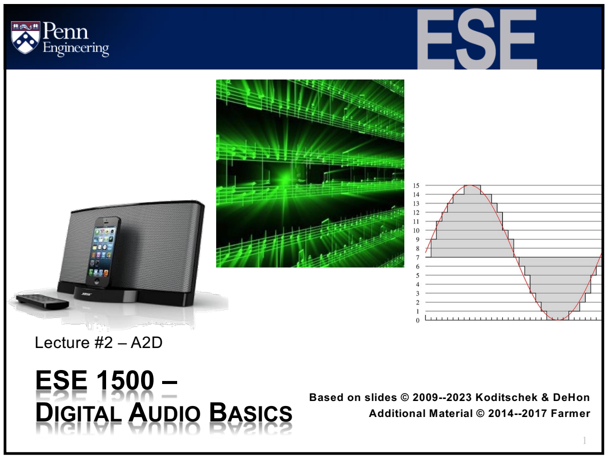

Penn Engineering

ESE

Lecture #2 – A2D

ESE 1500 – Digital Audio Basics

Based on slides © 2009--2023 Koditschek & DeHon
Additional Material © 2014--2017 Farmer

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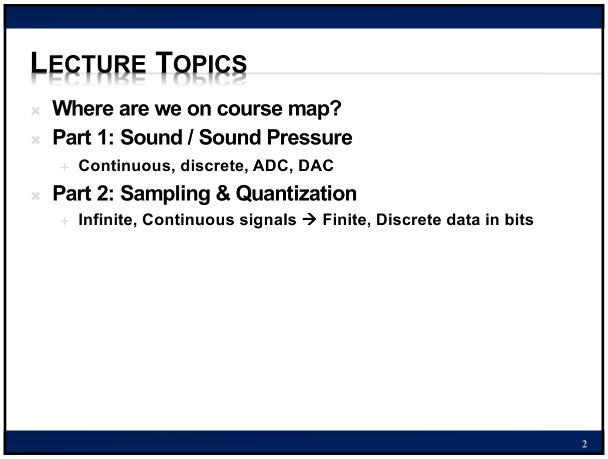
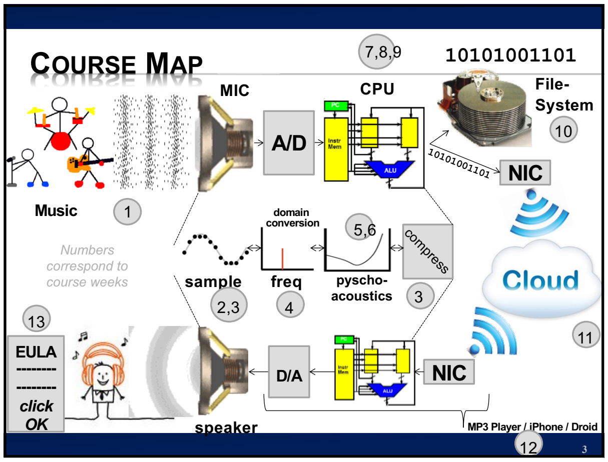


Lecture Topics

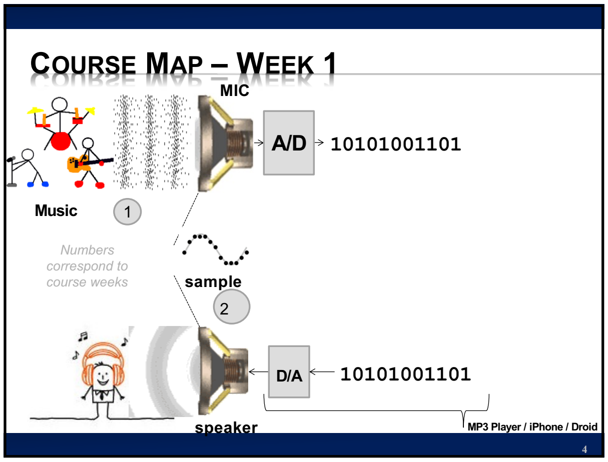
- Where are we on course map?
- Part 1: Sound / Sound Pressure
  - Continuous, discrete, ADC, DAC
- Part 2: Sampling & Quantization
  - Infinite, Continuous signals → Finite, Discrete data in bits

2



Course Map

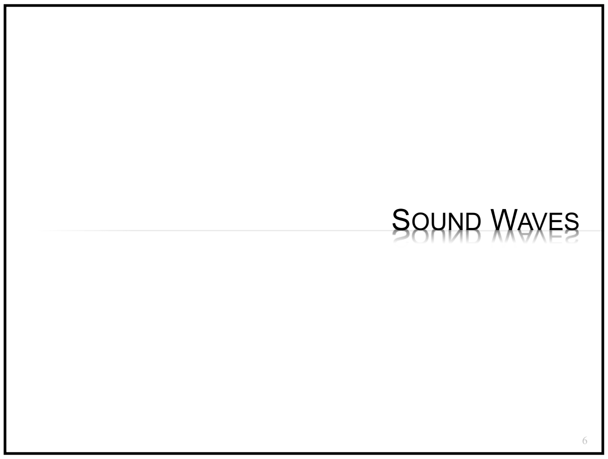
3



Course Map – Week 1

MIC
A/D
10101001101
Music
1
Numbers correspond to course weeks
sample
2
D/A
10101001101
speaker
MP3 Player / iPhone / Droid

4



Sound Waves

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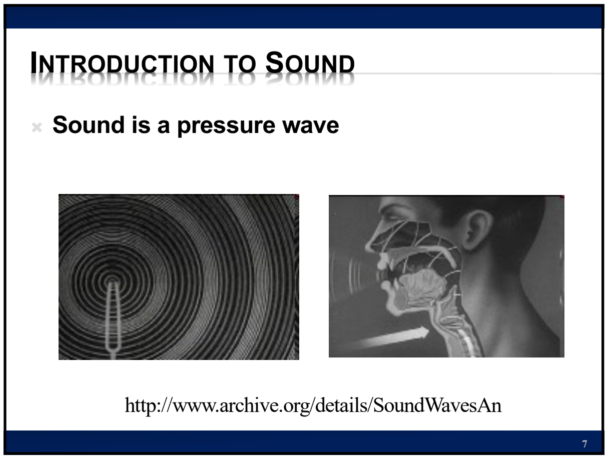
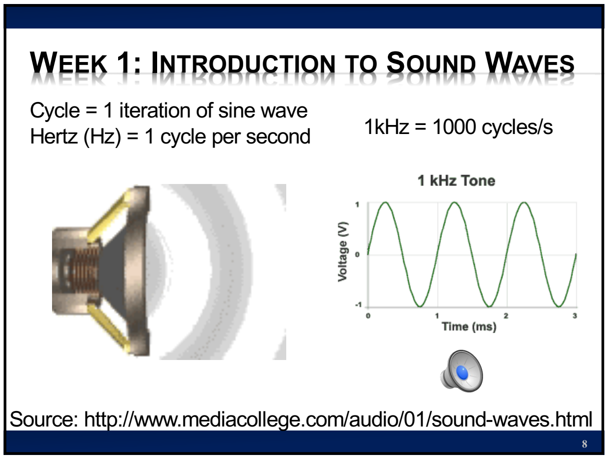


Introduction to Sound

- Sound is a pressure wave

http://www.archive.org/details/SoundWavesAn

7



Week 1: Introduction to Sound Waves

Cycle = 1 iteration of sine wave
Hertz (Hz) = 1 cycle per second

1kHz = 1000 cycles/s

1 kHz Tone
Voltage (V)
1
0
-1
0
1
2
3
Time (ms)

Source: http://www.mediacollege.com/audio/01/sound-waves.html

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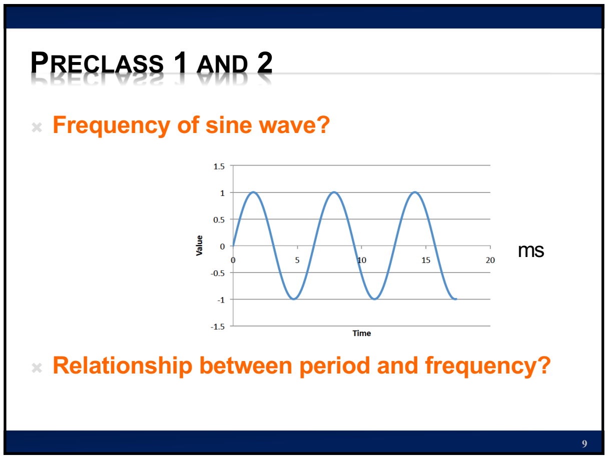

Preclass 1 and 2

- **Frequency of sine wave?**

1.5
1
0.5
0
-0.5
-1
-1.5
Value
0
5
10
15
20
Time
ms

- **Relationship between period and frequency?**

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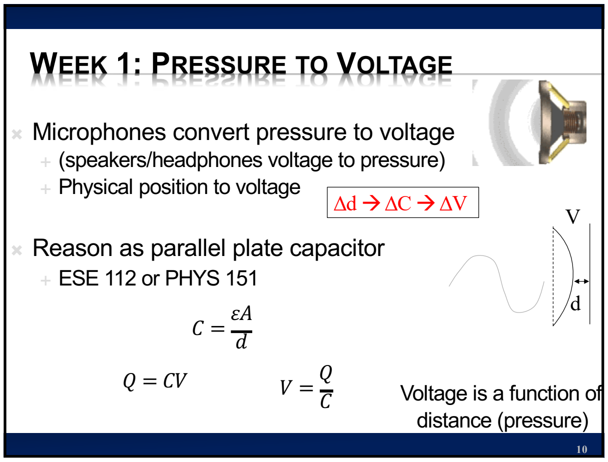

Week 1: Pressure to Voltage

- Microphones convert pressure to voltage
  - (speakers/headphones voltage to pressure)
  - Physical position to voltage

$\Delta d \rightarrow \Delta C \rightarrow \Delta V$

- Reason as parallel plate capacitor
  - ESE 112 or PHYS 151

$$C = \frac{\varepsilon A}{d}$$

$$Q = CV \qquad V = \frac{Q}{C}$$

Voltage is a function of distance (pressure)

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Signals

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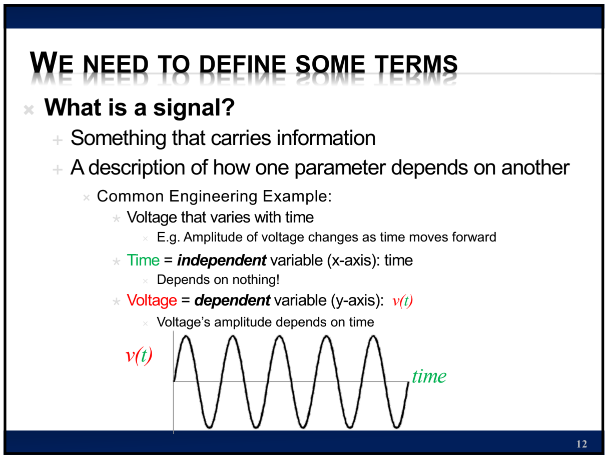

We need to define some terms

- **What is a signal?**
  - Something that carries information
  - A description of how one parameter depends on another
    - Common Engineering Example:
      - Voltage that varies with time
        - E.g. Amplitude of voltage changes as time moves forward
      - Time = ***independent*** variable (x-axis): time
        - Depends on nothing!
      - Voltage = ***dependent*** variable (y-axis): $v(t)$
        - Voltage's amplitude depends on time

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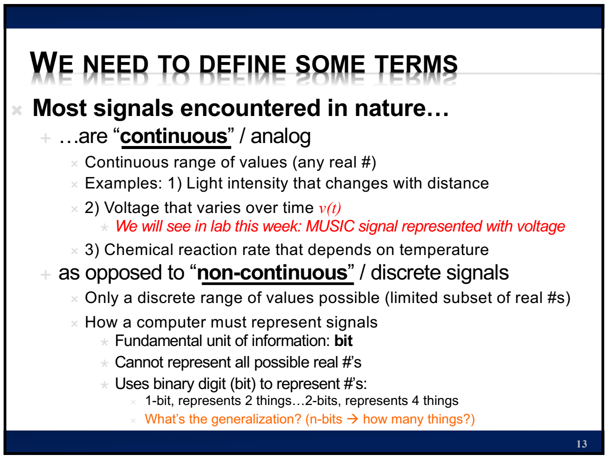

We need to define some terms

- **Most signals encountered in nature…**
  - …are "**continuous**" / analog
    - Continuous range of values (any real #)
    - Examples: 1) Light intensity that changes with distance
    - 2) Voltage that varies over time $v(t)$
      - *We will see in lab this week: MUSIC signal represented with voltage*
    - 3) Chemical reaction rate that depends on temperature
  - as opposed to "**non-continuous**" / discrete signals
    - Only a discrete range of values possible (limited subset of real #s)
    - How a computer must represent signals
      - Fundamental unit of information: **bit**
      - Cannot represent all possible real #'s
      - Uses binary digit (bit) to represent #'s:
        - 1-bit, represents 2 things…2-bits, represents 4 things
        - What's the generalization? (n-bits → how many things?)

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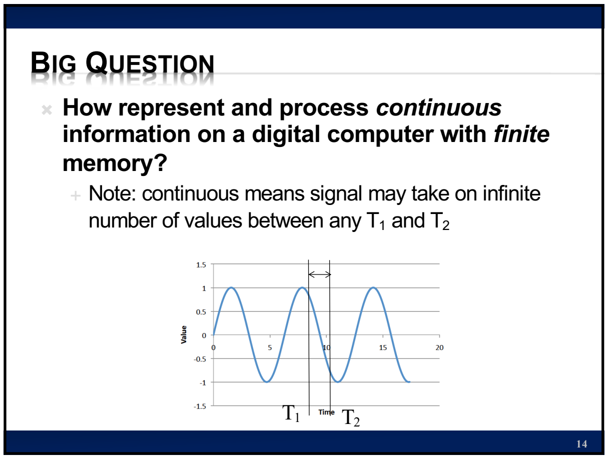

Big Question

- **How represent and process *continuous* information on a digital computer with *finite* memory?**
  - Note: continuous means signal may take on infinite number of values between any T_1 and T_2

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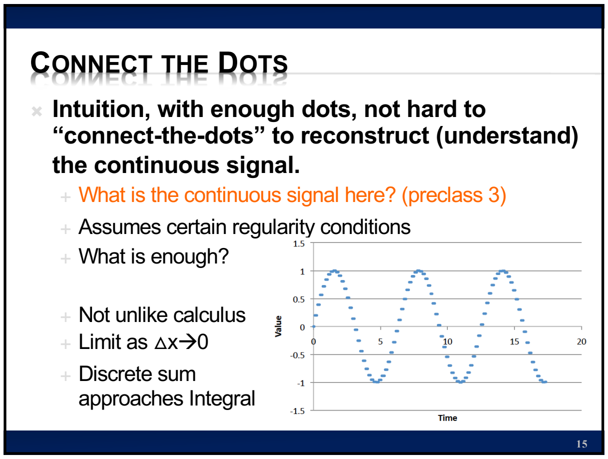

Connect the Dots

- **Intuition, with enough dots, not hard to "connect-the-dots" to reconstruct (understand) the continuous signal.**
  - What is the continuous signal here? (preclass 3)
  - Assumes certain regularity conditions
  - What is enough?
  - Not unlike calculus
  - Limit as ∆x→0
  - Discrete sum approaches Integral

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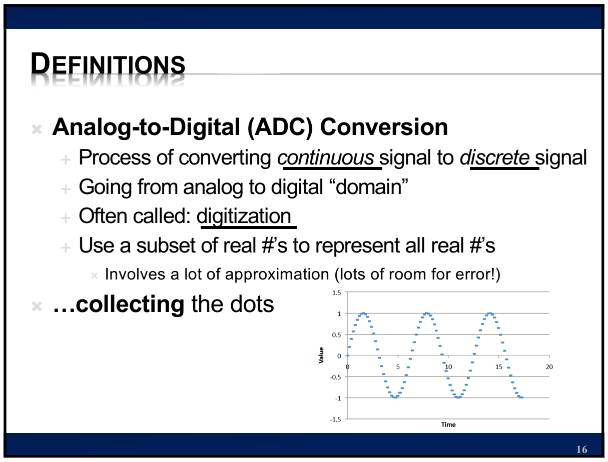

Definitions

- **Analog-to-Digital (ADC) Conversion**
  - Process of converting *continuous* signal to *discrete* signal
  - Going from analog to digital "domain"
  - Often called: digitization
  - Use a subset of real #'s to represent all real #'s
    - Involves a lot of approximation (lots of room for error!)
- **…collecting** the dots

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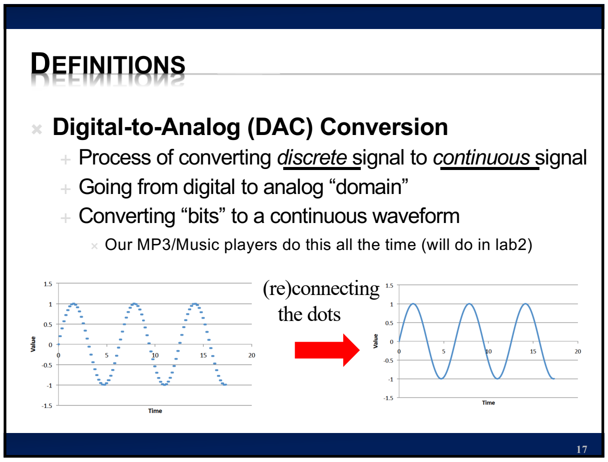

Definitions

- **Digital-to-Analog (DAC) Conversion**
  - Process of converting *discrete* signal to *continuous* signal
  - Going from digital to analog "domain"
  - Converting "bits" to a continuous waveform
    - Our MP3/Music players do this all the time (will do in lab2)

(re)connecting the dots

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Part 2

Sampling & Quantization

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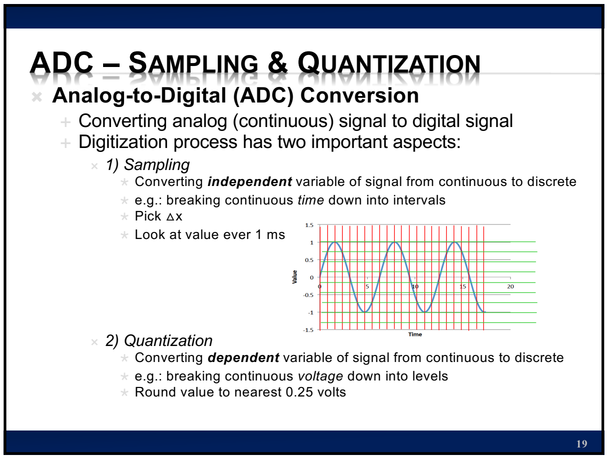

ADC – Sampling & Quantization

- **Analog-to-Digital (ADC) Conversion**
  - Converting analog (continuous) signal to digital signal
  - Digitization process has two important aspects:
    - *1) Sampling*
      - Converting ***independent*** variable of signal from continuous to discrete
      - e.g.: breaking continuous *time* down into intervals
      - Pick ∆x
      - Look at value ever 1 ms
    - *2) Quantization*
      - Converting ***dependent*** variable of signal from continuous to discrete
      - e.g.: breaking continuous *voltage* down into levels
      - Round value to nearest 0.25 volts

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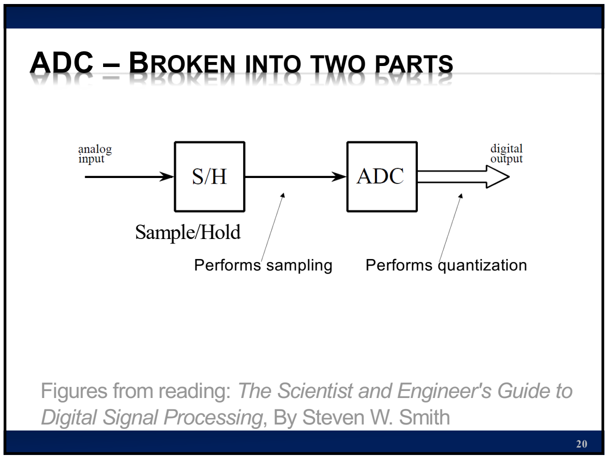

ADC – Broken into two parts

Performs sampling

Performs quantization

Figures from reading: *The Scientist and Engineer's Guide to Digital Signal Processing*, By Steven W. Smith

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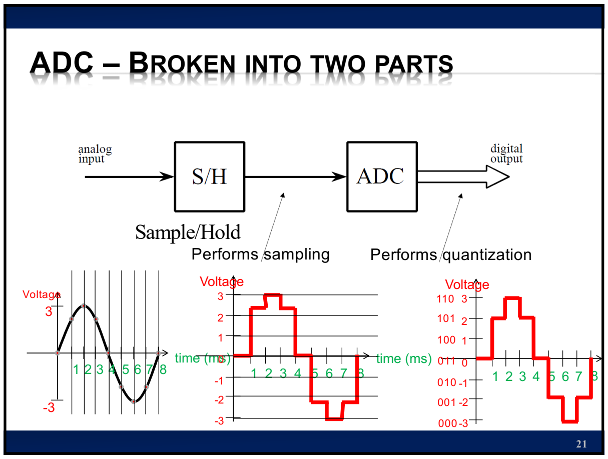
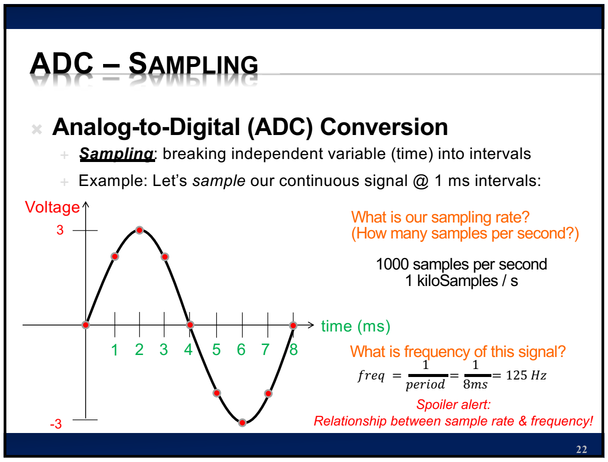


ADC – Broken into two parts

Performs sampling

Performs quantization

21



ADC – Sampling

- **Analog-to-Digital (ADC) Conversion**
  - ***Sampling***: breaking independent variable (time) into intervals
  - Example: Let's *sample* our continuous signal @ 1 ms intervals:

What is our sampling rate?
(How many samples per second?)

1000 samples per second
1 kiloSamples / s

What is frequency of this signal?

$$freq = \frac{1}{period} = \frac{1}{8ms} = 125\ Hz$$

Spoiler alert:
Relationship between sample rate & frequency!

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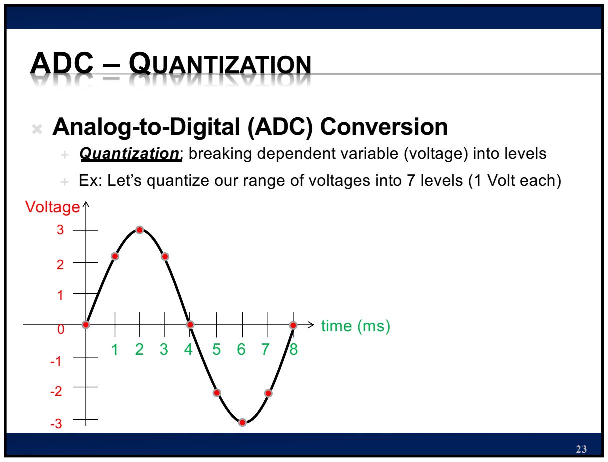

ADC – Quantization

- **Analog-to-Digital (ADC) Conversion**
  - ***Quantization***: breaking dependent variable (voltage) into levels
  - Ex: Let's quantize our range of voltages into 7 levels (1 Volt each)

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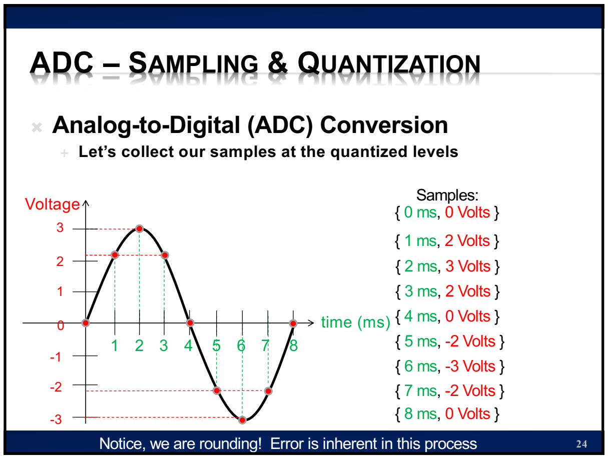

ADC – Sampling & Quantization

- **Analog-to-Digital (ADC) Conversion**
  - **Let's collect our samples at the quantized levels**

Samples:
{ 0 ms, 0 Volts }
{ 1 ms, 2 Volts }
{ 2 ms, 3 Volts }
{ 3 ms, 2 Volts }
{ 4 ms, 0 Volts }
{ 5 ms, -2 Volts }
{ 6 ms, -3 Volts }
{ 7 ms, -2 Volts }
{ 8 ms, 0 Volts }

Notice, we are rounding! Error is inherent in this process

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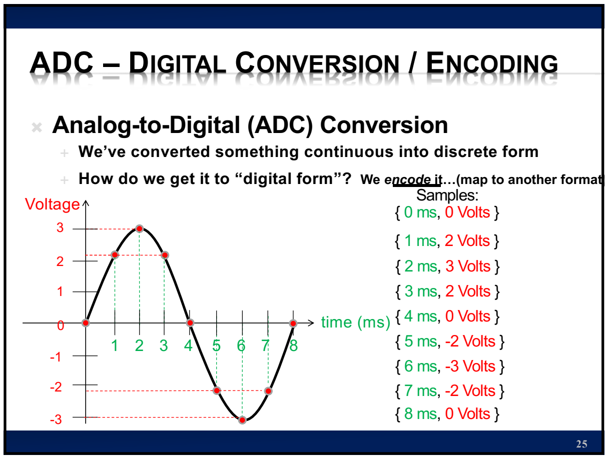

ADC – Digital Conversion / Encoding

- **Analog-to-Digital (ADC) Conversion**
  - **We've converted something continuous into discrete form**
  - **How do we get it to "digital form"? We *encode it*…(map to another format**

Samples:
{ 0 ms, 0 Volts }
{ 1 ms, 2 Volts }
{ 2 ms, 3 Volts }
{ 3 ms, 2 Volts }
{ 4 ms, 0 Volts }
{ 5 ms, -2 Volts }
{ 6 ms, -3 Volts }
{ 7 ms, -2 Volts }
{ 8 ms, 0 Volts }

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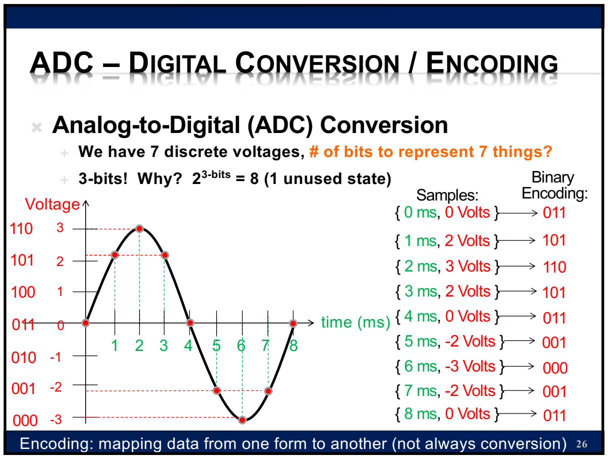

ADC – Digital Conversion / Encoding

- Analog-to-Digital (ADC) Conversion
  - We have 7 discrete voltages, # of bits to represent 7 things?
  - 3-bits! Why? $2^{3\text{-bits}} = 8$ (1 unused state)

Samples:	Binary Encoding:
{ 0 ms, 0 Volts } →	011
{ 1 ms, 2 Volts } →	101
{ 2 ms, 3 Volts } →	110
{ 3 ms, 2 Volts } →	101
{ 4 ms, 0 Volts } →	011
{ 5 ms, -2 Volts } →	001
{ 6 ms, -3 Volts } →	000
{ 7 ms, -2 Volts } →	001
{ 8 ms, 0 Volts } →	011

Encoding: mapping data from one form to another (not always conversion) 26

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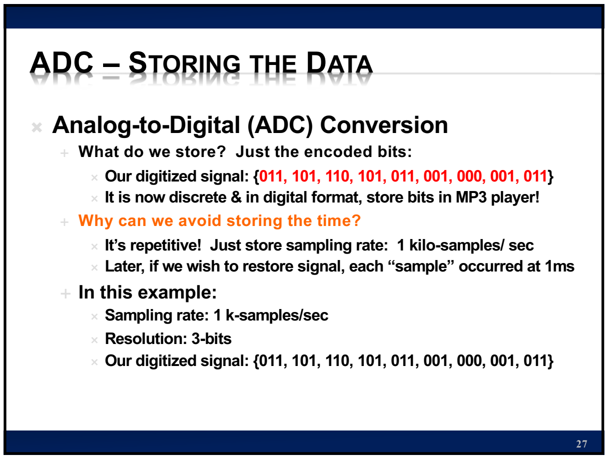

ADC – Storing the Data

- Analog-to-Digital (ADC) Conversion
  - What do we store? Just the encoded bits:
    - Our digitized signal: {011, 101, 110, 101, 011, 001, 000, 001, 011}
    - It is now discrete & in digital format, store bits in MP3 player!
  - Why can we avoid storing the time?
    - It's repetitive! Just store sampling rate: 1 kilo-samples/ sec
    - Later, if we wish to restore signal, each “sample” occurred at 1ms
  - In this example:
    - Sampling rate: 1 k-samples/sec
    - Resolution: 3-bits
    - Our digitized signal: {011, 101, 110, 101, 011, 001, 000, 001, 011}

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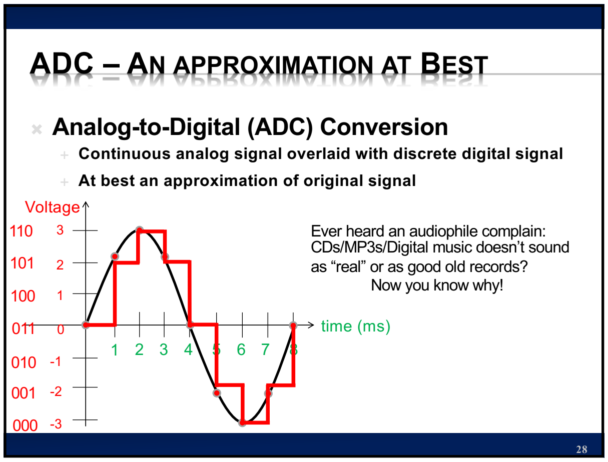

ADC – An Approximation at Best

- Analog-to-Digital (ADC) Conversion
  - Continuous analog signal overlaid with discrete digital signal
  - At best an approximation of original signal

Ever heard an audiophile complain:
CDs/MP3s/Digital music doesn't sound as “real” or as good old records?
Now you know why!

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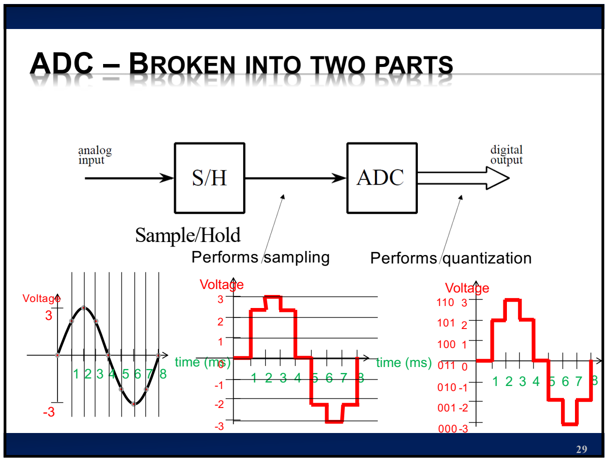

ADC – Broken into Two Parts

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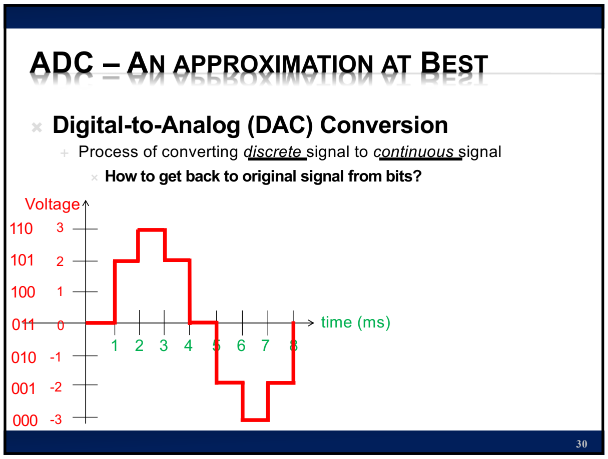
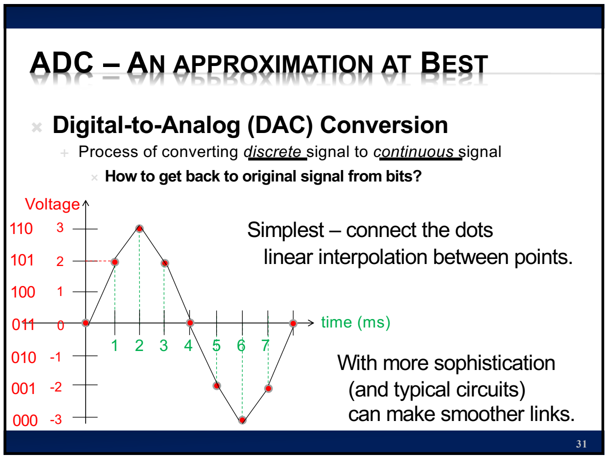


ADC – An Approximation at Best

- Digital-to-Analog (DAC) Conversion
  - Process of converting *discrete* signal to *continuous* signal
    - How to get back to original signal from bits?

30

30



ADC – An Approximation at Best

- Digital-to-Analog (DAC) Conversion
  - Process of converting *discrete* signal to *continuous* signal
    - How to get back to original signal from bits?

Simplest – connect the dots
linear interpolation between points.

With more sophistication
(and typical circuits)
can make smoother links.

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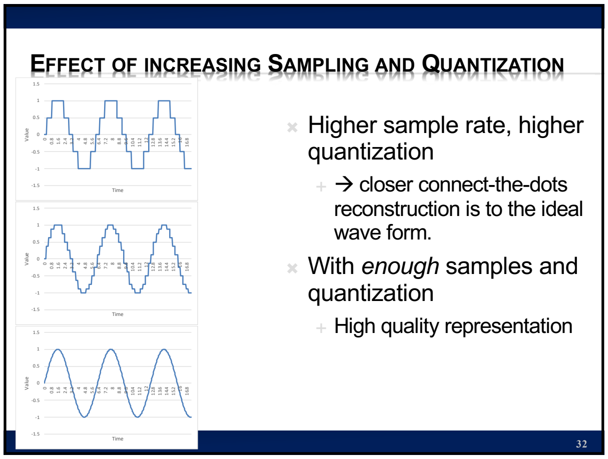

Effect of Increasing Sampling and Quantization

- Higher sample rate, higher quantization
  - → closer connect-the-dots reconstruction is to the ideal wave form.
- With *enough* samples and quantization
  - High quality representation

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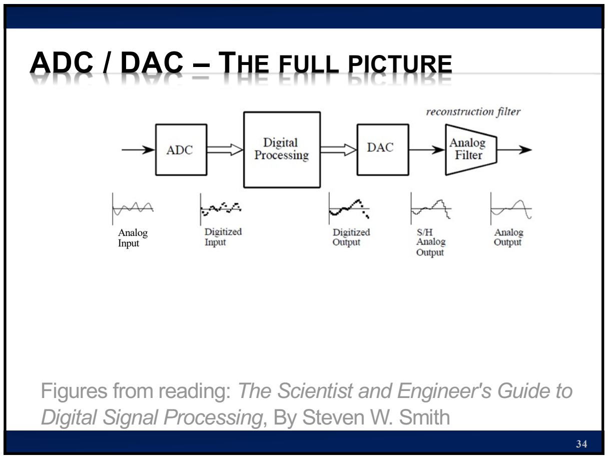

ADC / DAC – The full picture

Figures from reading: *The Scientist and Engineer's Guide to Digital Signal Processing*, By Steven W. Smith

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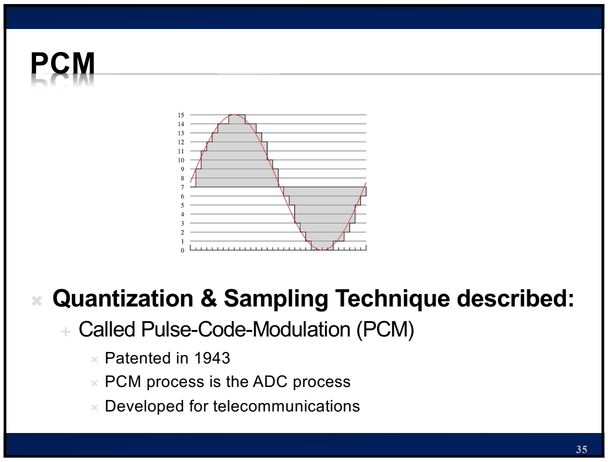

PCM

- **Quantization & Sampling Technique described:**
  - Called Pulse-Code-Modulation (PCM)
    - Patented in 1943
    - PCM process is the ADC process
    - Developed for telecommunications

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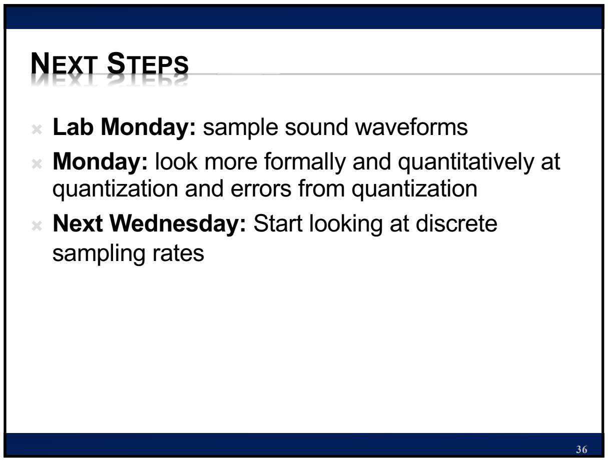

Next Steps

- **Lab Monday:** sample sound waveforms
- **Monday:** look more formally and quantitatively at quantization and errors from quantization
- **Next Wednesday:** Start looking at discrete sampling rates

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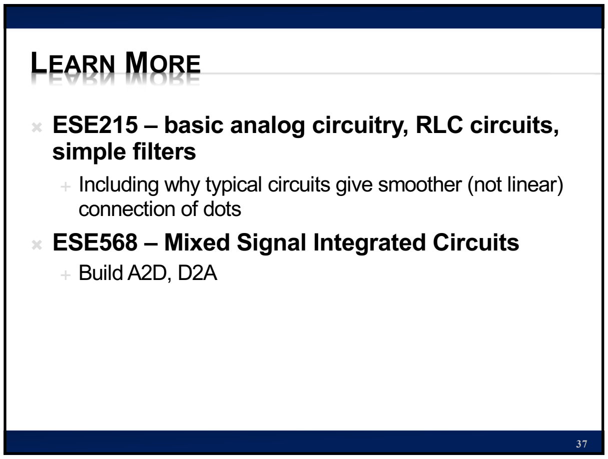

Learn More

- **ESE215 – basic analog circuitry, RLC circuits, simple filters**
  - Including why typical circuits give smoother (not linear) connection of dots
- **ESE568 – Mixed Signal Integrated Circuits**
  - Build A2D, D2A

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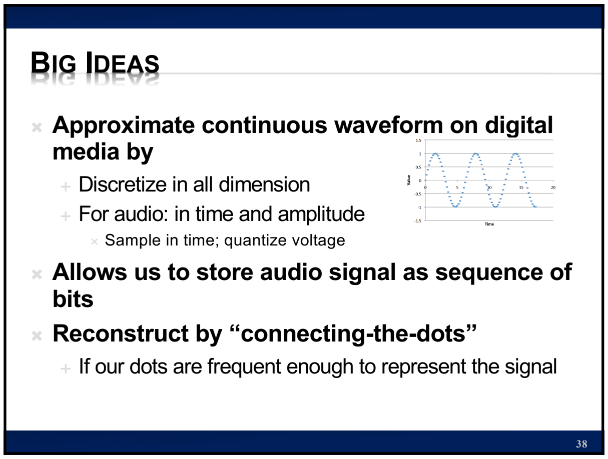

Big Ideas

- **Approximate continuous waveform on digital media by**
  - Discretize in all dimension
  - For audio: in time and amplitude
    - Sample in time; quantize voltage
- **Allows us to store audio signal as sequence of bits**
- **Reconstruct by "connecting-the-dots"**
  - If our dots are frequent enough to represent the signal

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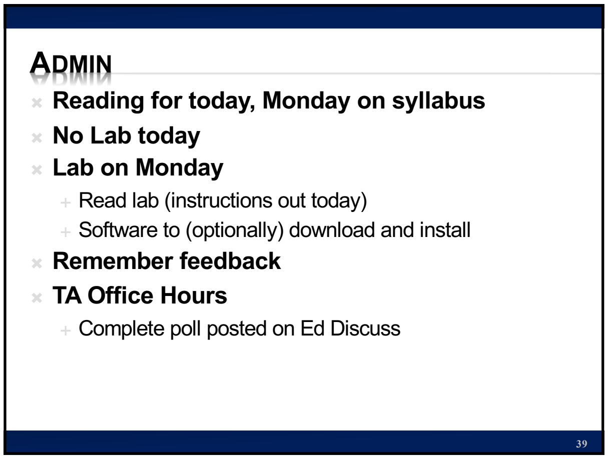

ADMIN

- Reading for today, Monday on syllabus
- No Lab today
- Lab on Monday
  - Read lab (instructions out today)
  - Software to (optionally) download and install
- Remember feedback
- TA Office Hours
  - Complete poll posted on Ed Discuss

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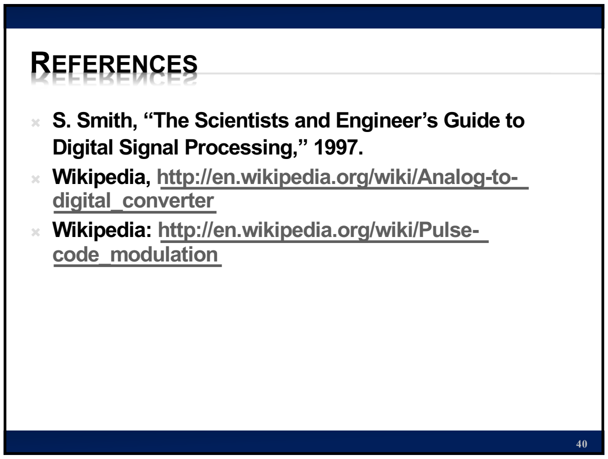

REFERENCES

- S. Smith, “The Scientists and Engineer’s Guide to Digital Signal Processing,” 1997.
- Wikipedia, http://en.wikipedia.org/wiki/Analog-to-digital_converter
- Wikipedia: http://en.wikipedia.org/wiki/Pulse-code_modulation

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