I. The Basic Concept

1. the frequency of a sine wave
   A. defined as the number of complete cycles it makes per second
   B. corresponds to "pitch" in the audio range—SHOW examples using function generator, speaker, and oscilloscope—set generator to 500 Hz, and connect 250-Ω resistor in series with speaker to reduce loading and distortion

2. frequency of non-sinusoidal wave
   A. defined in the same way
   B. but sounds different than sine wave of the same pitch (SHOW examples, switching back and forth between sine and square waves of the same 500-Hz frequency)
      i) is the pitch the same?
      ii) do they sound the same?
      iii) how does square wave sound different? can you hear any higher frequencies in it?

3. we say that sine waves are "pure," containing only a single frequency (the "fundamental frequency"), but non-sine waves contain higher frequencies called "harmonics" or "overtones"
   A. harmonics or overtones are the whole number multiples of the fundamental frequency
      i) e.g., if 500 Hz is the fundamental frequency
      ii) 1000 Hz is called the "second harmonic" ("first harmonic" is the same as the fundamental)
      iii) third harmonic is? (3 x 500 = 1500 Hz)
B. turns out that square wave contains the fundamental and all the odd harmonics

i) 3 x 500 Hz = 1500 Hz, 5 x 500 Hz = 2500 Hz, etc.

ii) can you hear the 1500-Hz third harmonic? (try it)

iii) can create any non-sinewave, such as a 500-Hz square wave, by adding together sine waves in the right amounts each

(a) the circuit for doing this (Fig. 1)

- includes generators connected in series so their outputs add (right-hand side of Fig. 1)
- one set to 500 Hz, the fundamental or "first harmonic"
• next one set to 1500 Hz, the third harmonic
• next to 2500 Hz, the fifth harmonic, etc.
• an infinite number of generators
• but their amplitudes set to lower and lower amounts, as shown
• impractical to make out of lab generators (hard to exactly synchronize the phase and frequencies)
• but can simulate using CircuitMaker (SHOW by running CircuitMaker program and loading file L.104.13.1A)

(b) how these sine waves add up to a square wave
• graphically (Fig. 2)
mathematically, make a table of values for $y = \sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \frac{1}{7} \sin 7x + \ldots$ (infinite series), every 30 degrees or so, use computer to take series out to 15 terms or so

result (run simulation using CircuitMaker: hit "simulation," "Run," and touch "V" (voltage) probe to different points in the circuit—the computer will display the waveform at that point (if waveform does not appear on the screen, pull down "Window," and select "transient analysis (oscilloscope")

as more and more higher frequency sine waves are added on, the waveform becomes more and more like a perfect square wave

C. sawtooth wave contains all the harmonics (Fig. 2A)
i) formula is similar to square wave's: \( y = \sin x + \frac{1}{2} \sin 2x + \frac{1}{3} \sin 3x + \frac{1}{4} \sin 4x + \ldots \)

ii) show by running simulation of "sawtooth.wave.generator" circuit using CircuitMaker program

II. The Spectrum

1. definition—bar graph of frequencies present versus the amount (amplitude) of each one
   
   A. frequency on horizontal axis (linear scale, not logarithmic)
   
   B. amplitude (voltage, peak or peak-to-peak) on vertical axis
   
   C. shows all the frequencies present in the waveform, like splitting white light into its component colors with a prism

2. example—the 500-Hz sine wave
A. contains only the fundamental at 500 Hz, so a single vertical line ("bar") is drawn there (SHOW, starting Fig. 3)

B. "pure tone," so no harmonics present

C. height of the bar = 1 V, the peak amplitude of the waveform

D. if the sine wave is distorted at all, e.g., by an amplifier, some harmonics will appear in the spectrum, called "harmonic distortion"

3. example—the 500-Hz square wave (Fig. 3A)
A. contains the fundamental at 500 Hz, so a vertical line is drawn there

B. contains the third harmonic at 1500 Hz, so a vertical line is drawn there, but only 1/3 as long as the fundamental, since the amplitude of the third harmonic is only 1/3 as much

C. line at 2500 Hz, 1/5 as long, etc.

4. in the *frequency* domain

A. as opposed to the time domain (oscilloscope)

B. frequency, not time, plotted on horizontal axis

C. like radio dial

5. computing—can be done mathematically, given the graph of the non-sinusoidal waveform
6. measuring

A. with a spectrum analyzer (SHOW examples)

SETUP FOR HP 3580A SPECTRUM ANALYZER CONNECTED TO LEADER FUNCTION GENERATOR

Adaptive Sweep: on, @ approximately 10 o'clock position
Function Generator @ maximum amplitude, 500 Hz frequency
Amplitude Mode: linear
Input Sensitivity: +20 (calibrated)
Sweep Mode: repeating
Sweep Time / Division: 2 seconds
Display Smoothing: 100 Hz
Frequency Span / Division: 500 Hz
Frequency: STR, adjust to 0

i) 500-Hz sine wave

ii) distorted 500-Hz sine wave (clip by using DC offset adjust on generator)

iii) 500-Hz square wave

iv) 500-Hz sawtooth

B. with bandpass filters (CONSTRUCT and SHOW circuit of Fig. 4)
i) quartz crystal acts as a very high Q (narrow) bandpass filter, only allowing the frequency of 1 MHz to pass through

ii) but the function generator is set to only 200 kHz, so will anything pass through the filter to the oscilloscope?

III. Applications

1. music and sound

A. the harmonic content of a waveform, the waveshape, gives the musical tone its unique quality (illustrate using synthesizer, if available)

i) SETUP FOR ROLAND HS 60 SYNTHESIZER

(a) oscilloscope to 50 mV, 1 ms per division, x 1 probe, DC input coupling

(b) insert phone plug into mono output jack, connect to oscilloscope probe (black to ground, red to plus)

ii) how you can tell an organ playing a 500-Hz note from a flute playing the same exact note (SHOW examples on music synthesizer)

iii) called the "timbre"

iv) flute is nearly pure sine wave (select voice B31 (flute), set LFO to 0 to eliminate vibrato)

v) clarinet and woodwinds are more of a square wave (select voice A41 (bass clarinet), set LFO to 0)

vi) strings have sawtooth like wave (B71 (violin) with LFO set to 0)

vii) other examples (SHOW using actual musical instrument, if available, and microphone)

B. to generate ("synthesize") a musical tone, need to know the desired harmonic content

i) then, can start with a harmonic rich sound
ii) put it into filters to remove the unwanted harmonics

iii) or make "digital recording" of actual ("sampled") sound wave

2. communications (to be studied later under "modulation")

IV. MATERIALS

1. oscilloscope

2. AC signal generator

3. DMM

4. musical synthesizer and manuals, if available

5. PC and projector

6. CircuitMaker software

7. L.104.13.1A and sawtooth_wave_generator files on disk

8. 1 MHz quartz crystal (unknown #1)

9. frequency counter

10. spectrum analyzer

11. speaker

12. optional: musical instrument(s) and microphone

13. 10-k\(\Omega\) resistor

14. 250-\(\Omega\) resistor