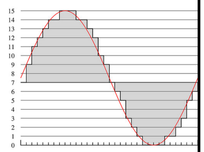
Penn Engineering

ESE



Lecture #3 – Quantization

ESE 150 – Digital Audio Basics

Based on slides © 2009--2022 Koditschek & DeHon
Additional Material © 2014--2017 Farmer

1

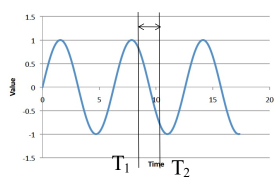
Lecture Topics

- **Part 1**
  - **Reminder:** Sampling and Quantization
  - Expressing Mathematically
- **<interlude: image resolution>**
- **Part 2**
  - Effects of Quantization
    - Discrete
    - Continuous (time permitting)
    - Engineering
- **Part 3**
  - System Capacity
  - Summary
- **References**

2

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



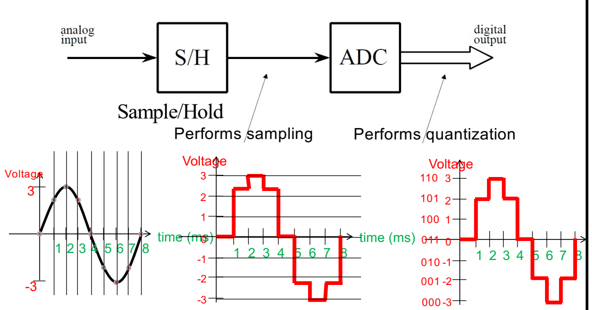
3

Strategy

- **Sample at periodic time intervals**
  - Discretize independent variable
- **Quantize to discrete levels**
  - Discretize the value of the dependent variable

4

ADC – Broken into two parts



5

Problem Decomposition

- **Powerful Engineering technique**
  - Formulate a parameterized solution strategy
  - Then identify the right parameters
- **Divides the problem**
- **Here**
  - Strategy of sampling and quantization
  - Then identify the right sampling rate, quantization level
- **Convergent:** limit of infinite samples, levels
- **Once have strategy, reduces to a well-defined optimization problem**
- **Parameterization admits to tuning for tradeoffs**

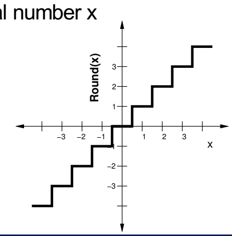
6

Mathematical Expression

7

Round

- **Rounding – select nearest discrete value as approximation of continuous value**
- **For sake of concreteness, we will define:**
  - Round(x) – nearest integer to real number x
    - Round(0.7) = 1
    - Round(-0.1) = 0
    - Round(2.4999) = 2
    - Round(1.50001) = 2
- **What is Round(3.3) ?**



8

Quantize

- **We will quantize to some level L**
- **Define as number of values between integers**
- **So, we have L steps of 1/L between integers**
  - (or only represent every L'th integer if L<1)
- **In terms of Round**
  - $Quantize_L(x)$ = Round(L*x)/L
  - E.g. $Quantize_8(0.7)$=Round(8*0.7)/8=6/8=0.75

9

Preclass 1

		0.333	1.246	-1.123
L=4	$Quantize_L(x)$			
	$QuantizationError_L(x)$			
L=16	$Quantize_L(x)$			
	$QuantizationError_L(x)$			

$Quantize_L(x)$ = Round(L*x)/L

10

Bits

- **If we quantize to L levels per integer**
- **Represent values between integers**
  - Max
  - Min
- **How many bits required per quantized value?**

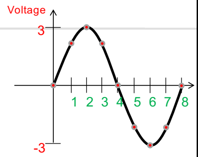
11

Bits per Quantized Value

- **Bits = $\lceil \log_2((Max-Min)*L+1) \rceil$**

12

Sample Values

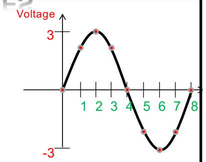


- When sample at time interval T
  - (for frequency = 1/T)
- We collect the points at times:
  - 0, T, 2T, 3T, 4T, …
- For signal f(t), we are collecting values:
  - f(0), f(T), f(2T), f(3T), f(4T), …
- Or in general, we are collecting the points
  - f(i*T) for i=0 to MaxSamples (or MaxTime/T)

13

13

Sample and Quantize Values



- When sample at time interval T
  - (for frequency = 1/T)
- We collect the points at times:
  - 0, T, 2T, 3T, 4T, …
- For signal f(t), we are collecting:
  - f(0), f(T), f(2T), f(3T), f(4T), …
- If we then Quantize the values to level L
  - Quantize_L(f(0)), Quantize_L(f(T)), Quantize_L(f(2T)), …

14

14

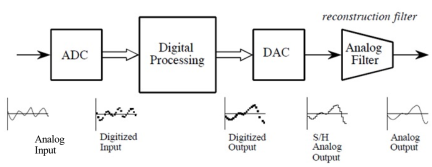
Sample and Quantize Values

- If we then Quantize the values to level L
  - Quantize_L(f(0)), Quantize_L(f(T)), Quantize_L(f(2T)), …
- Or in general, we are collecting the points
  - Quantize_L(f(i*T)) for i=0 to MaxSamples (or MaxTime/T)
- We store them in an array (or vector) F of MaxSamples+1
  - For i from 0 to MaxSamples: F[i]= Quantize_L(f(i*T))
  - This is what you collected on Monday!

15

15

ADC / DAC – The Full Picture



- **Formally:**
  - Analog input signal that varies with time: $s(t)$
  - Signal processing algorithm to digitize analog input signal:
    - F[i]=Round(s(i*T)*L)/L
      - T is sample period
  - Digitized signal produced by $F[\ ]$: $s_f(t)$

16

16

Preclass 2

Sample f(t)=sin(2π*110*t) at T=0.3ms, quantize L=10

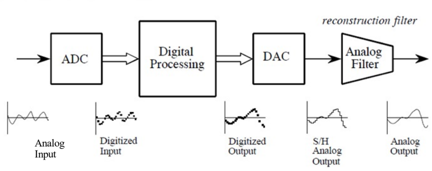
i	0	1	2	3	4
i*T	0	0.3ms			
Value f(i*T)	0				
F[i]	0				

Sine goes -1 to 1: how many bits for these 5 samples?

17

17

ADC / DAC – The Full Picture



- **Formally:**
  - Analog input signal that varies with time: $s(t)$
  - Signal processing algorithm to digitize analog input signal:
    - F[i]=Round(s(i*T)*L)/L
      - T is sample period
  - Digitized signal produced by $F[\ ]$: $s_f(t)$

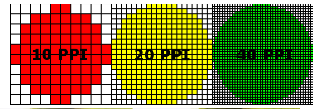
18

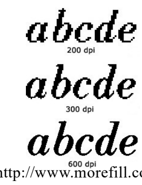
18

Interlude: 2D Images

Same Phenomena in Images

- World continuous
- Digital images on Zoom, TV, paper (even photographs) are discretized – limited resolution
  - Zoom…

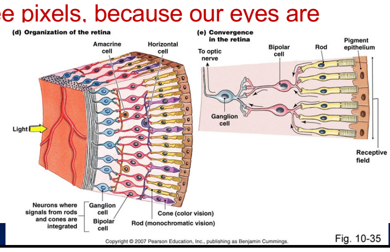




http://www.morefill.com/wpve
http://dslrphotographytutorials.com/wp-content/uploads/2014/05/PPI-Compare.png
http://blog.inkjetwholesale.com.au/wp-content/uploads/2015/07/DPI-comparison.png

Apple Retina Display

- **Why called retina?**
- **Claim (goal):** as much resolution as you have in your retina (at typical viewing distance)
- We cannot see pixels, because our eyes are themselves discrete!



Apple Retina Display

- **Why called retina?**
- **Claim (goal):** as much resolution as you have in your retina (at typical viewing distance)
- We cannot see pixels, because our eyes have discrete photo receptors (rods, cones)
- Human eye resolution 0.5 arc-minute (0.02 degrees)
  - Around 300 DPI (Dots-Per-Inch) at 20 inches

Part 2: Effects of Quantization

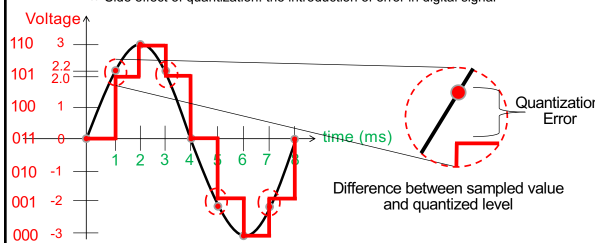
Effects of Quantization

Noise -- ``Formal'' Definition

- **Noise – difference between our ideal signal and the actual signal**
  - The one that we actually hear
  - The one that shows up when we transmit data
  - The one we store or reconstruct
- **Sometimes will see**
  - R(t) = S(t) + n(t)
    - Noise n(t) is added to the ideal signal S(t)
    - R(t) what we receive
  - Or, equivalently:
    - n(t)=S(t)-R(t)

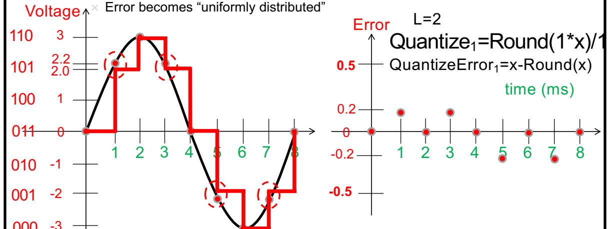
Quantization Error

- **In example, quantization algorithm required us to round**
  - At sample time, t=1ms, input signal was: 2.2V
  - It was lower than 2.5V, we rounded down to quantized level of 2.0V
    - Side effect of quantization: the introduction of error in digital signal



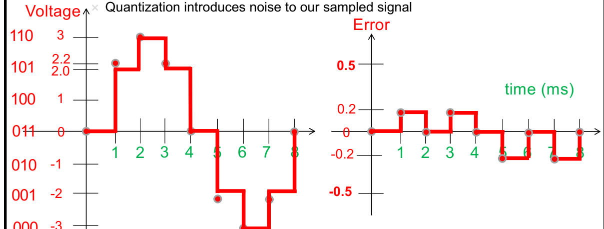
Quantization Error

- **How much error?**
  - In our case, we round up if equal to or above ½ a level…
    - …round down if below ½ a level
  - Generally, our input signal has 50/50 chance of being above/below
    - Error becomes "uniformly distributed"



Quantization Error / Noise

- **How much error?**
  - Looking at the plot of error, looks random
  - Sets up a way for us to model quantization error as noisy signal
    - Noise due to quantization = sampled signal (red dots) – quantized signal (red line)
    - Quantization introduces noise to our sampled signal



Preclass 2

Sample f(t)=sin(2π*110*t) at T=0.3ms, quantize L=10

i	0	1	2	3	4
i*T	0	0.3ms			
Value f(i*T)	0				
F[i]	0				
Quantization Error	0				

Penn Engineering ESE

(Time permitting) skip

Part 2b: Effects of Quantization Continuous Errors

Continuous Error

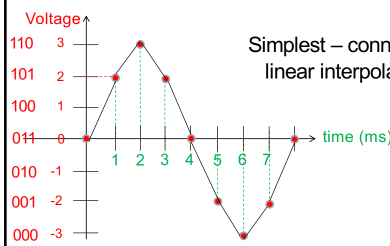
- **So far, focus on error at sample points**
- **Can also define error at any point**
- **Depends on reconstruction model**
  - How estimate/create continuous from samples
- **Simple connect-the-dots model linear interpolation**

31

31

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?**



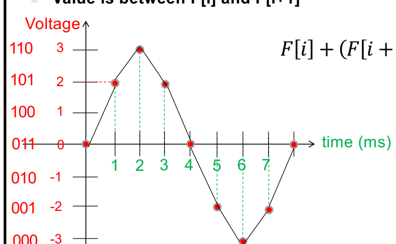
Simplest – connect the dots
linear interpolation between points.

32

32

Continous Reconstruction

- **What is reconstructed signal at time t?**
- **Find samples that bracket --- i: i*T<t<(i+1)*T**
- **Value is between F[i] and F[i+1]**



$$F[i]+(F[i+1]-F[i])\times\left(\frac{t-i\times T}{T}\right)$$

33

33

Preclass 3

- **Sampling and quantization error at t=1ms?**
- **T=0.3ms**
- **i?**
- **F[i], F[i+1]**
- **Reconstructed value?**
- **f(1ms)**
- **Error=f(1ms)-ReconstructedValue(1ms)**

$$F[i]+(F[i+1]-F[i])\times\left(\frac{t-i\times T}{T}\right)$$

34

34

Penn Engineering ESE

Part 2c: Effects of Quantization Engineering

35

35

Quantization Error / Design

- **Why model quantization error as noise?**
- **There is always noise present**
  - Something other than the signal we intend
  - Wires, electronics, background
  - Not gaining much if quantization noise < other noise
- **Quantization adds noise**
  - Reduce by increasing sampling, increasing resolution
  - More levels →(L) bits → makes more expensive
    - Bits = ⌈log2((Max-Min)*L+1)⌉
  - Increase L until reach desired noise level
    - Until other sources dominate quantization noise
- **SNR = Signal-to-Noise Ratio**
  - How much larger is the signal compare to noise?
  - Mean (average) value of signal / std. dev. of noise
  - Usually what we are optimizing in the system (including ADC)

36

36

Engineering

- "An Engineer can do for a dime what anyone else can do for a dollar."
- **Engineering is about optimization and efficiency**
- **Bits are costly**
- **Anyone:** Sample frequently with high resolution
- **Engineer ask:** how few bits can I use without sacrificing quality?
- **Engineering is about tradeoffs**
  - Quality vs. Cost

37

37

Problem Decomposition

- **Powerful Engineering technique**
  - Formulate a parameterized solution strategy
  - Then identify the right parameters
- **Divides the problem**
- **Here**
  - Strategy of sampling and quantization
  - Then identify the right sampling rate, quantization level
- **Once have strategy, reduces to a well-defined optimization problem**
- **Parameterization admits to tuning for tradeoffs**

38

38

Penn Engineering ESE

Part 3: System Capacity and Limits

39

39

Quantization, Sampling, Capacity

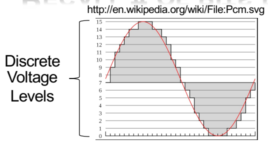
- **Quantization and Sampling**
  - Play enormous role in determining storage capacity of digital system
  - # of quantization levels ➔ # of bits per sample
    - Increasing resolution of ADC, reduces quantization noise…
    - But also increases amount of data we must store for each sample
    - Bits/sample = $\lceil \log_2((\text{Max-Min})*L+1) \rceil$
  - Sampling rate = how often we collect # of bits per sample
    - Typically sampling rate = twice frequency of signal (next week)
    - Increasing the rate, increases the amount of data to store!

40

40

Recall # of bits for typical song

http://en.wikipedia.org/wiki/File:Pcm.svg



http://en.wikipedia.org/wiki/File:Compact_disc.svg

- **Sampling rate & resolution effect on storage**
  - Compact Disks: 16bits at 44KHz
    - How many bits is a typical 3-minute song?

$$\left(44{,}000\ \frac{samples}{1\ sec}\right)\left(16\ \frac{bits}{sample}\right)\left(60\ \frac{sec}{1\ min}\right)\left(3\ \frac{min}{song}\right) = 15.1\ \frac{MB}{song}$$

41

41

Limits of Sampling

42

42

Sampling

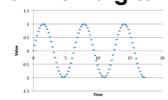
- **Definition of proper sampling**
  - If you can exactly reconstruct analog signal from samples,
  - you have done the sampling properly
    - Essentially: you have captured the key information from the signal to process can be reversed
- **Milestone of digital signal processing (DSP):**
  - Nyquist-Shannon Theorem (Wednesday)
    - Tells us our sampling rate should be:
      - twice the frequency of the signal!

43

43

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
- **Introduce error → noise**
  - Reason about tolerable (or noticeable) noise

44

44

Admin

- **Reading for Wednesday on syllabus**
- **Remember feedback**
  - Includes Lab 1
- **Office Hours**
  - Complete poll (only 4 answers so far)
  - So far,
    - Friday 4pm looking promising
    - Thursday not attractive?
- **Lab 1 Reports due today**
- **Lab 2 Wednesday in Detkin**
  - Same hardware, software
    - can use machines in Detkin; lab kits at in-person lab session
  - Prelab

45

45

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

46

46