An Introduction to Real-time Digital Signal Processing through Parallelism

Sherwyn Sen
CS 159

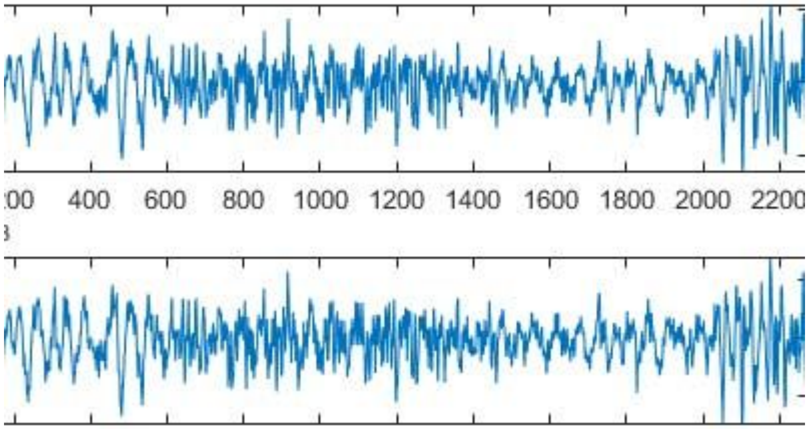
DISCLAIMER

The code I will show in the presentation is not the actual code. It is simplified for the sake of explanation.

REAL CODE (feel free to look at this during the presentation)
https://github.com/ika-musuko/parallelizing-dsp/tree/master/wave_analyzer

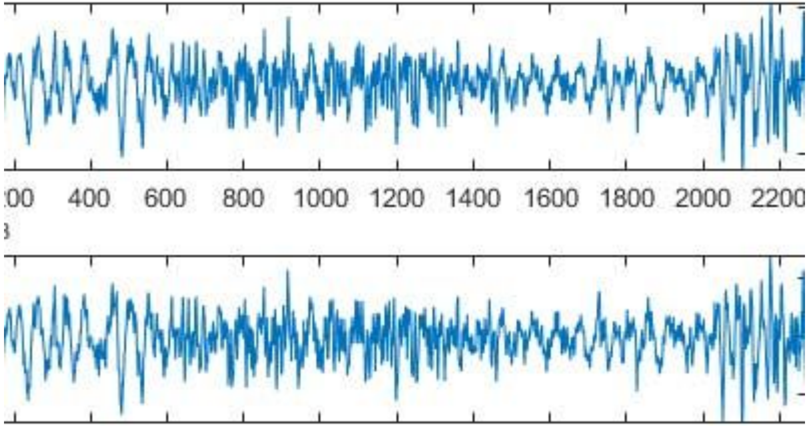
What is Digital Signal Processing?

- Take a signal and modify it
- Signals
  - Motion
  - Sound
  - Image Data



What is Digital Signal Processing?

- Take a signal and modify it
- Signals
  - Motion
  - Sound
    - Easiest to explain
  - Image Data



How Signals Get Processed By Computers

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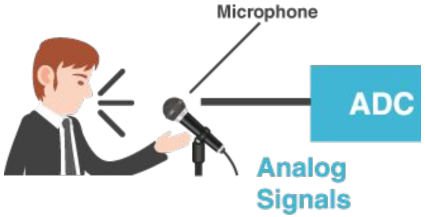
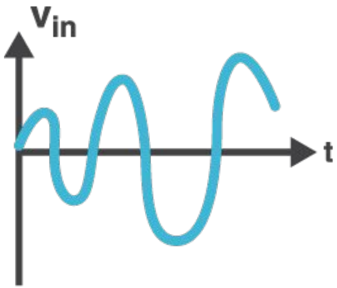
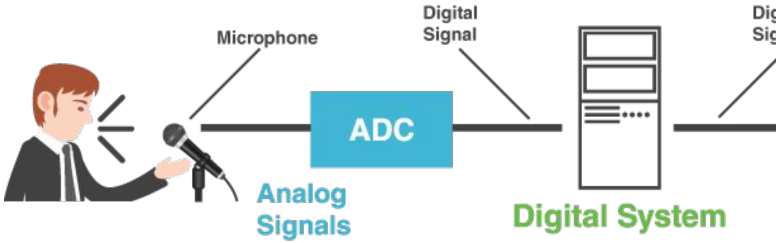
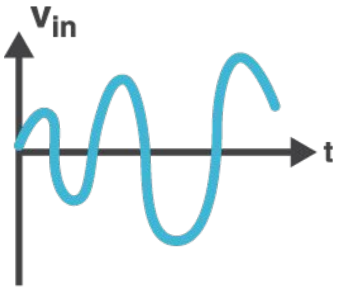
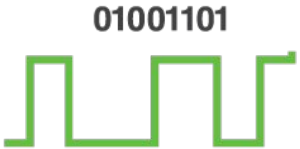




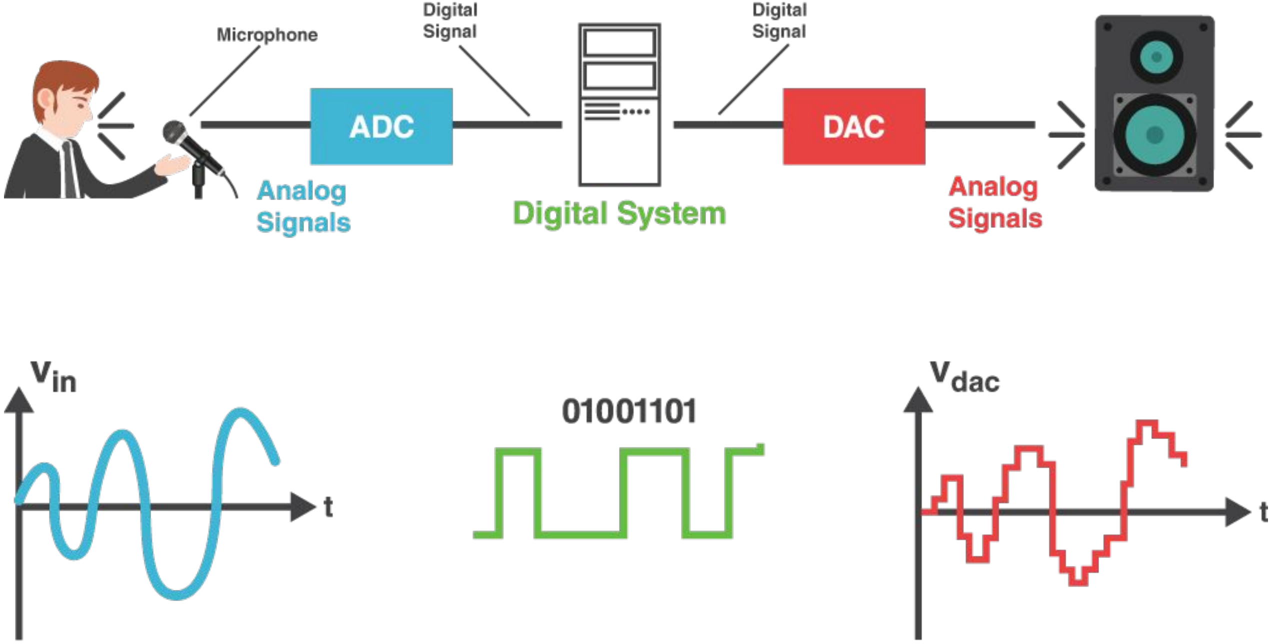
How Signals Get Processed By Computers





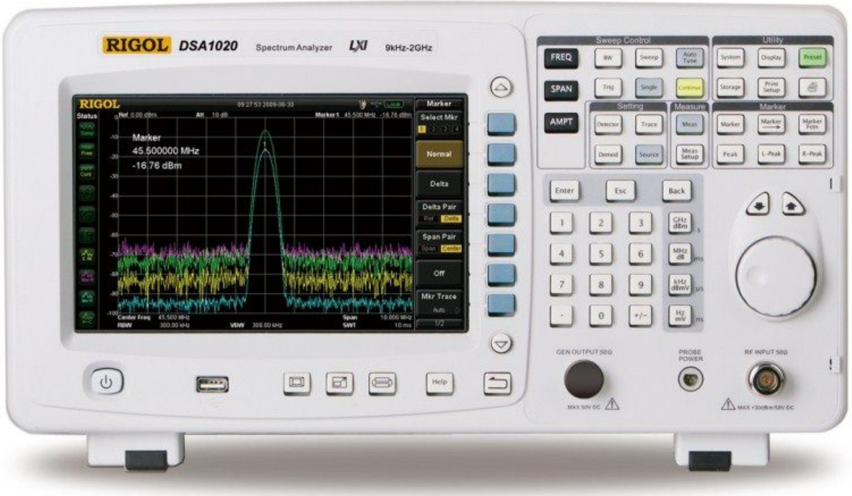


How Signals Get Processed By Computers



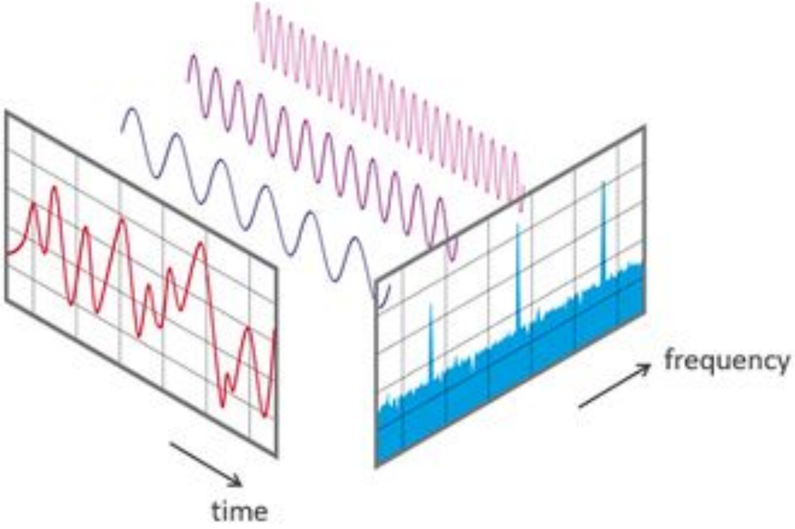
How are we going to Parallelize DSP?

- Let’s make a spectrum analyzer! (in software)



What is a Spectrum Analyzer?

- Measures magnitude of an input signal based on its frequencies



How does a Spectrum Analyzer work?

- Fourier Transform

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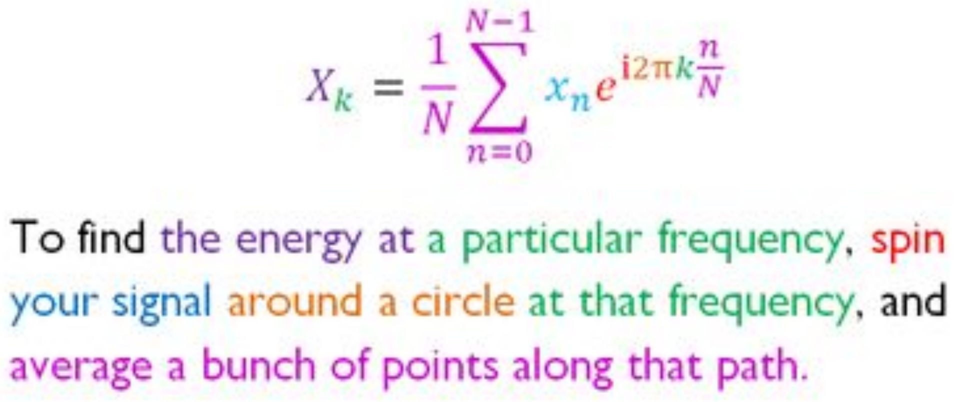
- Fourier Transform

$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n e^{\mathrm{i}2\pi k\frac{n}{N}}$$

How does a Spectrum Analyzer work?

- Fourier Transform



$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n e^{i2\pi k\frac{n}{N}}$$

To find the energy at a particular frequency, spin your signal around a circle at that frequency, and average a bunch of points along that path.

How does a Spectrum Analyzer work?

- Fourier Transform

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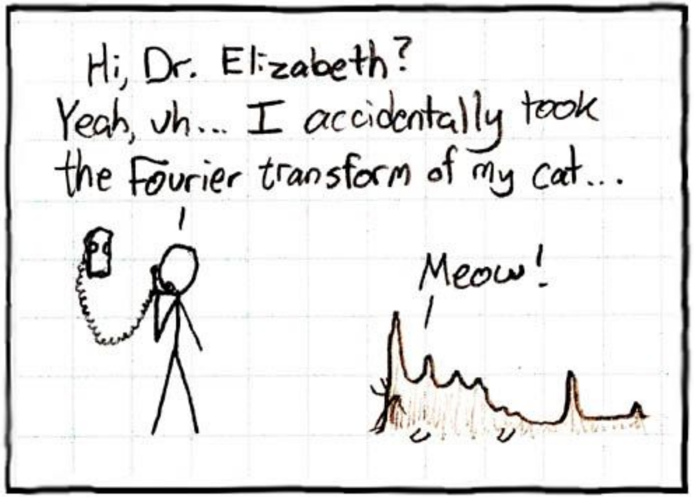
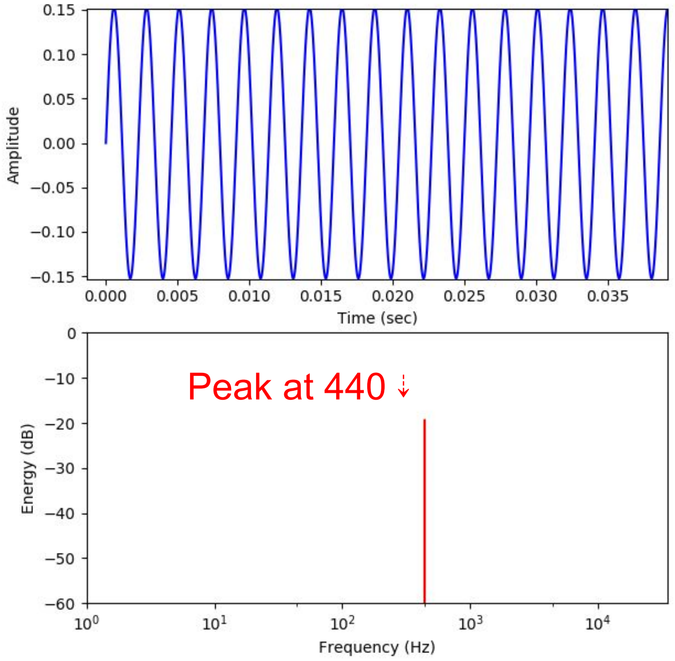
For a more in-depth explanation of the Fourier Transform, consult But what is the Fourier Transform? A visual introduction *by 3blue1brown*


Hi, Dr. Elizabeth?
Yeah, uh... I accidentally took the Fourier transform of my cat...
Meow!

Basic Spectrum Analysis (not real time)

“Result of the Fourier Transform”

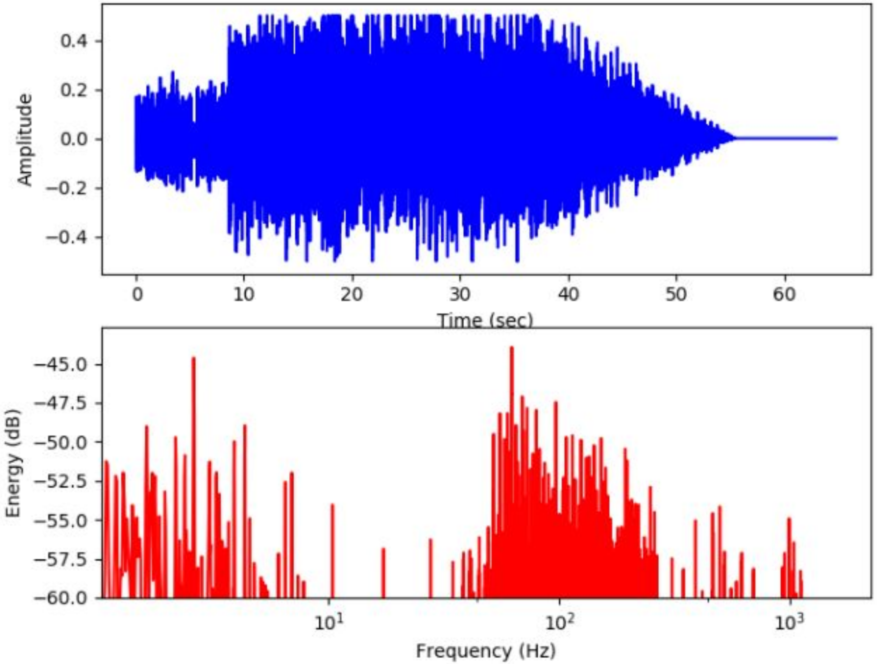
440 Hz Sine Wave



Peak at 440 ⇣

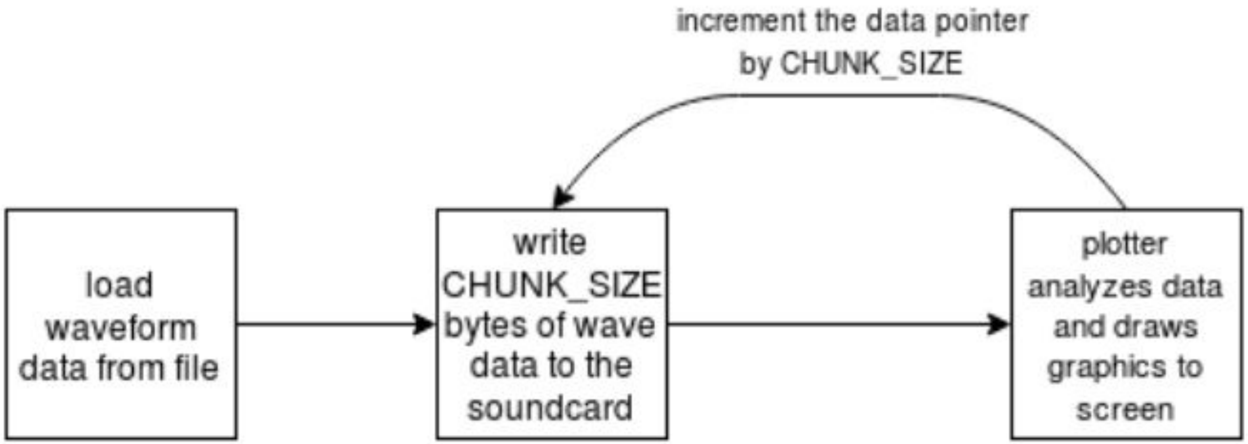
fft_plotter.py

Basic Spectrum Analysis (not real time)



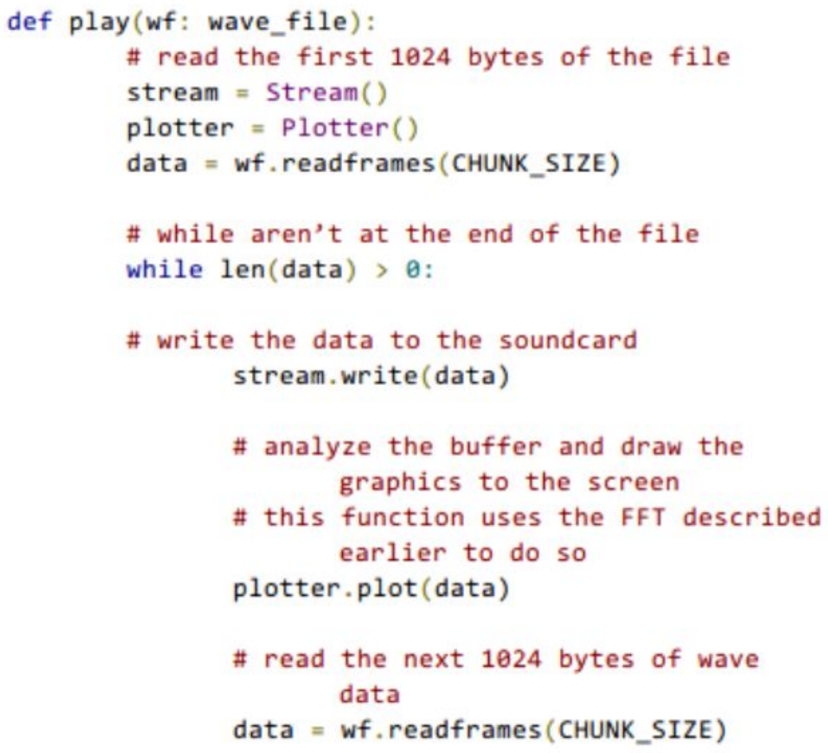
fft_plotter.py

Simple approach to attempt real-time analysis



increment the data pointer by CHUNK_SIZE
load waveform data from file
write CHUNK_SIZE bytes of wave data to the soundcard
plotter analyzes data and draws graphics to screen

Simple approach to attempt real-time analysis



```
def play(wf: wave_file):
        # read the first 1024 bytes of the file
        stream = Stream()
        plotter = Plotter()
        data = wf.readframes(CHUNK_SIZE)

        # while aren't at the end of the file
        while len(data) > 0:

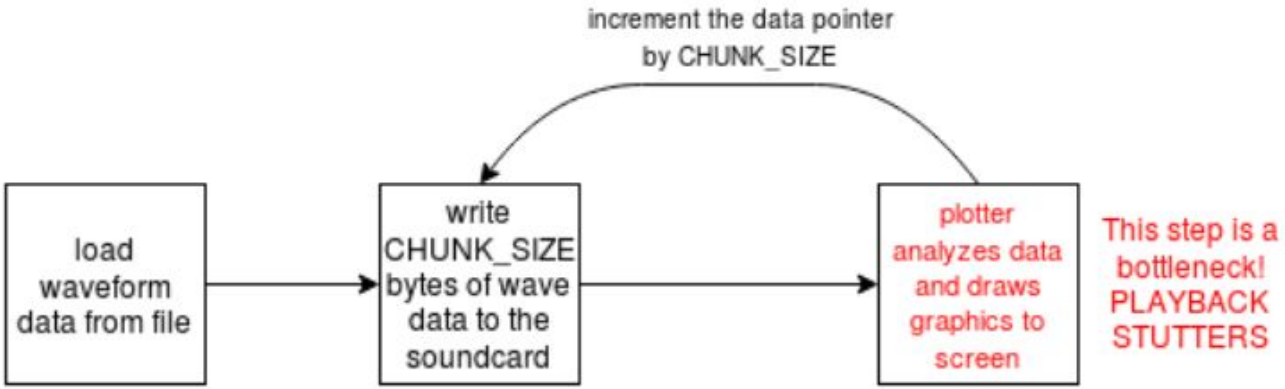
        # write the data to the soundcard
                stream.write(data)

                # analyze the buffer and draw the
                        graphics to the screen
                # this function uses the FFT described
                        earlier to do so
                plotter.plot(data)

                # read the next 1024 bytes of wave
                        data
                data = wf.readframes(CHUNK_SIZE)
```

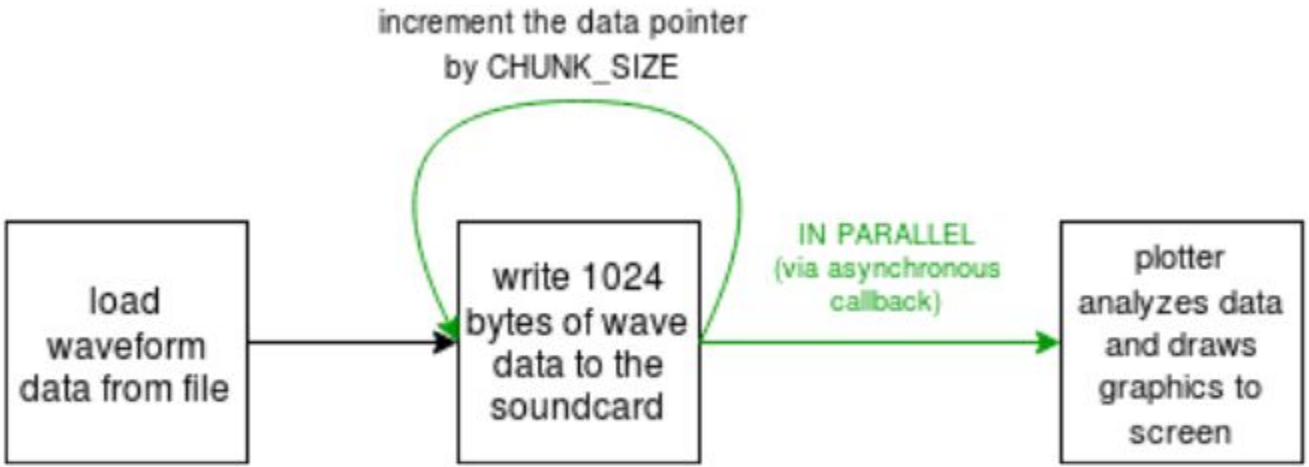
okay! let’s try it...

What happened???


increment the data pointer by CHUNK_SIZE
load waveform data from file
write CHUNK_SIZE bytes of wave data to the soundcard
plotter analyzes data and draws graphics to screen
This step is a bottleneck! PLAYBACK STUTTERS

bad_analyzer.py

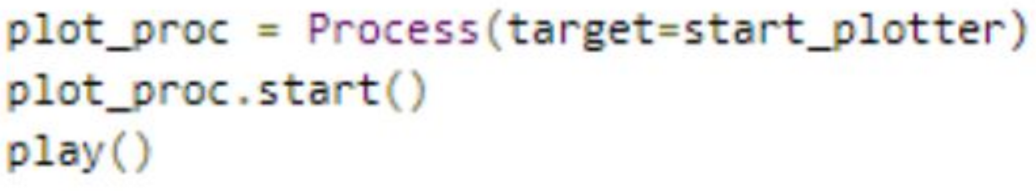
Basic Parallel Analysis - Strategy


increment the data pointer
by CHUNK_SIZE
load waveform data from file
write 1024 bytes of wave data to the soundcard
IN PARALLEL
(via asynchronous callback)
plotter analyzes data and draws graphics to screen

better_analyzer.py

Basic Parallel Analysis - Strategy

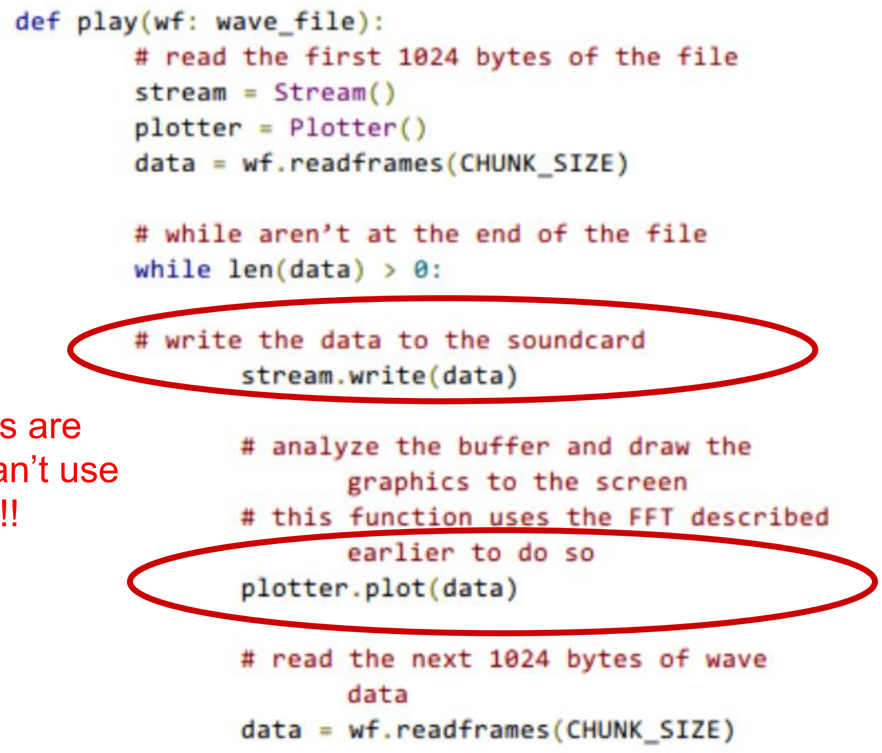
Splitting the player and plotter into processes



```
plot_proc = Process(target=start_plotter)
plot_proc.start()
play()
```

better_analyzer.py

Basic Parallel Analysis Strategy - Problems



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               plotter.plot(data)

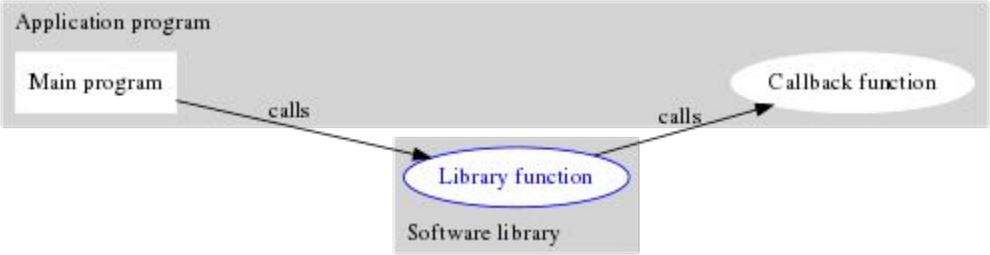
               # read the next 1024 bytes of wave
                      data
               data = wf.readframes(CHUNK_SIZE)
```

!!! These functions are blocking I/O !!! Can't use with parallelism !!!!

bad_analyzer.py

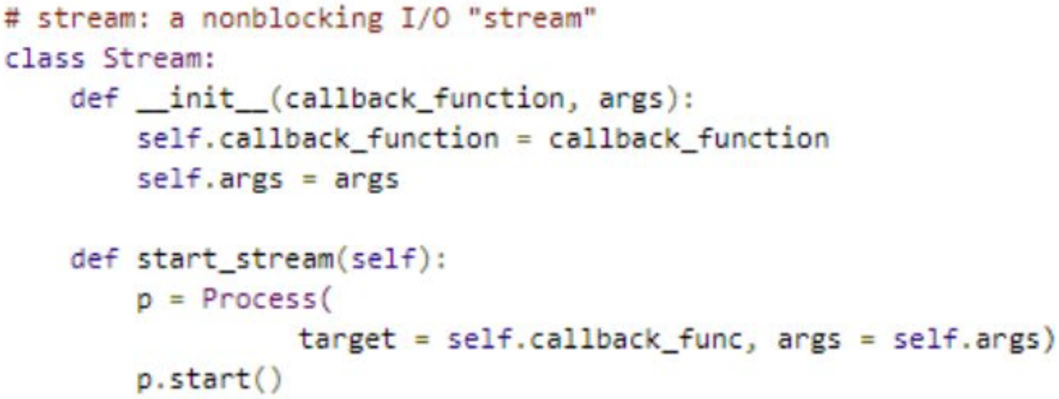
The Solution? Asynchronous Callback Functions

- Callback functions
  - Functions passed to another function or object
  - Called when some sort of event happens
  - Asynchronous callbacks done in parallel using threads/processes
  - Well known examples: Javascript `setTimeout/setInterval`



The Solution? Asynchronous Callback Functions

- “Stream” example



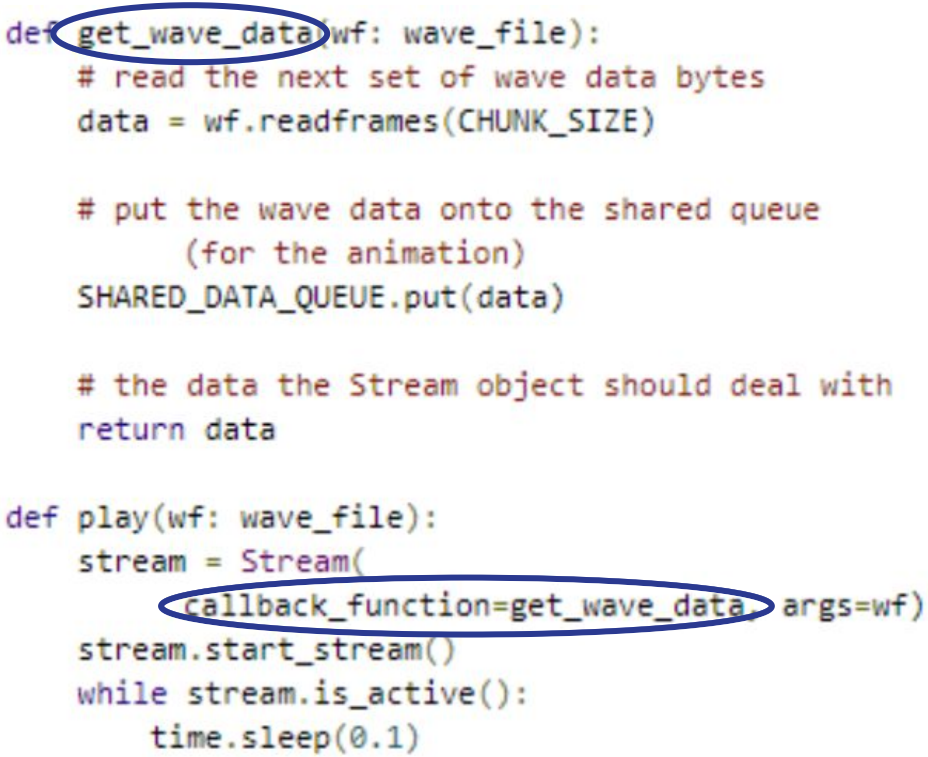
```
# stream: a nonblocking I/O "stream"
class Stream:
    def __init__(callback_function, args):
        self.callback_function = callback_function
        self.args = args

    def start_stream(self):
        p = Process(
                  target = self.callback_func, args = self.args)
        p.start()
```

for audio stream example, see PortAudio’s `portaudio_startstream.c`

The Solution? Asynchronous Callback Functions

audio playback



```
def get_wave_data(wf: wave_file):
    # read the next set of wave data bytes
    data = wf.readframes(CHUNK_SIZE)

    # put the wave data onto the shared queue
          (for the animation)
    SHARED_DATA_QUEUE.put(data)

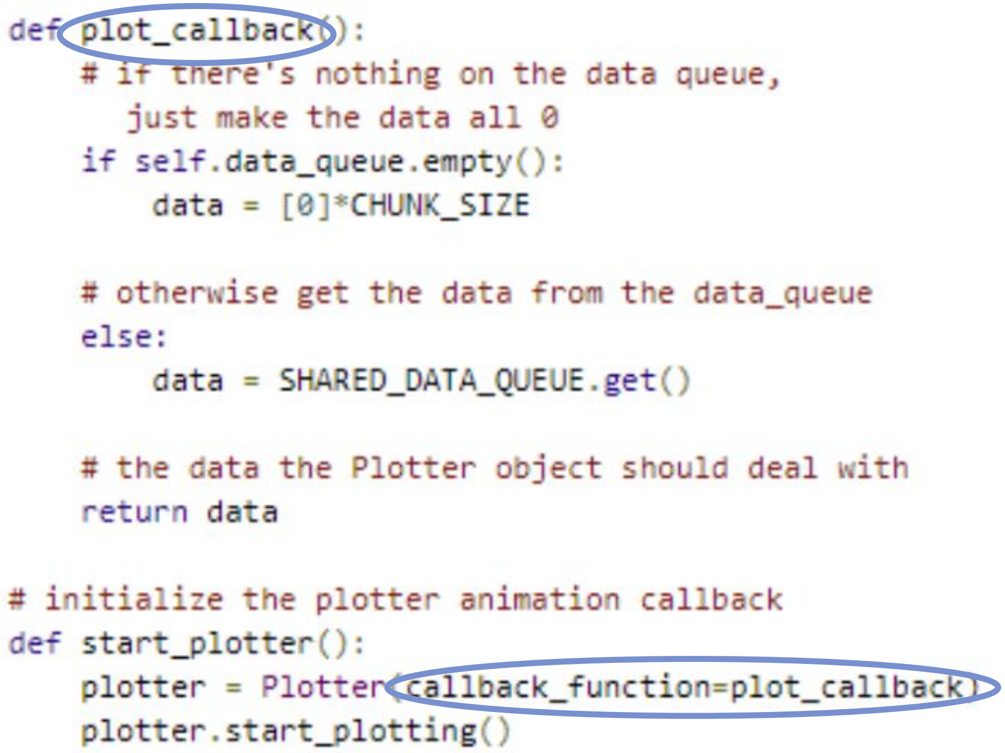
    # the data the Stream object should deal with
    return data

def play(wf: wave_file):
    stream = Stream(
          callback_function=get_wave_data, args=wf)
    stream.start_stream()
    while stream.is_active():
        time.sleep(0.1)
```

better_analyzer.py

The Solution? Asynchronous Callback Functions

plotting on the graph



```
def plot_callback():
    # if there's nothing on the data queue,
      just make the data all 0
    if self.data_queue.empty():
        data = [0]*CHUNK_SIZE

    # otherwise get the data from the data_queue
    else:
        data = SHARED_DATA_QUEUE.get()

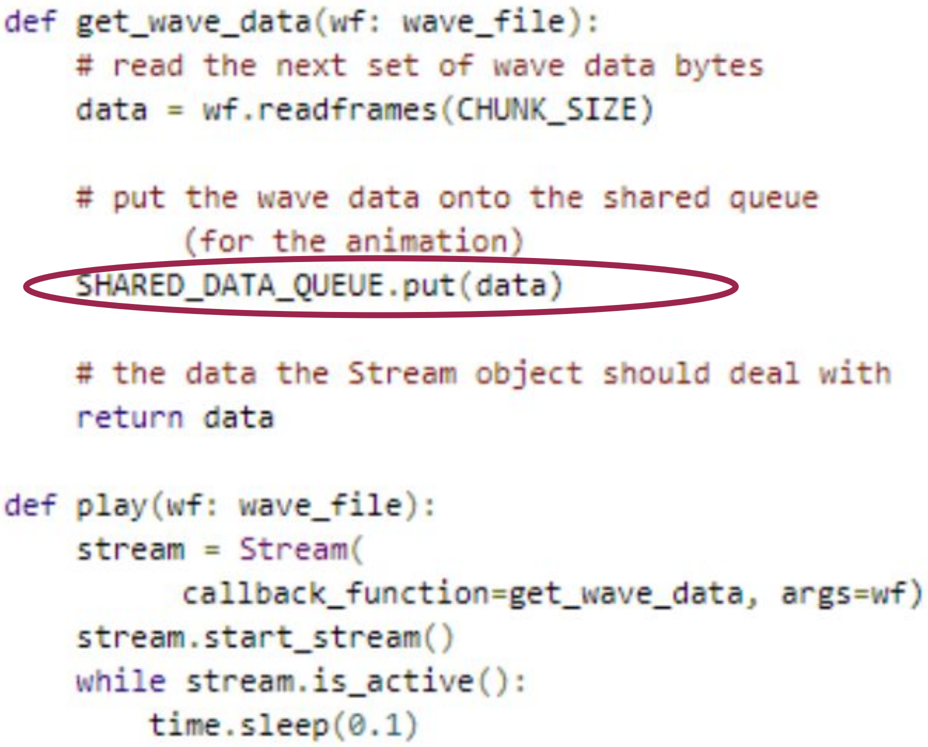
    # the data the Plotter object should deal with
    return data

# initialize the plotter animation callback
def start_plotter():
    plotter = Plotter(callback_function=plot_callback)
    plotter.start_plotting()
```

better_analyzer.py

Shared Data Queue - Audio Playback Side

audio playback



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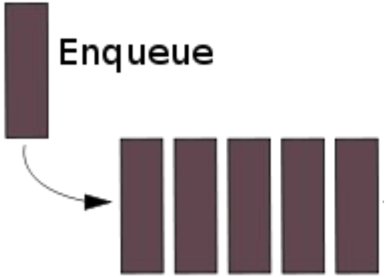
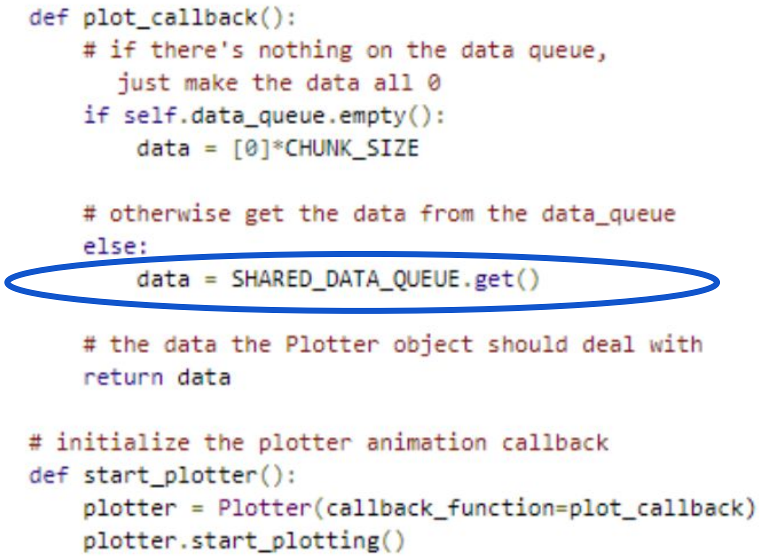


PUT audio data chunks onto the queue before playing them

better_analyzer.py

Shared Data Queue - Graph Plotting Side

plotting on the graph



```
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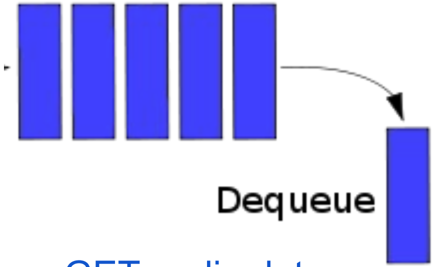
    # otherwise get the data from the data_queue
    else:
        data = SHARED_DATA_QUEUE.get()

    # the data the Plotter object should deal with
    return data

# initialize the plotter animation callback
def start_plotter():
    plotter = Plotter(callback_function=plot_callback)
    plotter.start_plotting()
```



GET audio data chunks from the queue and graph them

better_analyzer.py

QUESTION

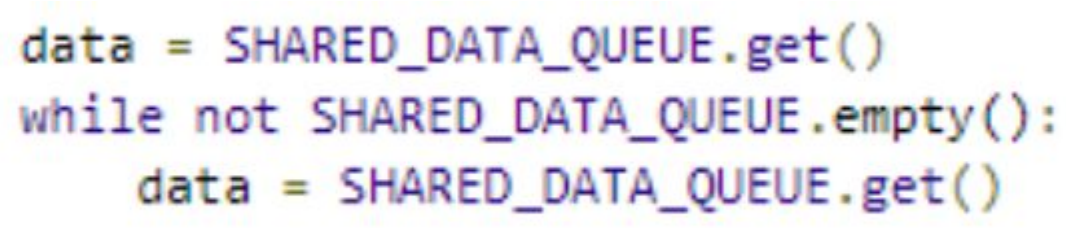
Why not just use a shared data variable between the two processes?

ROUND 2

Almost there...What's the problem?

- The chunk producing audio player is much faster than the chunk consuming graph plotter
- Cause of the LAG!!

Solution: Queue Eating



```
data = SHARED_DATA_QUEUE.get()
while not SHARED_DATA_QUEUE.empty():
    data = SHARED_DATA_QUEUE.get()
```

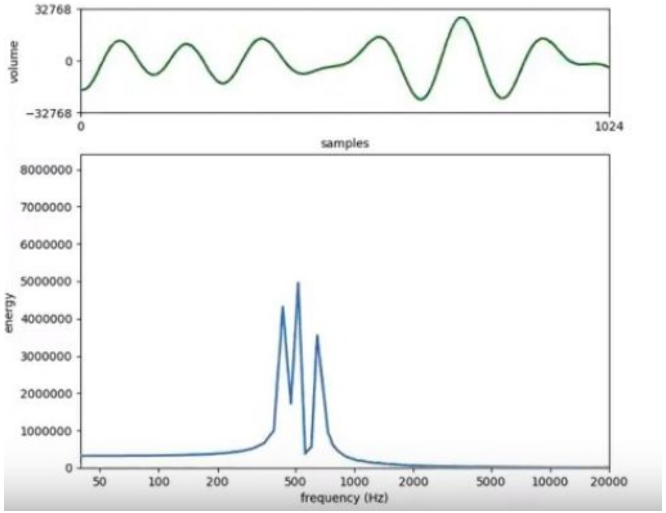
- Plotter pops off all of the items in the queue (“eats” the items)
    - Relatively fast operation compared to processing the chunk
- Only processes the last data chunk on the queue
- *The screen needs to show “now”, not 20 chunks ago!*

wave_analyzer.py

WILL THIS WORK?

Conclusion

- Took a basic digital signal processing routine
- Identified the bottleneck
- Partitioned the tasks
- Parallelized the partitioned tasks



What can be done from here?

- Use multiple wave analyzers, each with their own inputs to create a simple mixer
  - The “master” channel could have its own analyzer as well
- Create an interface for applying effects to the audio in real time
  - Filters
  - Delays
  - Reverb
- Possibilities are endless