Tu. 2/19: Ch 8 *Spectra and Electronic Synthesis* **Th. 2/21:** Ch 9 *Percussion Instruments*	HW6:Ch8: 1^w,2^w,3,5^w,6… Ch9: 3,10^w,18^w, 20,23,25^W	**Mon. 2/18** or **Tues. 2/19:** Lab 7 *Audio Spectra*

Equipment

- 4 speakers, 4 function generators
- Fourier ppt
- Graph paper for all
- Laptop and LabPro with differential voltage probe and microphone & Sound Spectrum setup
  - Set up as follows: Start with Sound Spectrum, then plug in differential voltage probe, unplug microphone, and switch over to display voltage probe's input and stretch to cover over FFT window (so we don't have to see it first)
- Fourier synthesis box
- O'scope plugged into computer with "Open choice" up
- guitar
- Recorder
- Little electric piano
- Symbol / pan lid
- LoadedString applet (or Fourier Series applet?)
- Clickers and receiver

Administration

- Exam
  - People generally did well – average of 85%
  - You'll see two grades inside the exam, one is what you got on the exam (in blue), the other is what you have in the course (in red).
- Topics
  - To everyone who's turned one in, thanks; I'll get back to you all on Thursday with the go-ahead or recommendations. To everyone who *hasn't* turned one in – do so before Spring Break or you're not doing a project.

Ch 8 Sound Spectra and Electronic Synthesis

Introduction

Thus far in this course we've given sinusoidal variations in air pressure, with frequencies between 20 Hz and 20,000 Hz, the place of honor, calling them "pure" tones, and whenever possible conceptualizing sound in terms of these. There are three justifications for this special treatment:

1) In as far as we can approximate all matter, and thus all natural sound sources, as springy (having an equilibrium position, a restoring force, and inertia), we can approximate their motions, and resulting motions of the air, as sinusoidal.
2) The workings of the ear are also springy so they respond sinusoidally to incident sound – we'll get to that after break.
3) *Even the most complicated sound can be rigorously mathematically described as a combination of simultaneous sinusoidal sounds.*

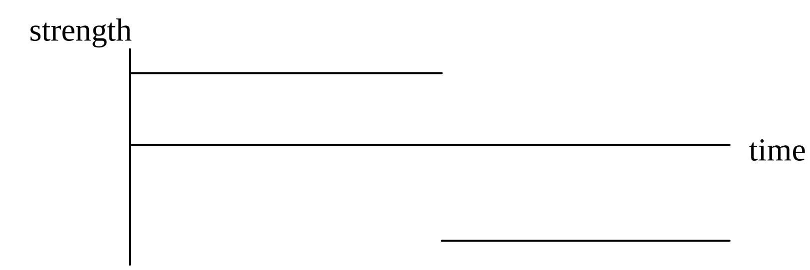
We've already investigated and made use of the springy-ness of sound sources. I've suggested the springy-ness of the ear, and later chapters will get more detailed on that topic. Today we'll mostly focus on the third point – that simple sinusoidal, i.e., 'pure', tones can be combined to produce complicated ones and, conversely, that a single complicated ones can be conceptualized as a combination of simple 'pure' tones.

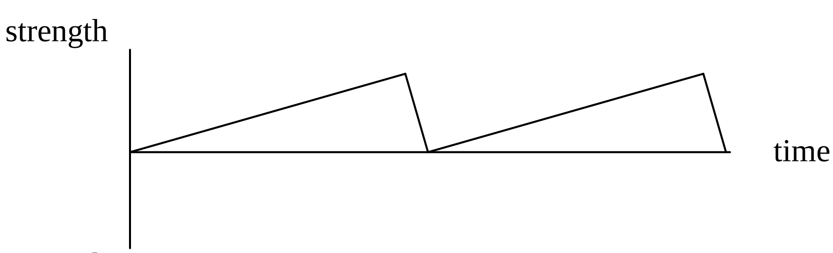
8.1 Steady tones

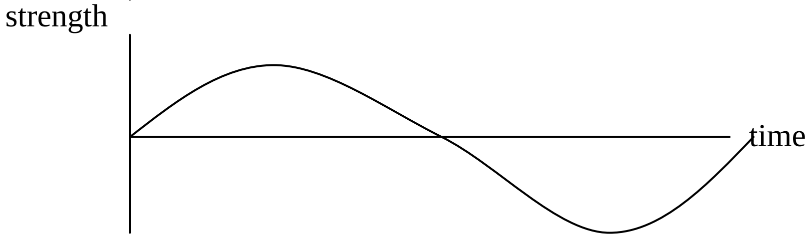
- Though mathematically *possible*, describing sounds as combinations of sine waves of sound wouldn't be terribly *desirable* without the second point above – that these are the building blocks of our sound perception. Thus, this description aids our understanding of the phenomena we perceive as sound.
- To validate our choice of sine waves as the basis set of sound, we'll start off with a 'blind taste test' of a few different periodic sounds. Let your ears judge the "simplest."

- **Demo:** without showing them the wave forms, drive a speaker with a saw-tooth, a square, and a sine wave. Have driver also hooked up to LabPro through Differential Voltage Probe.

- **Clicker Question:**
  - **Q:** Which sounds cleaner?
  - **A** (square wave)
  - **B** (saw tooth / positive ramp)
  - **C** (sine wave)
  - **Then show them the waveforms of what they heard.**
  - **A:** show them the waveforms on the oscilloscope. The sinusoidal sound wave is our choice.







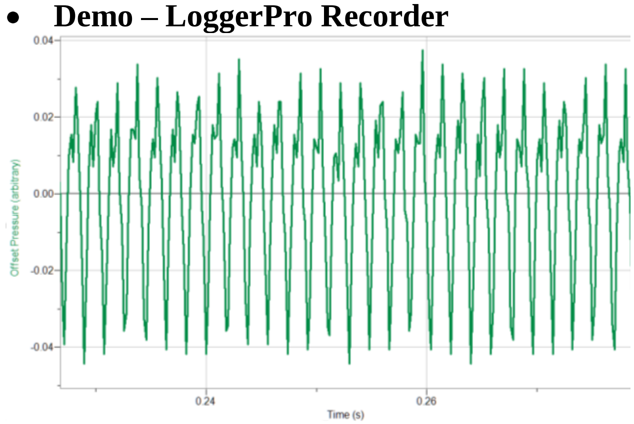
So, indeed, we perceive the sinusoidal tone as the simplest and in fact…

Demo: Use Loaded String app to produce sound with two very different frequencies at the same time,

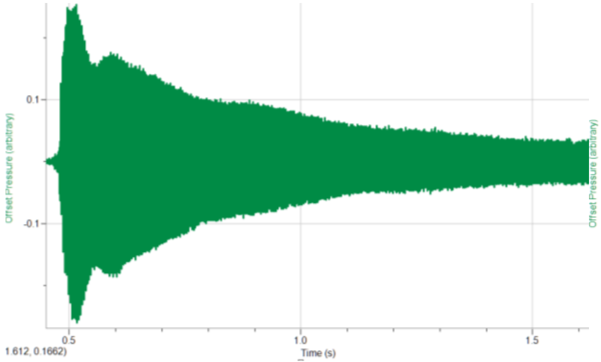
- Look within Loaded String to see each mode's contribution, and see it like high frequency / short wavelength ripples ridding on top of low-frequency / long-wavelengths ones.
- Listen with mic plugged into LoggerPro – see complicated pattern.

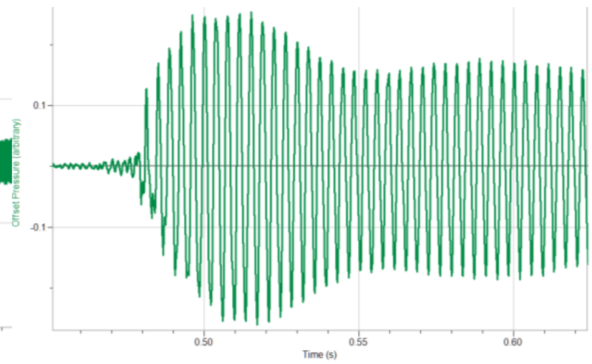
…we perceive complicated waveforms as sums of these simple ones.

- **Steady Tones**
  - There are two broad categories of complex sounds: **Steady tones** are those we perceive to remain constant through time. **Transient tones** are those we perceive to vary.
  - Relating this to a musical performance, musical sounds tend to be a mix of the two. You can break the performance of a note into three pieces:
    - the **attack**
    - the **sustain**
    - and the **release**.
  - During the attack, the sound is varying, coming into being, then the sound is sustained (fairly) steadily, and then released – varying again.
    - **Transitory Example – Symbol.** The sound of a percussive instrument like a cymbal is dominated by the transient pieces
      - **Demo – LoggerPro Symbol** (unplug voltage probe, plug in microphone, change Experiment/ Data Collection to 2 seconds and wait 1 second after "waiting for data…" before striking)
    - **Sustained Example – Recorder.** While the sound of a wind like a flute is dominated by the steady piece.
      - **Demo – LoggerPro Recorder**



    - **Mixed Example – plucked string.** The sound of a plucked string is somewhere in between.
      - **Demo – Logger Pro guitar**





- We will see in a moment that these two types of sounds are described by two fundamentally different combinations of pure tones.

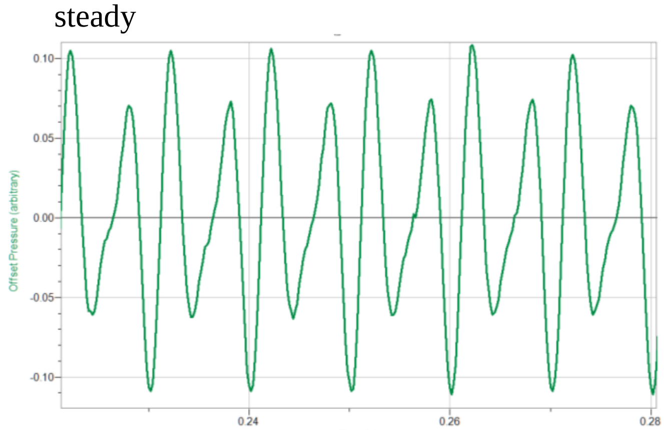
8.2 Periodic Waves and Fourier Spectra

Demo: play Examples of some Steady Tones: Square wave and Saw tooth tone

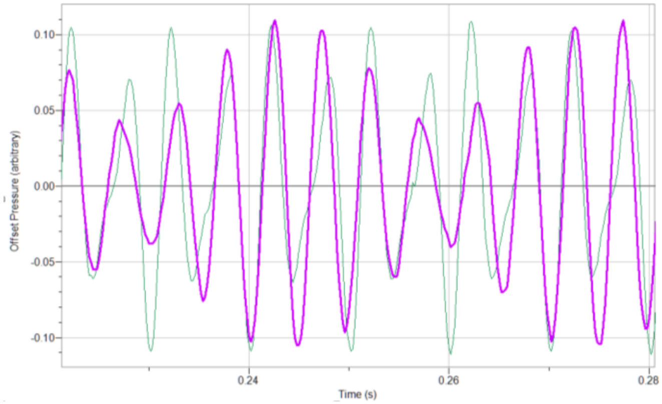
- **Complex Steady Tones**
  - Though not 'pure', both of these are steady tones. From one second to the next, they sound *exactly* the same. If I just left this going, you could get up, go get a drink, come back and it would sound *exactly* the same. So, the character which we perceive does not change.
- **Condition for being a Steady tone**
  - **Pure Tone:** Still, we've come to understand that what we perceive as sound is itself a process of change – the air repeatedly pushes on and then draws back from our eardrum. Only if this happens *periodically* do we perceive this as steady. More specifically, if the variations are 20 times a second or more, we perceive them as a pitch.
  - **Complex:** Complex tones must satisfy the same requirement of periodicity to qualify as steady. A complex tone must have a pitch, an overall frequency. This imposes a very strict constraint on the constituents. They must align periodically.

Demo: Two function generators driving two speakers, see source waves on scope.

- With a common fundamental (200, & 300Hz) – steady



- Without a common fundamental (200, 233) – unsteady

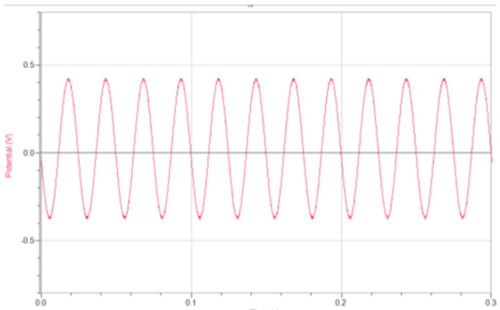


- Flip between seeing constituents and seeing sum.

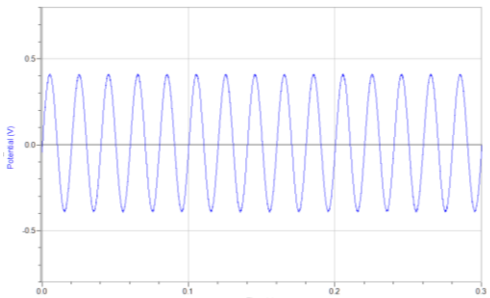
- Watching the signals on LoggerPro, the steadiest tone occurred for the two waves that periodically are in synch. At even intervals in time, they are both maximized or both minimized.

Example: 40Hz & 50Hz

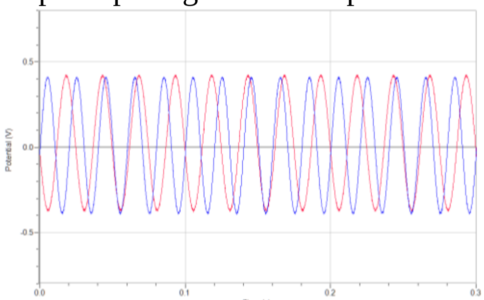
Say we have a 40Hz sound wave coming from one speaker, it repeats itself once every 0.25s.



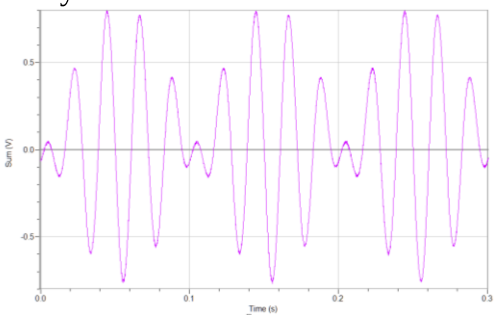
And a 50 Hz sound wave coming from the other speaker, it repeats itself once every 0.02s:



Superimposing those on top of each other, you can see that they synch up once every 0.1s:



If we put a microphone equidistant between the two speakers, the air pressure would vary in a sort of complicated way that repeats itself everytime the two sources synch up – once every 0.1 s:



In other words, the complex tone built of the two pure tones has a frequency of 10Hz.
In general: *a comlex tone's frequency is the greatest common denominator of all the pure tones that it's built of.*

Example

- Similarly, 500 Hz, 400 Hz, the combination repeats at 100 Hz.

- **Q:** Do you recognize the relation of these three frequencies?
  - **A:** They're members of the same *harmonic series*.
- **Condition for being a steady tone:** A combination of members of a harmonic series produces a steady tone with an over-all frequency of the series' fundamental.

- **Q:** Where did we see harmonic series' before?
  - **A:** The family of vibrations that can be supported on a string, or in a tube of air, on that demo I *keep* bringing in with all the little bars … A simple harmonic oscillating system can support a harmonic series of frequencies. In practice, when you pluck a string, or blow on an organ pipe, each member of the series *is* produced simultaneously. So, in practice, most any natural sound is (approximately) a complex tone composed of a harmonic series of pure tones.

- **Transient Tones:** On the other hand, 5.6346… Hz and 4.32455 Hz together, never repeat perfectly, but they *almost* do, the mind tries to pick out a pattern, and looses it, picks it, looses it.. working over time, very distracting and unsettling. That's why
- **Demo: 400 Hz and 200Hz** is okay but
- **Demo: 400 Hz and 217.123Hz** gets to be annoying

- Let's run an example in a little more detail so we can see the specific tools for solving it.

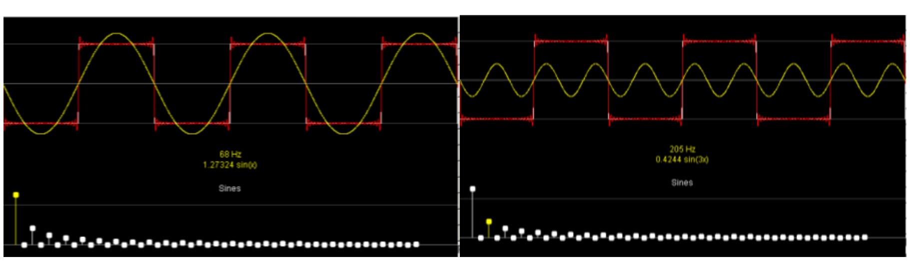
(next page)

Example: Say we simultaneously play a 440 Hz tone and a 330 Hz tone. With what frequency does the complex tone repeat?

- **Given**
  - $f_a = 440\ Hz$
  - $f_b = 330\ Hz$
- **Relations**
  - $f_a = \frac{n_{a.cycles}}{time} = n_a f_1, \quad f_b = \frac{n_{b.cycles}}{time} = n_b f_1,$
- Mathematically, f_1 is the greatest common denominator of the two frequencies. This is the larges number that can be multiplied by an integer to get f_a and by another integer to get f_b. If we knew the integers, we could then divide f_a or f_b by them to recover f_1.
- Often, the greatest common denominator jumps out at you, but if it doesn't, we can find the integers by dividing f_a by f_b and reducing to the ratio of the smallest integers:
- Mathematically,
  - $f_a = n_a f_1, \quad f_b = n_b f_1$
  - $\boxed{\frac{f_a}{f_b} = \frac{n_a f_1}{n_b f_1} = \frac{n_a}{n_b}}$
- For this example,
  - $\frac{f_a}{f_b} = \frac{440\ Hz}{330\ Hz} = \frac{4}{3} = \frac{n_a}{n_b}$
  - $\boxed{f_1 = \frac{f_a}{n_a}} = \frac{440\ Hz}{4} = 110\ Hz$

- **Vocab:** Since $fa = 4*f_1$, f_a is called the "fourth harmonic" of f_1. Which harmonic is f_b of f_1?

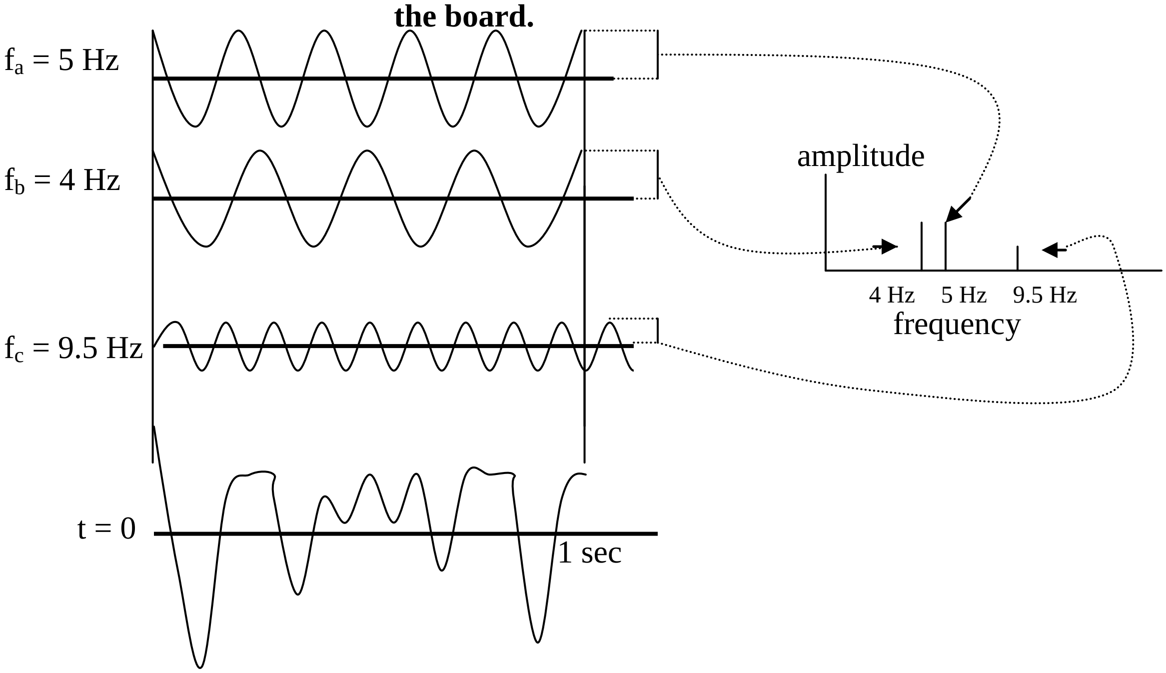
- **Building Complex Waves**
  - **Fourier**
    - A mathematician named Fourier proved that if you had every member of a harmonic series at your disposal, you could build *any* defined, repeating function you wanted.
    - If you expand your vocabulary to pure tones *not* in a harmonic series, then you could even draw non-repeating functions.
    - That means we could draw all sorts of pictures by adding sine waves.
      - **Demo: falstad's Fourier Series applet,** square wave (turn on sound.)



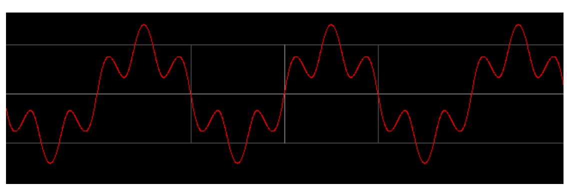
- **Acoustically**,
  - *any steady tone* can be resolved into components, all members of a *harmonic Series.*
  - *Any transitory tone* can be resolved into components, including *at least some* that are *not* members if the same series.

- **Example:** Say you have a complex, steady, sound that repeats every 2ms. What is the family of frequencies?
  - Fundamental frequency = 1/(2ms) = 500 Hz,
  - Family = f_n = n * 500 Hz

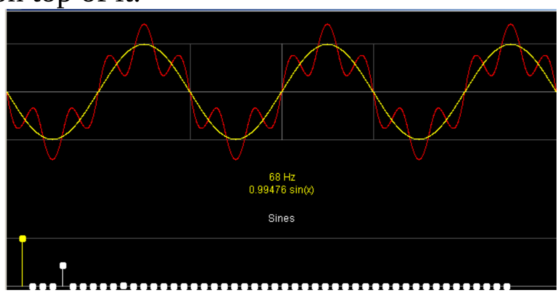
- **Fourier Spectrum**
  - We'd like to apply this tool to describing musical sounds. But you can imagine that looking at a plot of the complex sound wave can be rather, well, complex. It proves simpler to make a separate plot. Showing the relative strengths of the different constituent pure tones. This plot is known as the *Spectrum* of the sound.
  - **Example: Plot strength vs. frequency for the 3 sine waves on the board.**



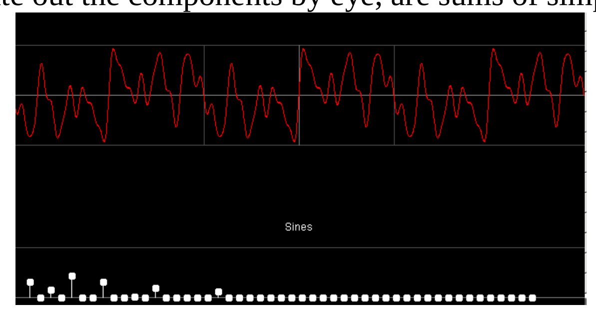
- **Recipe**
  - One way of looking at the Fourier Spectrum is as a recipe for building back up a sound.
- **Demo: Fourier Series app. –** Large 1st with a smaller 5th harmonic ridding on it



- Fourier's big idea, and one that's particularly useful for us studying sound production and perception, is that a complex oscillation can be considered the superposition of simple, sinusoidal ones.
- The simulated oscillations we see here look kind of complicated, but, (highlight the 4th so it shows as a yellow line), maybe you can see that it's really this simple large oscillation with this smaller ripple on top of it.



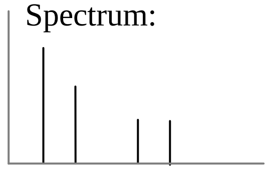
- Even the most complicated of wave forms, even when we can't separate out the components by eye, are sums of simple ones.



- Let's have a little fun and build up a complex wave.

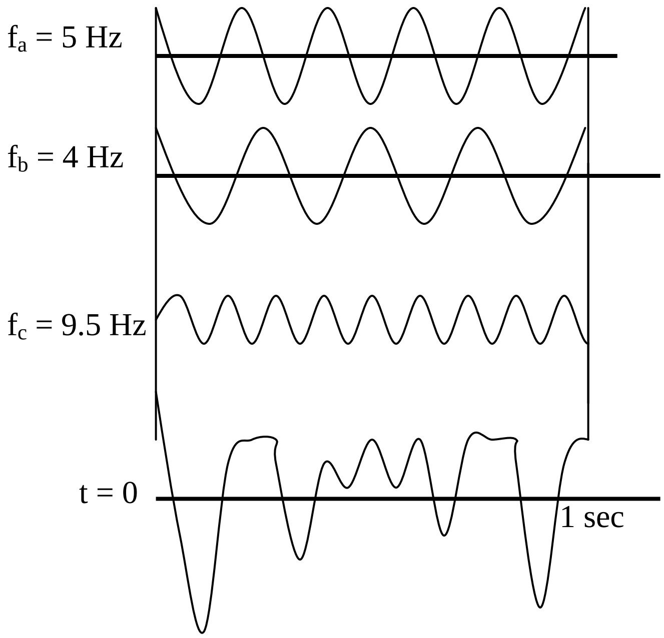
- **Demo: Fourier Synthesis App**
  - Add one, and then another frequency, each of the same family.
  - **Fourier Synthesis ppt**

- **Worksheet** – they do something similar (hand out graph paper)
  - Try your hand at it. Say there's a fundamental with amplitude, on the scale of the graph paper, 4 squares (so 8 squares top to bottom), a second harmonic with 3-square amplitude, a fourth harmonic that's 2 squares and a fifth harmonic that's 2 squares.
  - Spectrum:



  - Now, if the period of the fundamental, on the scale of the page, is 20 squares wide, then, draw each
  - Finally, add them together to see what the composite wave form looks like.

- **Example: For the first 3, add them on the board**



- By varying the relative strengths and phases of the first 9 members of a series, I can build almost any repeated shape I want!
- **Demo: Look at Fig 8.7 on page 137.** Build a Flute sound.

Sections 8.3 and 8.4. We'll not get much into these, but they may be of interest to anyone thinking of presenting on the human voice / singing or synthesizers.

Add material about 8.3: Modulated tones - Labrato, Vibrato, Synthesis – Fig 8.11 ?