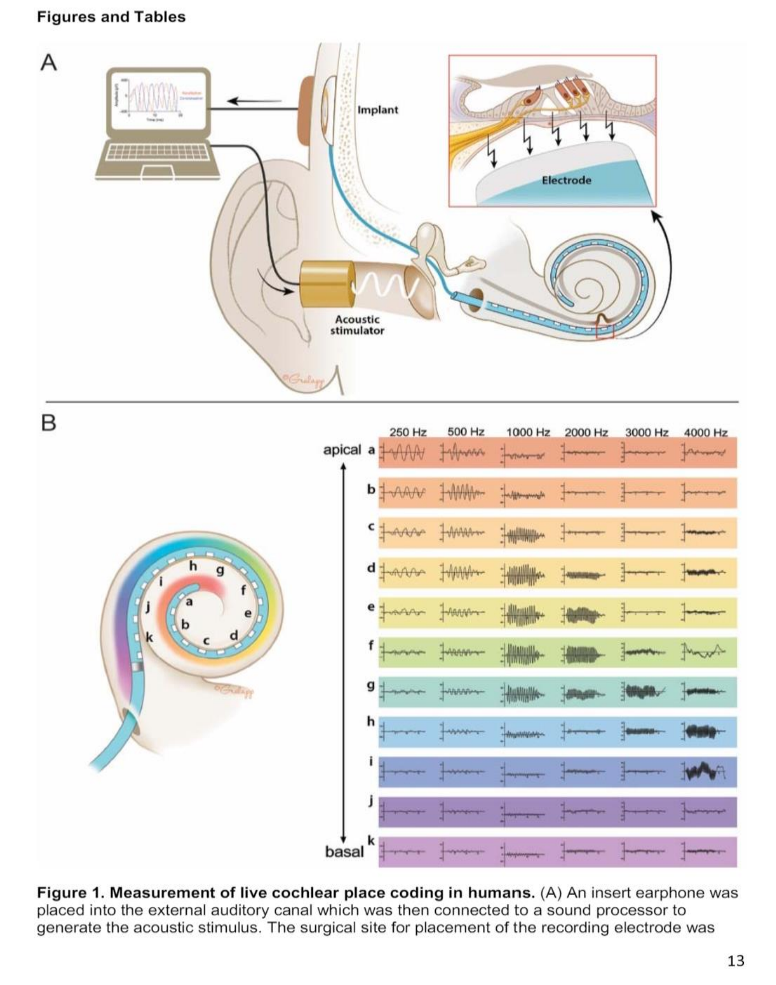

Figure 1. Measurement of live cochlear place coding in humans. (A) An insert earphone was placed into the external auditory canal which was then connected to a sound processor to generate the acoustic stimulus. The surgical site for placement of the recording electrode was

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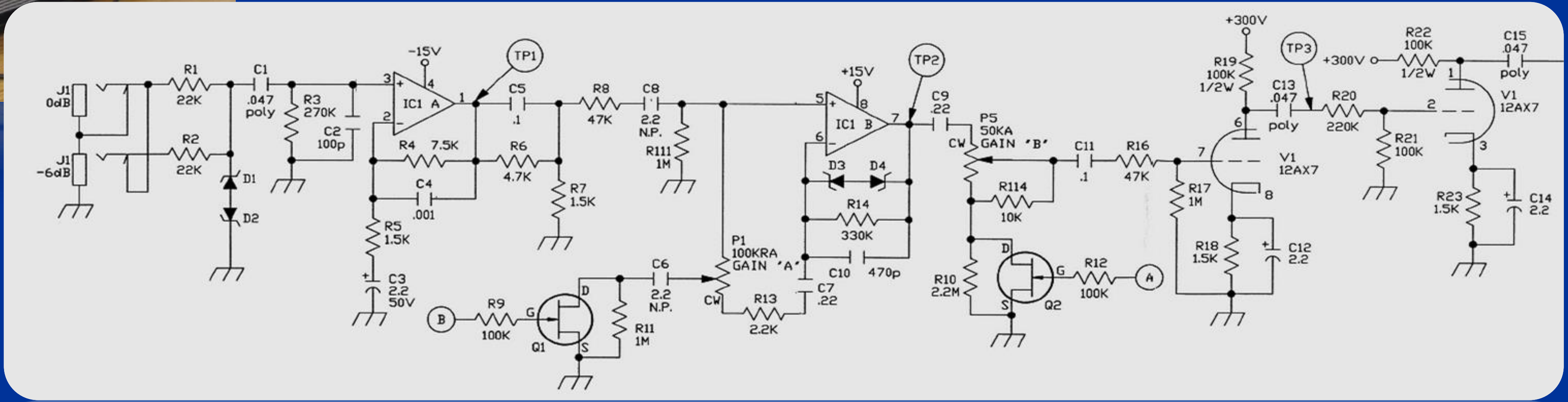
PREPRINT - Accessed 05 June 2024 at
https://www.medrxiv.org/content/10.1101/2023.04.13.23288518v2.full.pdf

Demo Video

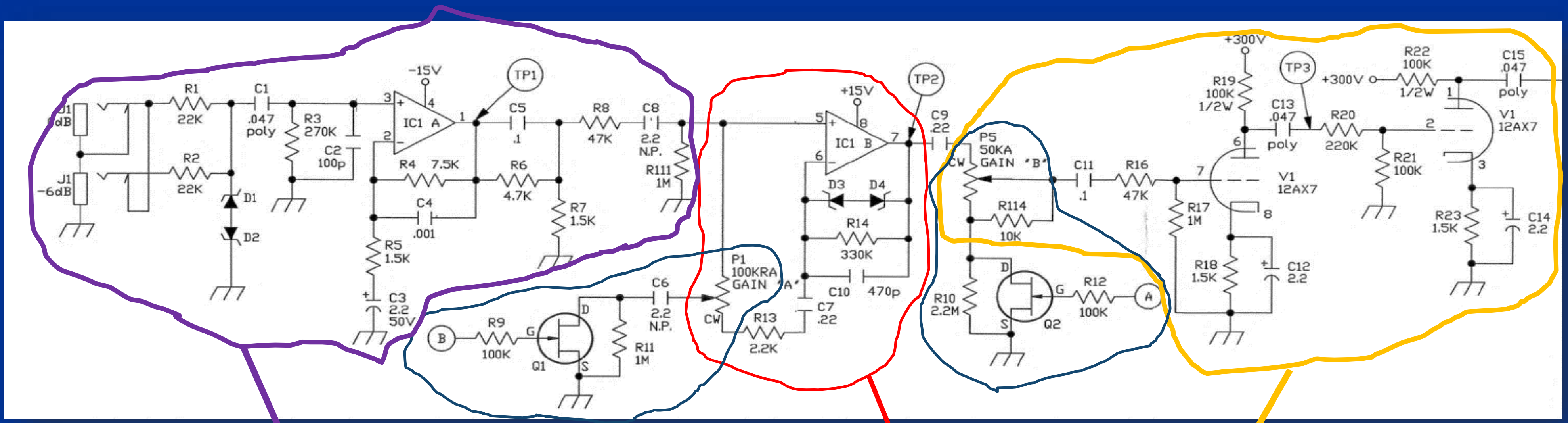
https://www.youtube.com/watch?v=VF78yEnNUhw

Real World Signals and Circuits
(from Episodes 3 and 4)

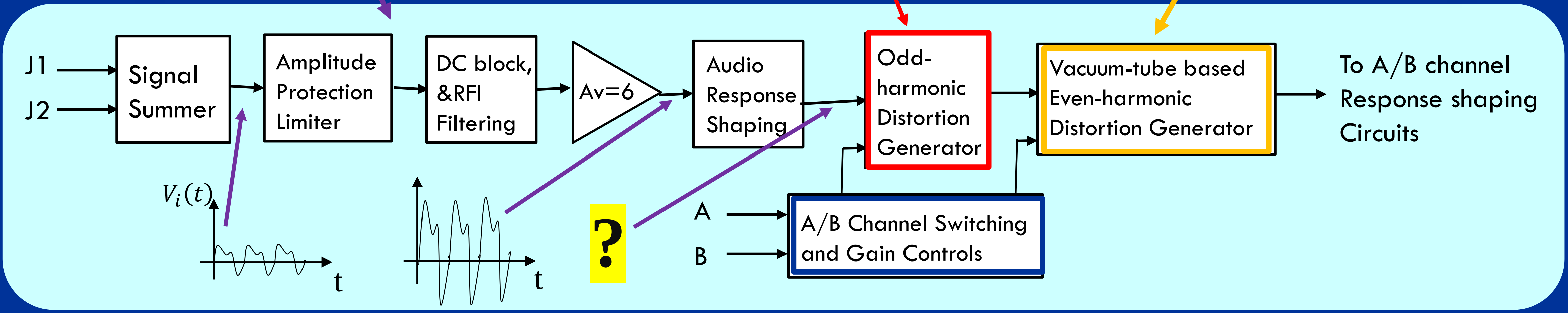
http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf



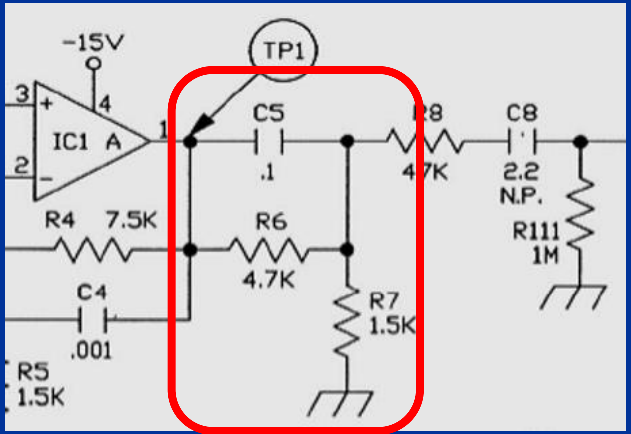
Parsing Schematic into Block Diagram



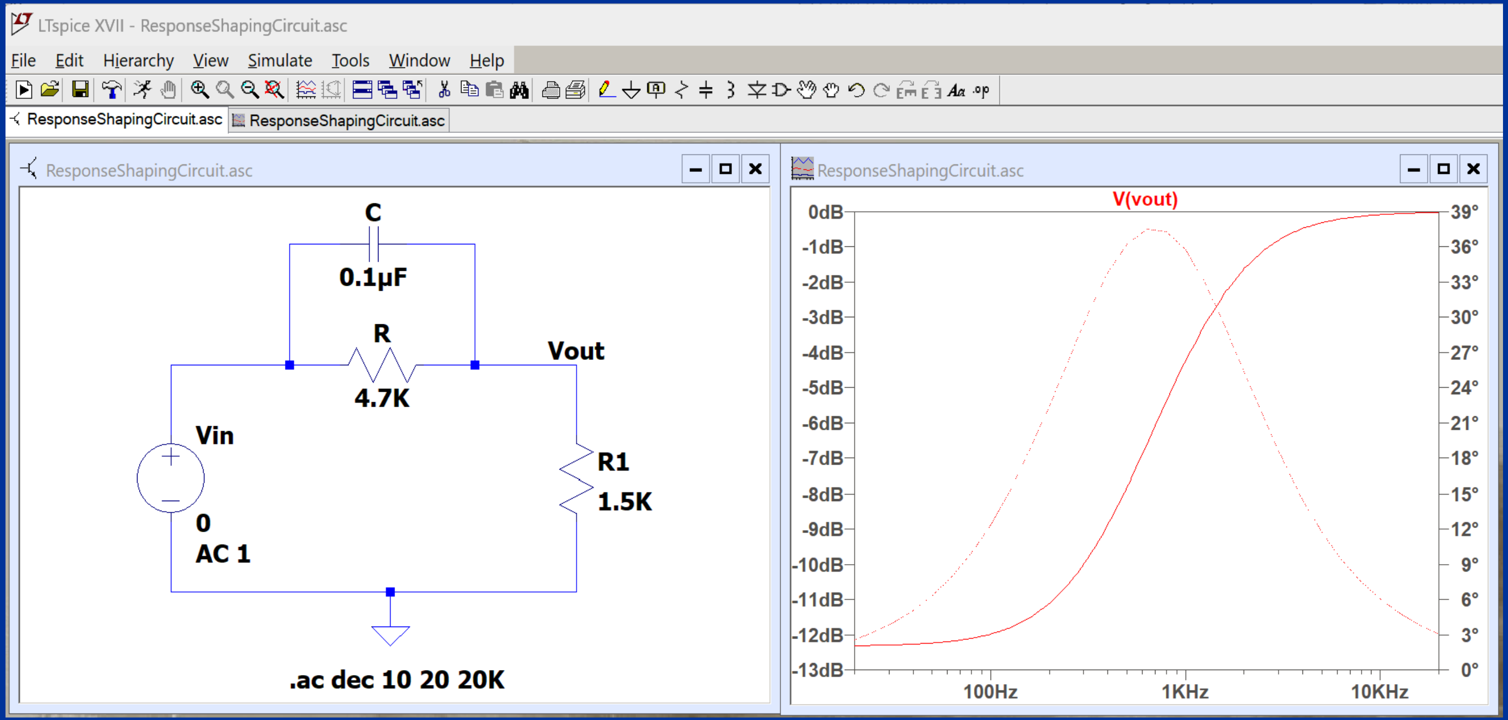
http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf



Circuit Simulation



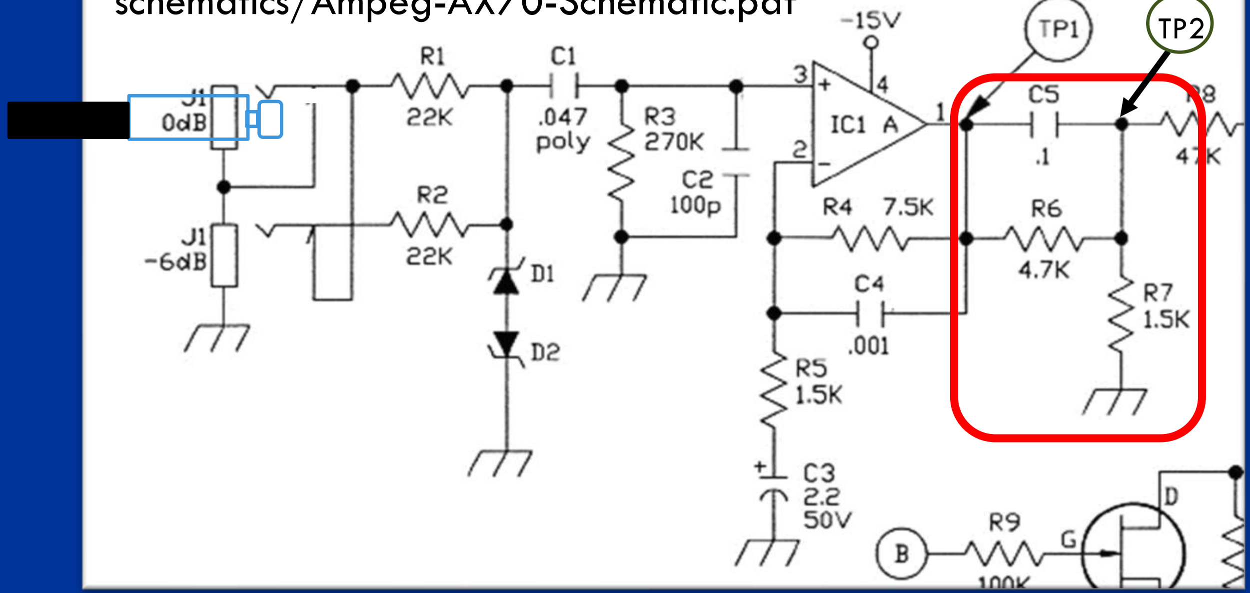
http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf



Circuit Analysis/Understanding

(from Episode 4)

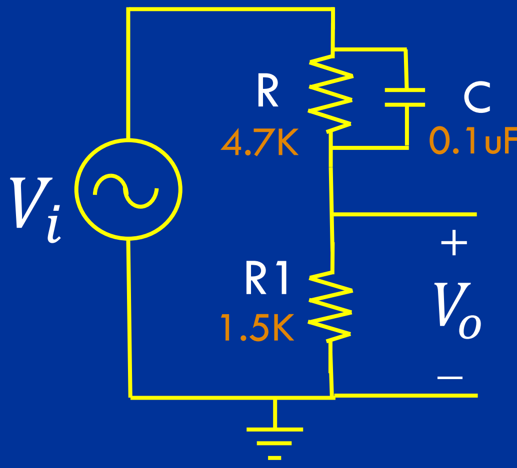
http://www.guitarnucleus.net/resources/schematics/Ampeg-AX70-Schematic.pdf

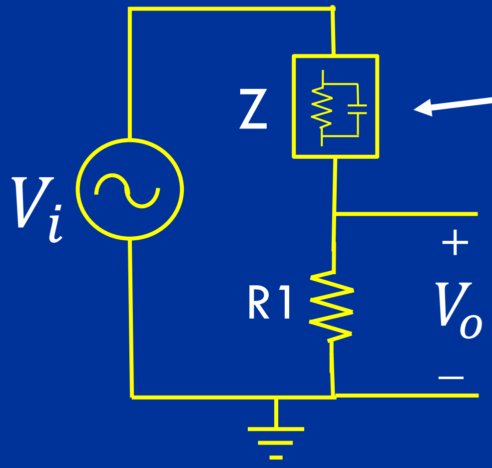


- R6, C5, R7 create a **<u>frequency-dependent voltage divider</u>**
- At low-frequency (<< 340 Hz), X_{C5} >> R6, so division is approx R7/(R7+R6) = 0.24
- At high-frequency (>> 1.4 kHz), X_{C5} << R7, so not much voltage division. C5 just couples signal to next stage
- Response is 12 dB ***bass-cut,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

Need complex math and voltage divider equation for full solution …

Circuit Design





First:

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

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 …

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

$$\boldsymbol{where \quad s = j\omega = j2\pi f}$$

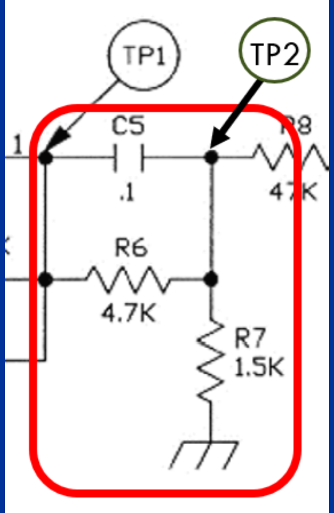
Checking:

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

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

Putting Transfer Function into Standard Form

V_i V_o



$$\frac{V_o}{V_i} = \frac{R_1}{R_1 + \left(\frac{R}{1+sCR}\right)} = \frac{R_1(1+sCR)}{R_1(1+sCR)+R} = \frac{R_1(1+sCR)}{R_1+R+sCRR_1\frac{R_1+R}{R_1+R}} = \left(\frac{R_1}{R_1+R}\right)\frac{1+sCR}{1+sC\frac{R_1R}{R_1+R}}$$

$$= \left(\frac{R_1}{R_1+R}\right)\frac{1+s/\omega_z}{1+s/\omega_p}$$

Where:

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

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

Or, in terms of f:

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

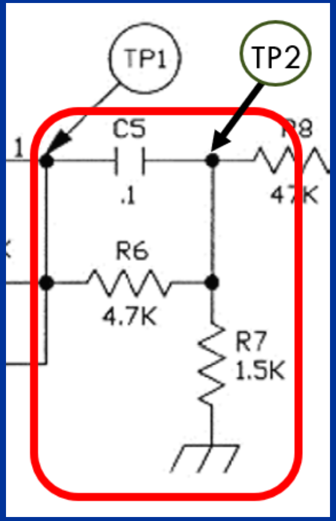
$$f_p = \frac{1}{2\pi(R||R_1)C} = 1.4\ kHz$$

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

$|H(f)|$ Evaluation with Excel

(Following Examples in Episodes 6, 7)

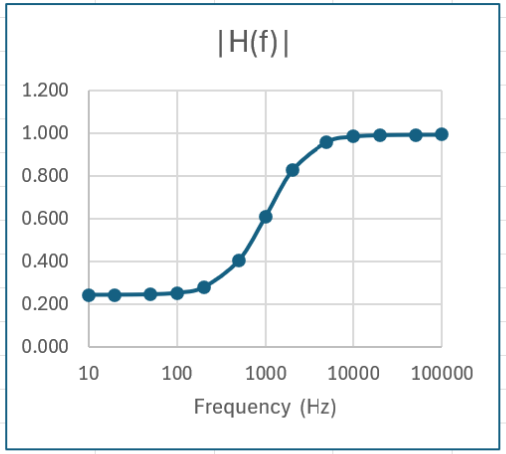
$V_i(f)$ $V_o(f)$

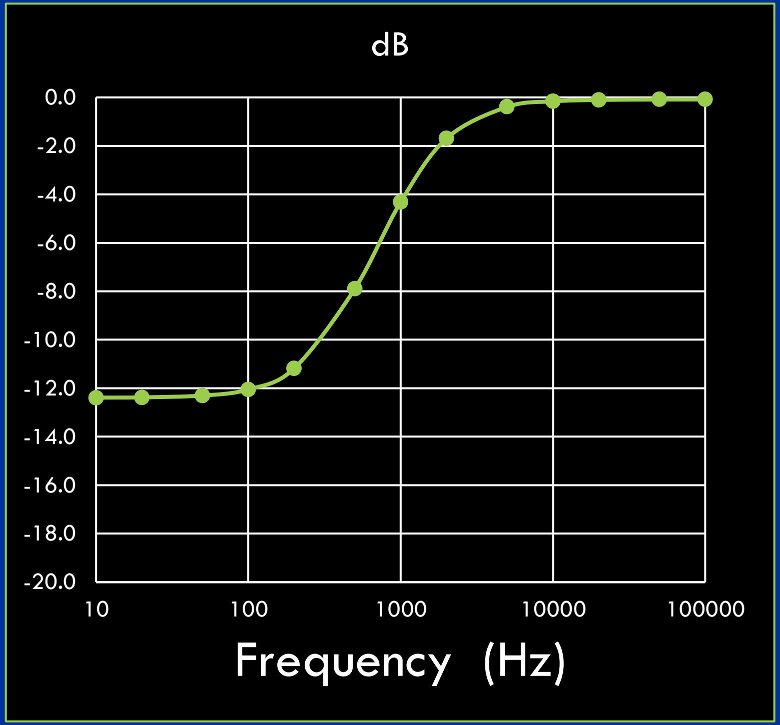


$$H(f) = \frac{V_o(f)}{V_i(f)} = 0.242\,\frac{1 + j\dfrac{f}{339}}{1 + j\dfrac{f}{1400}}$$

B8 =0.24*SQRT((POWER((A8/339),2)+1))/SQRT((POWER((A8/1400),2)+1))

Frequency	|H(f)|	dB(|H(f)|)
10	0.240	-12.4
20	0.240	-12.4
50	0.242	-12.3
100	0.250	-12.1
200	0.276	-11.2
500	0.403	-7.9
1000	0.608	-4.3
2000	0.824	-1.7
5000	0.957	-0.4
10000	0.982	-0.2
20000	0.989	-0.1
50000	0.991	-0.1
100000	0.991	-0.1

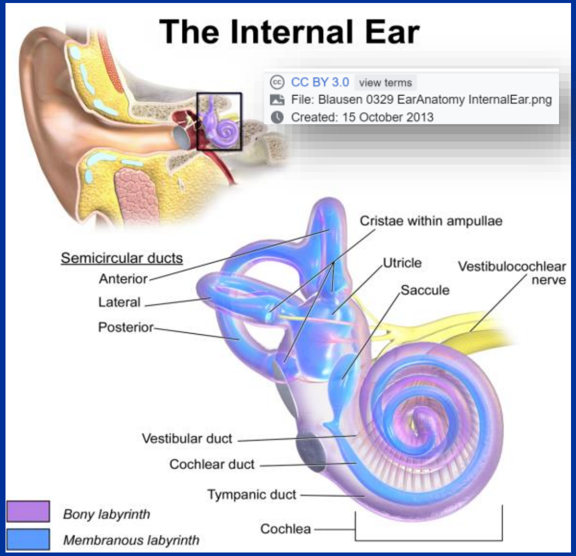




Amplitudes and dB in Audio

(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"*



https://en.wikipedia.org/wiki/Decibel

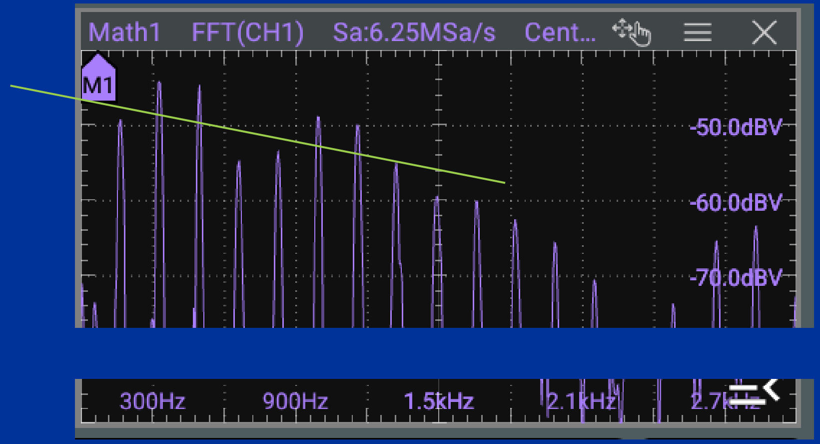
E on 4th String (330/2 Hz)

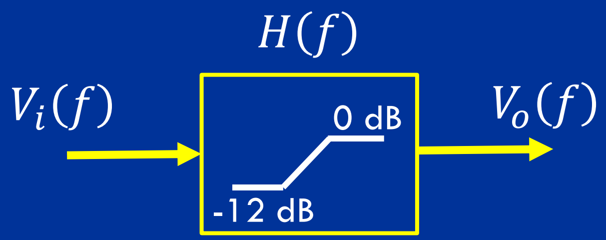
Effect of Response Shaping On Spectrum

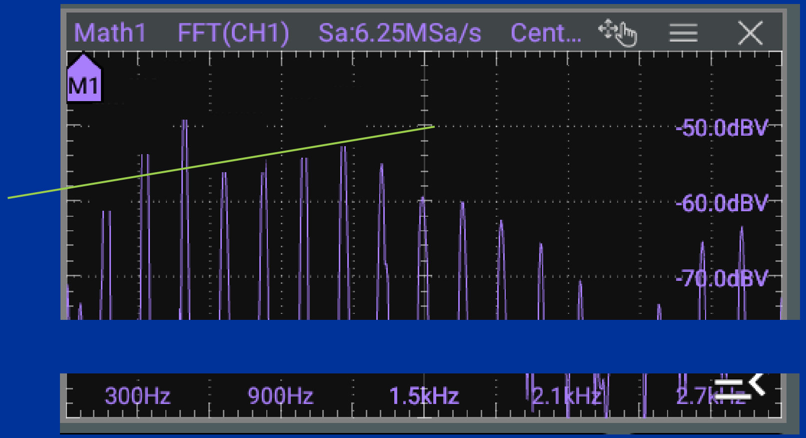
"Adding dB:" ☺

$$20log|V_o(f)| = 20log|H(f)\ V_i(f)|$$
$$= 20log|H(f)| + 20log|V_i(f)|$$

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







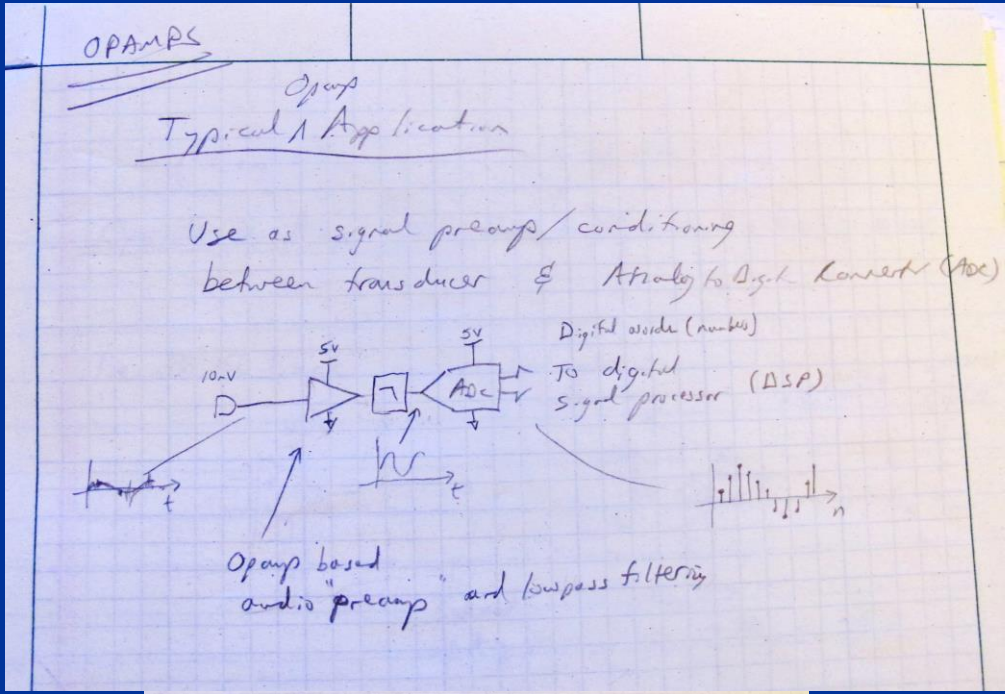
$$V_o(f) = H(f)V_i(f)$$

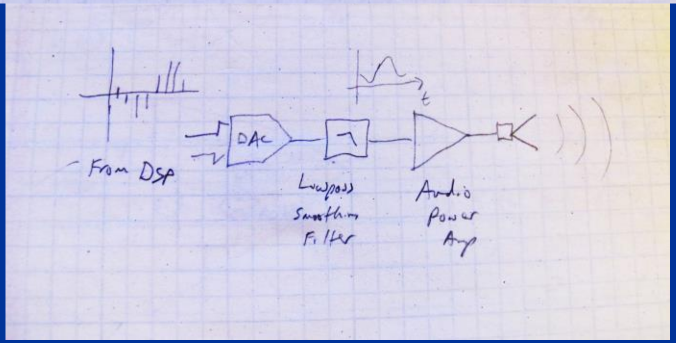
Spectrums

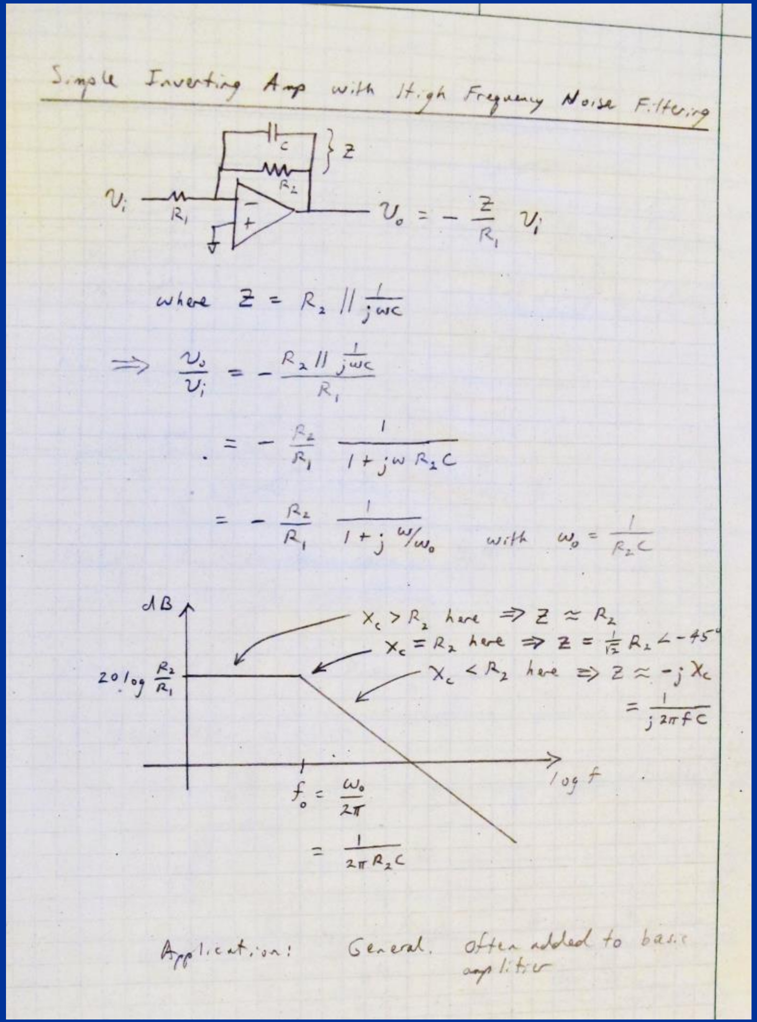
Possible Future Videos?

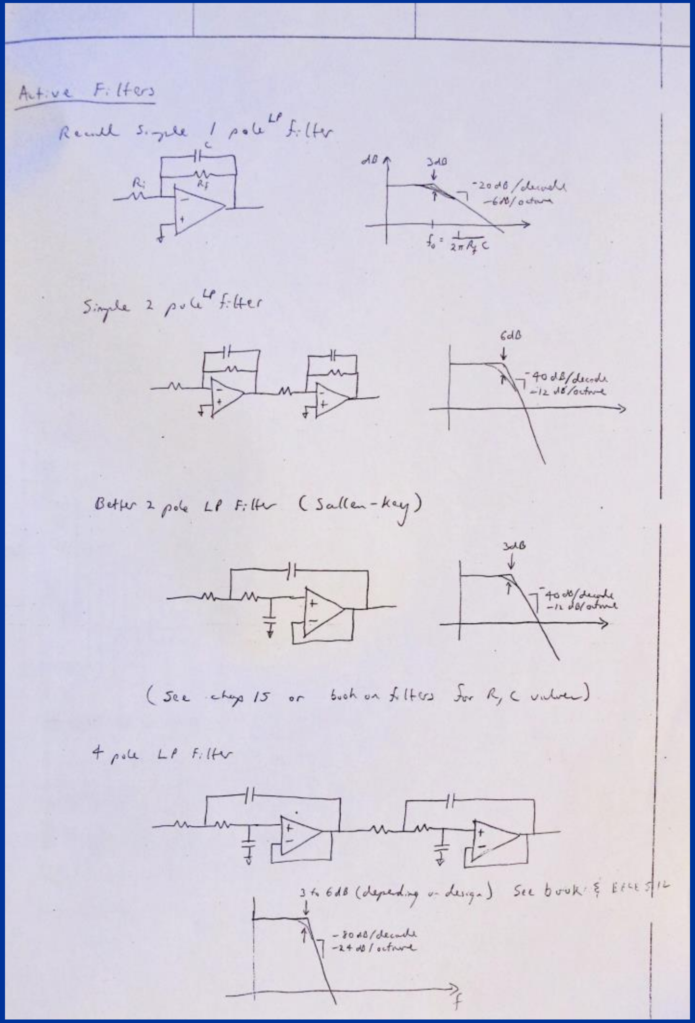
- Analog and Digital Filter Design
- Fourier Transform pairs and properties, including radio modulation
- Using the FFT in practice
- Speech production, recognition, and data compression
- Applications beyond circuits and systems …

Filter Design Preview



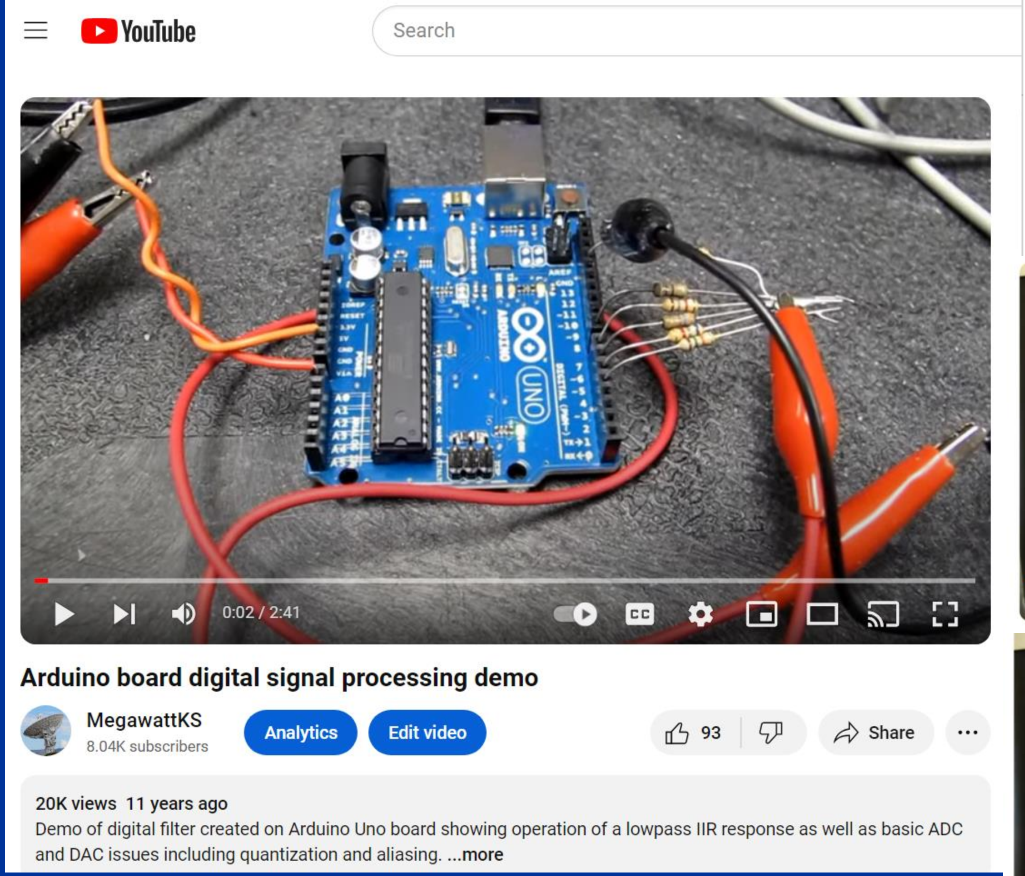




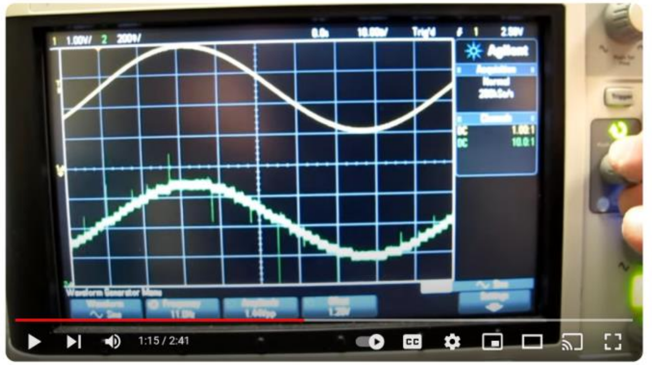


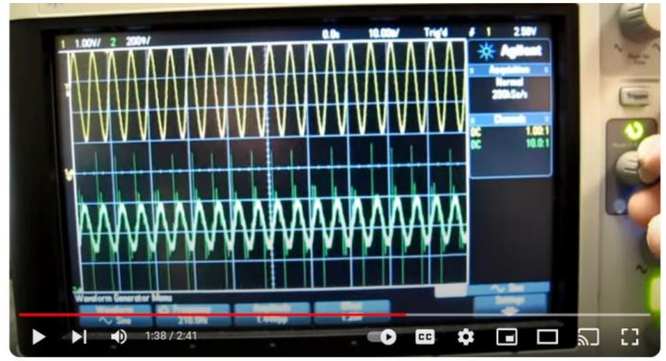
Simple DSP Demo on Arduino

One-pole IIR Digital Filter




```
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 ouptut pin, scaled back to 0 to 255
```





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

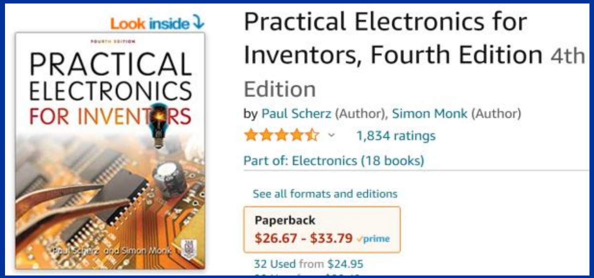
Ways to Learn More

Videos and Websites

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

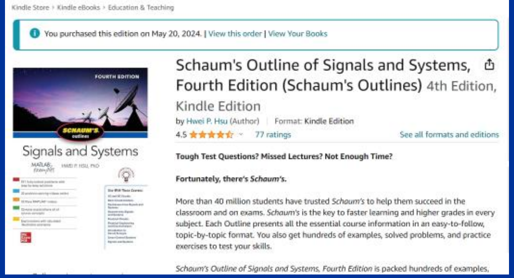
Books

Circuits/filters for broad audience



https://www.amazon.com/Practical-Electronics-Inventors-Fourth-Scherz-dp-1259587541/dp/1259587541/

College-level review



https://www.amazon.com/gp/product/B07QP9N7XD/

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 !