Audio DSP

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Sound

- Sound: vibration transmitted through a medium (gas, liquid, solid and plasma) composed of frequencies capable of being detected by ears.
  - Note: sound cannot travel through a vacuum.
- Human detectable sound is often characterized by air pressure variations detected by the human ear.
- The amplitude, frequency and relative phase of the air pressure signal components determine (in part) the way the sound is perceived.

Sinusoids and Sound: Amplitude

- A fundamental unit of sound is the sinusoidal signal.

$$x_a(t) = A\cos(2\pi F_0 t + \theta), \qquad t \in \mathbb{R}$$

  - $A \equiv$ volume
  - $F_0 \equiv$ pitch (more on this ...)
  - $\theta \equiv$ phase (more on this ...)

Sound Volume

- Volume = Amplitude of sound waves/audio signals
- quoted in dB, which is a logarithmic measure; $10\log(A^2)$
  - no sound/null is $-\infty$ dB
- Loudness is a subjective measure of sound psychologically correlating to the strength of the sound signal.
  - the volume is an objective measure and does not have a one-to-one correspondence with loudness
  - perceived loudness varies from person-to-person and depends on frequency and duration of the sound

Music Volume Dynamic Range

Tests conducted for the musical note: C6 ($F_0 = 1046.502$ Hz).

Dynamic Level	Decibels
Threshold of hearing	0
ppp (pianissimo)	40
p (piano)	60
f (forte)	80
fff (fortississimo)	100
Threshold of pain	120

Sinusoids and Sound: Frequency

- A fundamental unit of sound is the sinusoidal signal.

$$x_a(t) = A\cos(2\pi F_0 t + \theta), \qquad t \in \mathbb{R}$$

  - $A \equiv$ volume
  - $F_0 \equiv$ pitch
  - $\theta \equiv$ phase (more on this . . .)

Pure Frequency

- **Q:** What type of sound does a pure frequency produce?
  - **A:** A pure tone with a single pitch.
- **Q:** Can any instrument produce a pure tone by playing a single note?
  - **A:** No.

Tuning Forks

- A tuning fork is a two-pronged instrument that is an acoustic resonator. It is usually made out of steel and resonates at a specific constant pitch which is a function of the length of the prongs.
  - Striking the tuning fork will produce the required sounds although initially there may be overtones that die out quickly.
  - A very common tuning fork used by musicians produces the A note ($F_0 = 440$ Hz), which is international concert pitch used to tune orchestras.

Frequency and Pitch

- Sinusoids can be represented either as:

$$x_a(t) = A\cos(2\pi F_0 t + \theta), \qquad t \in \mathbb{R}$$

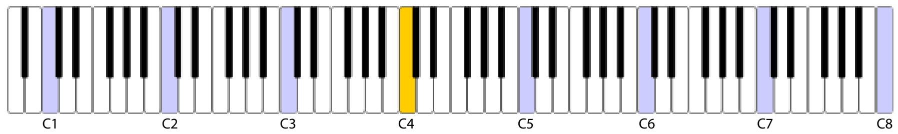
or for mathematical convenience when interpreting as Fourier signal components as:

$$x_a(t) = Ae^{j(2\pi F_0 t + \theta)}, \qquad t \in \mathbb{R}$$

- Pitch is directly related to the frequency F_0.
- To be able to hear a frequency F_0, it has to be in the human audible range.

Harmonically Related Frequencies and Pitch

Scientific Designation	Frequency (Hz)	k for $F_0 = 8.176$
C1	32.703	4
C2	65.406	8
C3	130.813	16
C4 (middle C)	261.626	32
C5	523.251	64
C6	1046.502	128
C7	2093.005	256
C8	4186.009	512



Harmonically Related Frequencies

- Recall harmonically related sinusoids have the following analytic form for $k \in \mathbb{Z}$:

$$x_{a,k}(t) = A\cos(2\pi k F_0 t + \theta)$$

or

$$x_{a,k}(t) = Ae^{j(2\pi k F_0 t + \theta)}$$

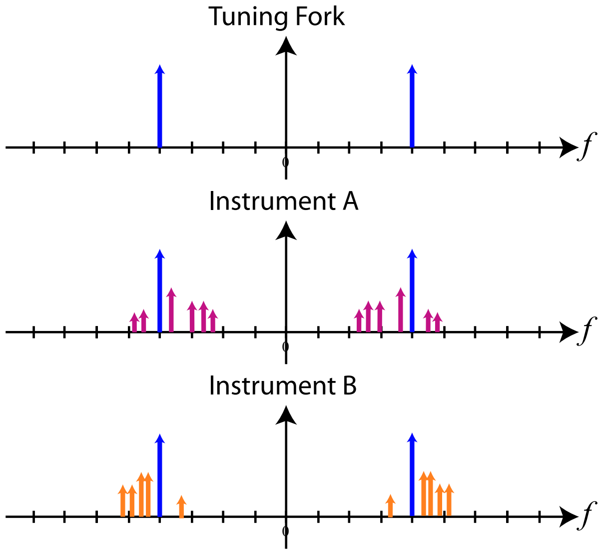
- They are used in the context of the Fourier Series to build periodic signals:

$$x(t) = \sum_{k=-\infty}^{\infty} X(k) e^{j(2\pi k F_0 t)}$$

Signature Sounds

- **Q:** If two different people sing the same note or two different instruments play the same note, why do they sound different?
  - The notes are not pure tones. There are natural <u>overtones</u> and <u>undertones</u> that provide distinguishing signatures that can be viewed in the associated spectra.

Fourier Transforms of the Same Note



Human Audible Range

- Hearing is usually limited to frequencies between 20 Hz and 20 kHz.
- The upper limit decreases with age.
  - The audible frequency range is different for animals

Animal Audible Range

Species	Approx Range (Hz)
human	20 - 20,000
dog	67 - 45,000
rabbit	360 - 42,000
bat	2,000 - 110,000
goldfish	20 - 3,000

Reference: R.R. Fay (1988), Hearing in Vertebrates: A Psychophysics Databook.

Sinusoids and Sound: Phase

- A fundamental unit of sound is the sinusoidal signal.

$$x_a(t) = A\cos(2\pi F_0 t + \theta), \qquad t \in \mathbb{R}$$

  - $A \equiv$ volume
  - $F_0 \equiv$ pitch
  - $\theta \equiv$ phase

Phase and Sound

Consider a general sound signal $x(t)$ that is comprised of frequency components each with a specific phase shift.

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi f t} df$$

- $|X(f)|$: relative volume of a sinusoidal component
- $\angle X(f)$: relative phase of a sinusoidal component

Phase and Sound

- If $x(t)$ is the general sound signal, then $x(-t)$ is the sound signal in reverse.
- **Q:** Do $x(t)$ and $x(-t)$ sound similar?
  - **A:** No.

Phase and Sound

- Recall, from the continuous-time Fourier transform (CTFT) that for a real signal $x(t)$:

$$\begin{aligned} x(t) &\overset{\mathcal{F}}{\longleftrightarrow} X(f) \\ x(-t) &\overset{\mathcal{F}}{\longleftrightarrow} X(-f) \end{aligned}$$

and

$$X(f) = X^*(-f)$$

Phase and Sound

- Taking the magnitude and phase of both sides we have:

$$\begin{aligned} X(f) &= X^*(-f) \\ |X(f)| &= |X^*(-f)| = |X(-f)| \\ \angle X(f) &= \angle X^*(-f) = -\angle X(-f) \end{aligned}$$

- Conjugate Symmetry (for real signals $x(t)$):
  - CTFT magnitude is even
  - CTFT phase is odd

Phase and Sound

- Therefore, for

$$x(t) \overset{\mathcal{F}}{\longleftrightarrow} X(f)$$
$$x(-t) \overset{\mathcal{F}}{\longleftrightarrow} X(-f)$$

  - $|X(f)| = |X(-f)| \Rightarrow$ the CTFT magnitudes for forward and reverse sound signals are exactly the same.
  - $\angle X(f) \neq \angle X(-f) \Rightarrow$ the CTFT phases for forward and reverse sound signals are different.
- Therefore, the relative phase of the sinusoidal components of sound contains very salient perceptual information much like for images.

Auditory Masking

- occurs when the perceived quality of one (primary) sound is affected by the presence of another (secondary) sound
  - Simultaneous masking: the secondary sound is heard at the same time as the primary sound
- Can be exploited (as we see in an upcoming lab) to mask non-ideal signal processing.

Why Digitize Audio?

- Fidelity of digital audio is much higher than analog audio.
- Manipulation tools for digital audio are much more sophisticated than those available for analog audio.
- Compression of digital audio provides significantly reduced storage requirements.
- Storage of digital audio (e.g., CDs) are much more convenient and compact.
- Duplication of digital audio is exact in contrast to analog audio.

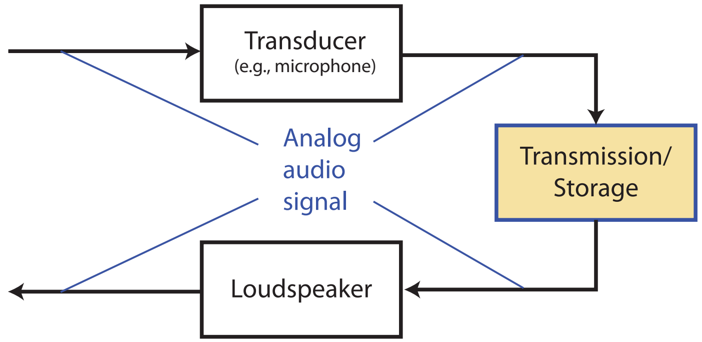
Benefits of Digital Audio

- Convenient recording, enhancement, mass-production and distribution.
  - CDs, online stores such as iTunes, etc.
  - data files are distributed instead of physical media storing the information such as records and tapes.

Concerns about Digital Audio

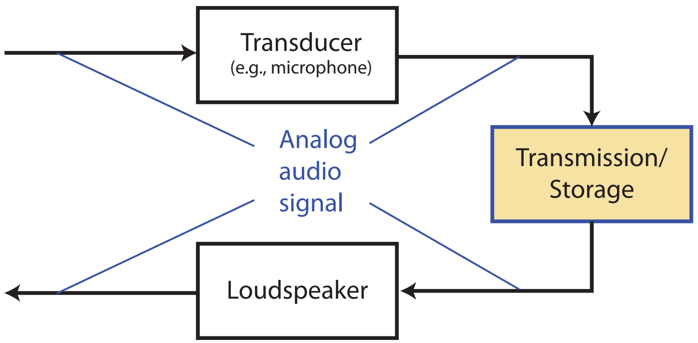
- Convenient recording, enhancement, mass-production and distribution.
  - unlawful manipulation of recorded audio is difficult to detect
  - piracy: unlawful copying and redistribution of copyrighted content

Analog vs. Digital Audio: Analog Audio System



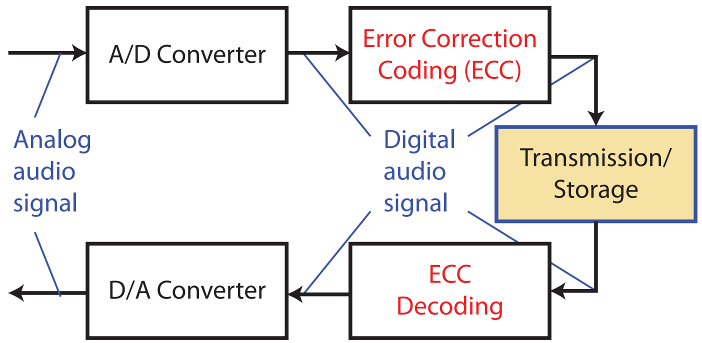
- microphone: converts sound into an electrical signal;
  air pressure → motion of conductor/coil → magnetic field → electrical signal
- loudspeaker: converts electrical signal into acoustic waves;
  electrical signal → magnetic field → motion → air pressure

Analog vs. Digital Audio: Analog Audio System



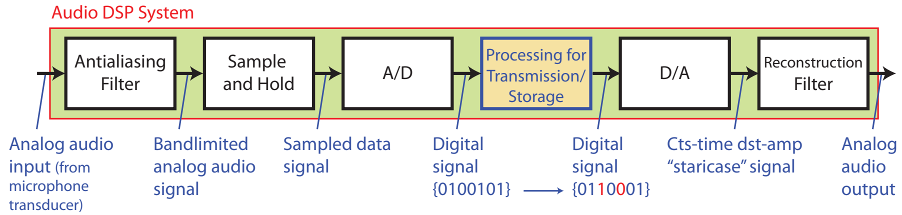
- associated circuits suffer from inherent noise (noise floor)
- capacitance and inductance of the circuits limit bandwidth, and resistance limits amplitude

Analog vs. Digital Audio: Digital Audio Chain

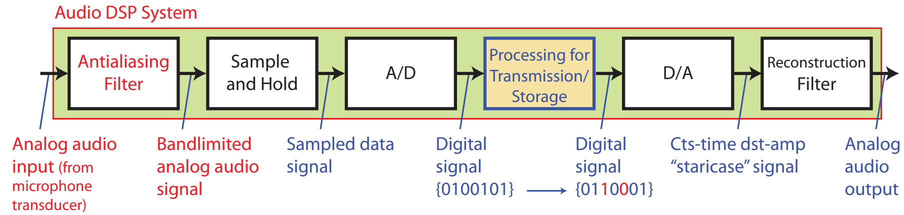


- fidelity limited by quantization noise
- bandwidth limited by sampling rate
- dynamic range limited by bit resolution

Digitizing Audio



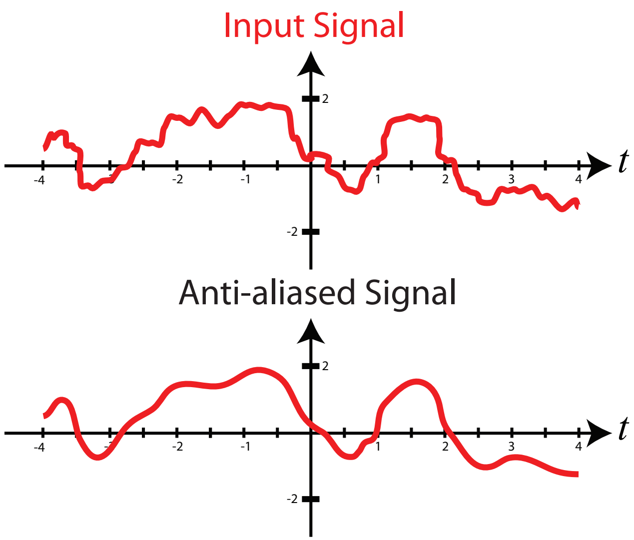
Digitizing Audio



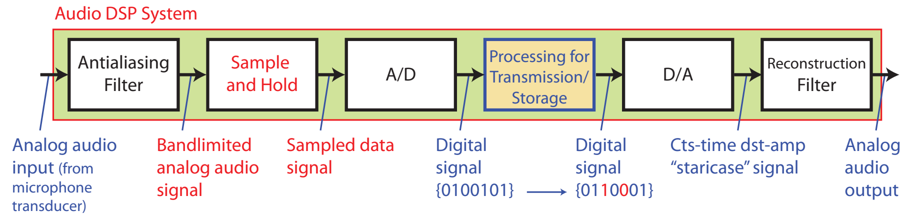
Anti-aliasing Filter:

- ensures that analog audio input does not contain frequency components higher than half of the sampling frequency (to avoid aliasing)
- Example: C6713 DSP, $F_s = 8$ kHz, therefore anti-aliasing filter must have a passband of 0 Hz to 4000 Hz.

Digitizing Audio



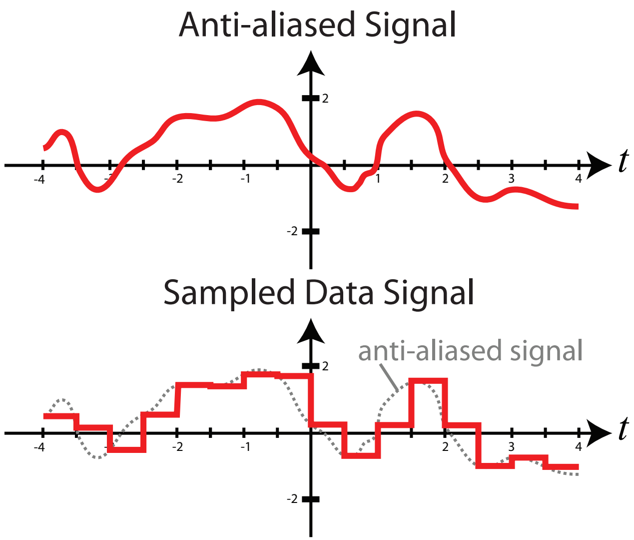
Digitizing Audio



Sample and Hold:

- holds a sampled analog audio value for a short time while the A/D converts and interprets the value as a digital

Digitizing Audio



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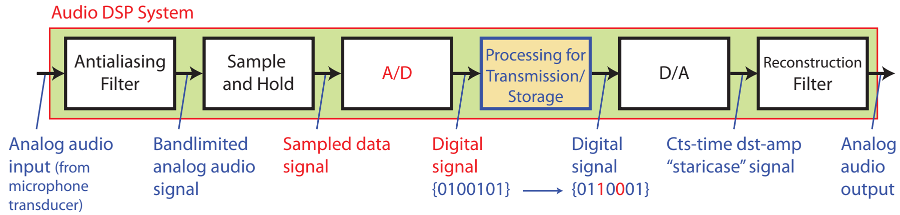
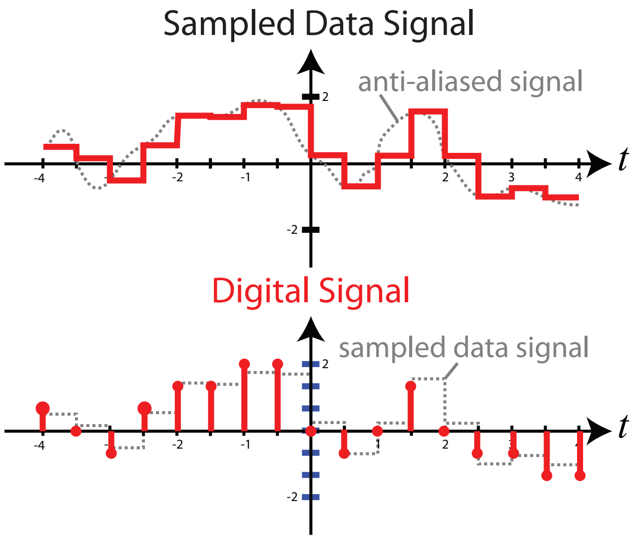


A/D:
- converts a sampled data audio value into a digital number, in part, through quantization of the amplitude

Digitizing Audio



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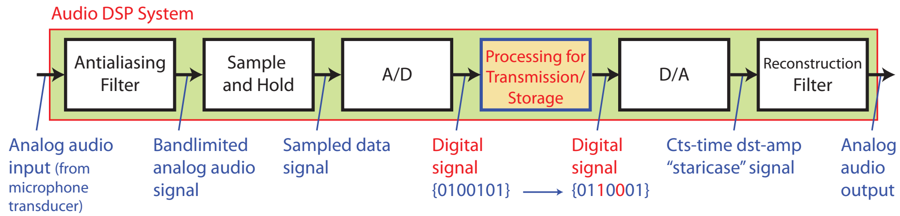


Processing for Transmission/Storage:
- transmission/storage contains inherent non-idealities that cause errors in the received/retrieved data symbols
- error correction coding (ECC) is employed to add redundancy to the digital signal so that errors can be compensated for during decoding

Error Correction Coding

Example: N-repetition code

Input Signal Bit	Coded Sequence
0	$\underbrace{0\ 0\ 0\ \cdots\ 0}_{N \text{ zeros}}$
1	$\underbrace{1\ 1\ 1\ \cdots\ 1}_{N \text{ ones}}$

Therefore, for $N = 3$ the following input signal sequence: 0 0 1 would be coded as follows: 0 0 0 0 0 0 1 1 1.

Error Correction Coding

Q: How would you interpret receiving the following coded sequence (with possible error):

1 1 1 0 1 0 0 0 0?

$$\underbrace{1\ 1\ 1}_{1}\ \underbrace{0\ 1\ 0}_{0}\ \underbrace{0\ 0\ 0}_{0}$$

A: Decoding can make use of majority vote logic.

Error Correction Coding

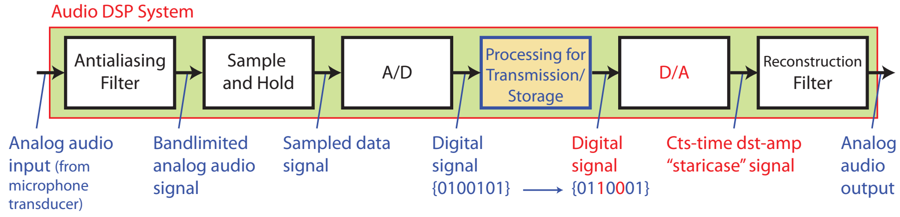
Coder for $N = 3$:

Input Signal Bit	Coded Sequence
0	0 0 0
1	1 1 1

Majority vote logic decoder for $N = 3$:

Received Coded Seq	Decoded Signal Bit
0 0 0	0
0 0 1	0
0 1 0	0
0 1 1	1
1 0 0	0
1 0 1	1
1 1 0	1
1 1 1	1

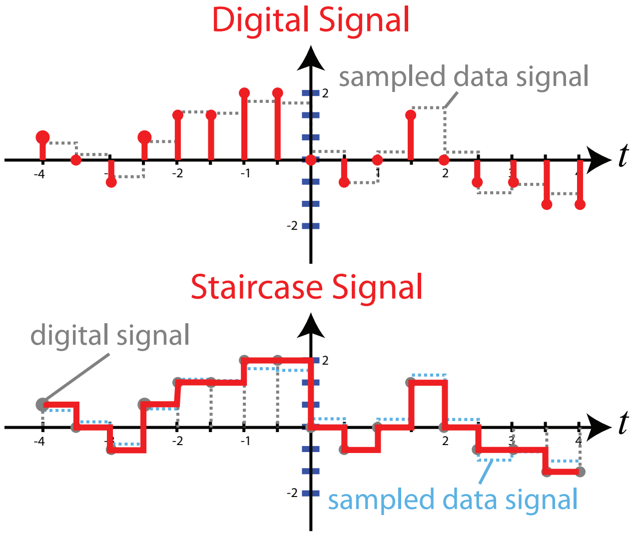
Digitizing Audio



D/A:

- converts a digital audio signal into a "staircase"-like signal for further reconstruction

Digitizing Audio



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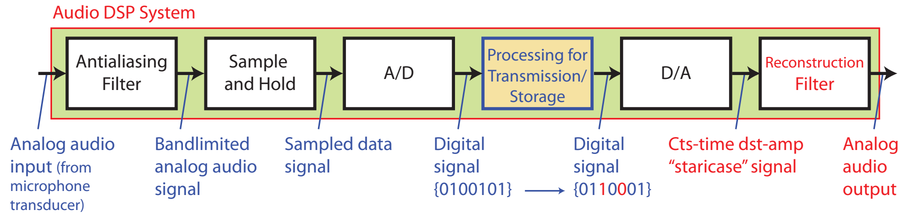
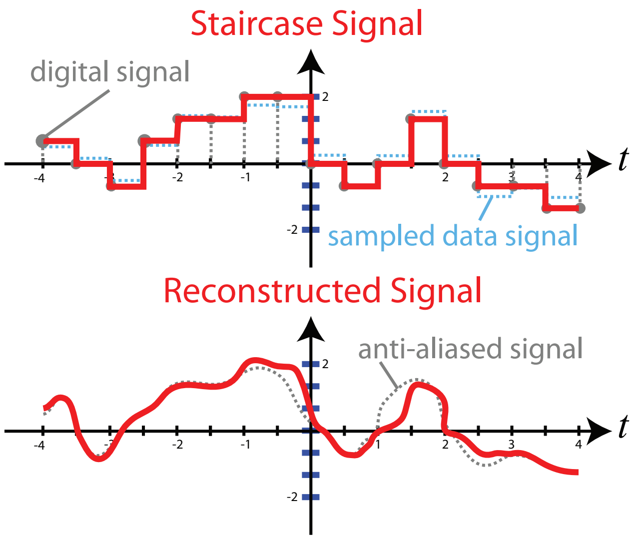


Reconstruction Filter:

- converts a "staircase"-like signal into an analog filter through lowpass filtering
- depending on the application the filter can be similar to the anti-aliasing filter, or may be very cheap (e.g., compact disk receivers), or may using a different sampling rate for special effects

Digitizing Audio



Digitizing Audio

The "quality" of digitizing audio is related to the following parameters:

- sampling rate (Hz)
- bit depth (bits/sample) and dynamic range (related to number of quantization levels)
- mono vs. stereo

Digitizing Audio

Note: For the same cost, digital audio provides higher signal-to-noise ratio or lower mean-square error between the real sound and what is recorded/played.

- It is less expensive to increase sampling rate and quantization depth (i.e., reduce quantization noise) than to use less noisy analog circuitry (i.e., reduce noise floor)
- When signals are represented digitally the natural noise in the circuits can be circumvented via error correction coding. Thus, it is possible to have near perfect storage/transmission.

Audio Quality and Sampling Rate

Audio Quality as a Function of Sampling Rate:

Sampling Rate (Hz)	Quality Similar to
8,000	telephone
11,025	AM radio
22,050	FM radio
44,100	CD
48,000	DAT

Audio Quality, Sampling Rate, and Bit Depth

Audio Quality as a Function of Sampling Rate, Bit Depth and Stereo/Monophony:

Sampling Rate (Hz)	Bit Depth	Stereo/Mono	Quality
8,000	8	mono	telephone
11,025	8	stereo	low
22,050	8	stereo	·
22,050	16	mono	·
22,050	16	stereo	·
44,100	16	mono	good
44,100	16	stereo	CD quality

Audio Quality

Q: Why do some people insist that analog audio is superior to digital audio?

A: What they think sounds good isn't the exact original sound, but a nonlinearly distorted version generated from the analog components.

Note: Some digital audio companies now make digital amplifiers that mimic the distortion from analog audio amplifiers.

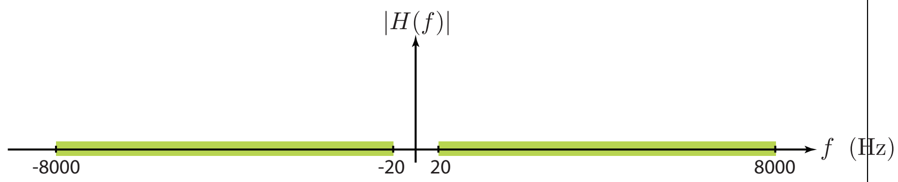
Quality of audio is a qualitative and psychological measure that is user-specific.

Audio Equalization

- Equalization ≡ Equalisation ≡ EQ
  - amplifying or attenuation different frequency components of an audio signal
  - Example: bass/treble control in inexpensive car radios
- Common goals of equalization:
  - provide fine granularity of frequency amplification/attenuation control without affecting adjacent frequencies.
  - correct for unwanted frequency attenuation/amplification during recording processes
  - enhancing the presence of certain sounds
  - reducing the presence of unwanted signals such as noise

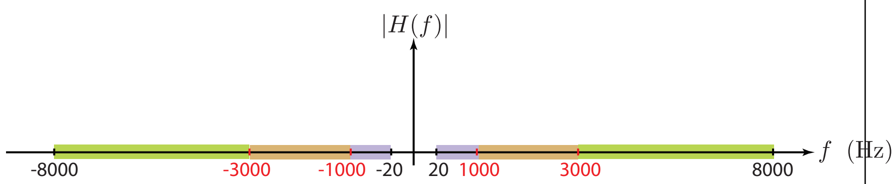
Equalizer Design Basics

1. Determine the processing band of your audio signal.
   - human audible range is: 20 Hz to 20 kHz
   - if sampling rate of a DSP is F_s then, the bandwidth of the audio signal to process is: 20 to $\frac{F_s}{2}$ Hz
   - Example: $F_s = 16,000$ Hz



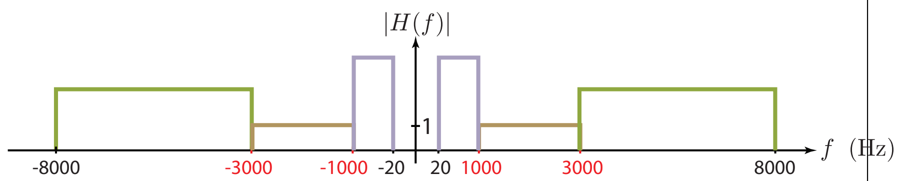
Equalizer Design Basics

2. Determine the granularity of your equalizer (i.e., number of frequency bands to independently control).
   - one approach might be to equally partition the audio signal bandwdith
   - more popular approaches suited to human auditory system models have bands that increase in width by two
   - Example: 3 frequency bands



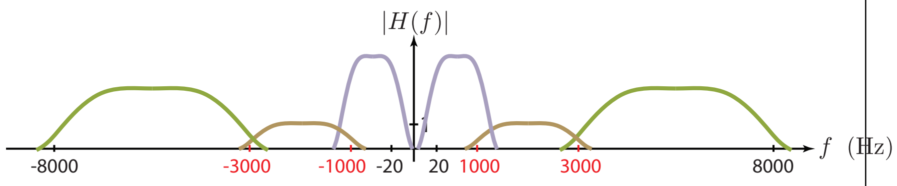
Equalizer Design Basics

3. Design your bandpass filters.
   - each bandpass filter is independently set/controlled from the others
   - ideally, many people would like shelving EQ
   - Example: Ideal bandpass filters



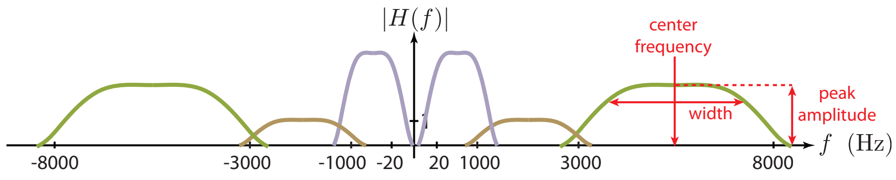
Equalizer Design Basics

3. Design your bandpass filters.
   - each bandpass filter is independently set/controlled from the others
   - ideally, many people would like shelving EQ
   - Example: Bell EQ



Common Types of Equalizers

- All bell filters and many other bandpass filters can be characterized by three parameters:
  - center frequency
  - width of the bell curve
  - gain (i.e. peak) of the bell curve



Common Types of Equalizers

- Parametric Equalizers: the center frequency, passband width and peak amplitude can be independently selected for each filter
  - most powerful EQ, predominantly used for recording and mixing
- Graphic Equalizers: the center frequency and passband width of each filter are pre-set; the gains of each filter can be independently controlled
  - used for live applications such as concerts

Common Types of Equalizers

- Notch Filters: the passband width is small and fixed for each filter; center frequencies and gains are variable.
  - used in multimedia applications/audio mastering

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