Problem Set 8: Synthesizer I

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- A zip archive named as
  `PS08_<your name as Last_First>.zip`
  containing the C code files that implements all aspects of all problems.

Total points: 100

Points are awarded as follows:

- 15 Points – Complete `paCallback()` in main.c
- 15 Points – Complete `init_key()` in synth.c
- 40 Points – Complete `synth_block()` in synth.c
- 10 Points – Submit waveform showing one note from onset to "drop out"
- 20 Points – Clear code, sensible formatting, good comments

References

The following URL provides a good reference for C language library function usage:
http://www.cplusplus.com/reference/cstdlib/

portAudio reference
http://www.portaudio.com/

libsndfile reference
http://www.mega-nerd.com/libsndfile/api.html/

Problem Overview

In this assignment you will create a simple 3-octave keyboard synthesizer, where the synthesizer keyboard is the computer keyboard. Each key is associated with a note to play, and each note is the fundamental frequency of that note (that is, there are no harmonics). Multiple notes can be played simultaneously.

The tone samples are computed as

```
v = sin(phase);
```

For each new sample of an output channel, the phase is incremented according to the frequency of the tone. The increment for a frequency f0 is

```
phase_inc = 2*PI*f0/samping_rate;
```

If f0 is 1 Hz, then after sampling_rate audio samples, the phase will have run from 0 to 2*PI, or one complete cycle. If f0 is 2 Hz, then 2 complete cycles.

In addition, the synthesized tone has an exponential attack so there is no "click" at tone onset and slower exponential decay so the tone "fades away" after the key is pressed.

Each segment of the assignment creates a portion of the synthesizer or adds additional functionality to the synthesizer. You need to add code where you see the comment

```
//Your code here
```

You are given the complete code of the following files:

```
synth.h
freq.h
key_tables.c
key_tables.h
paUtils.c
paUtils.h
build.h
```

You are given portions of the code for the following files, and your assignment is to add to the code in these files, as described below:

```
main.c
synth.c
```

Code Overview

main.c

There are no command line arguments for this program, so main.c does not have code to parse the command line or print a Usage statement.

An instance to the Synth struct is defined at the top of main(), and a pointer to the instance:

```
Synth synth, *ps = &synth;
```

Struct Synth, and also struct Tone are declared in synth.h. An array of struct Tone is in the struct Synth.

Next in main() is that the table key2index[] is initialized (in file key_tables.c).

```
/* initialize tables */
init_key2index();
```

This provides a mapping from your laptop keys to synthesizer tone frequencies.

Next is initialization of the values in the Synth struct. The definition of `init_synth()` is in synth.c.

```
/* initialize Synth */
init_synth(ps, NUM_CHAN, SAMP_RATE);
```

Next is that the pointer to the Synth struct is copies to the buf struct, which is the PortAudio callback structure.

```
/* initialize struct for callback */
buf.ps = ps;
```

Next the code starts PortAudio and then starts Ncurses and waits for user key input. Ncurses prints:

```
Welcome to my synthesizer!
```

```
Keyboard to piano key mapping is:
qwertyQWERTY -> C3 to B3
asdfghASDFGH -> C4 to B4
zxcvbnZXCVBN -> C5 to B5
'.' to stop playing oldest tone
SpaceBar to quit

Key:
```

If the user hits SpaceBar, then Ncurses exits its loop, PortAudio exits and the program exits.

Key_table.c

This code does is complete as is. It implements the following functions:

```
bool valid_key(int key);
```

This function returns `false` if the key pressed in the Ncurses loop is not associated with a note.

```
double key2freq(int key);
```

This function maps a valid key to a tone frequency to synthesize.

```
void init_key2index(void);
```

This function initializes the key2freq table, which is used in the `key2index()` function.

Synth.c

```
void init_synth(Synth *ps, int num_chan, int samp_rate);
```

This function converts initializes the Synth and Tone structures.

```
void execute_cmd(Synth *ps, int cmd);
```

This function converts a command (cmd) to calls to the appropriate functions.

```
double *synth_block(Synth *ps, int len);
```

You will complete this function. It is described below.

```
void add_key(Synth *ps, int new_key, double new_freq);
```

This function adds key information to the array of Synth struct that are the keys that are being voiced by your synthesizer.

```
void rm_key(Synth *ps);
```

This function removes key information from the array of Synth struct that are the keys that are being voiced by your synthesizer.

```
void shift_keys(Synth *p);
```

This function shifts the information in the Synth array down by one place.

```
void init_key(Synth *ps, int new_key, double new_freq);
```

This function writes information for a new key into the highest available position in the Synth array.

Your Assignment

You must add code to two files: main.c and synth.c. The specifics are described below.

main.c

(15 Points) paCallback()

In function

```
static int paCallback(
    const void *inputBuffer,
    void *outputBuffer,
    unsigned long framesPerBuffer,
    const PaStreamCallbackTimeInfo* timeInfo,
    PaStreamCallbackFlags statusFlags,
    void *userData)
```

Add code that declares

```
double *syn_buf;
```

and then assigns to this pointer a block synthesized by a call to `synth_block()`, which is located in the file synth.c, as shown here:

```
syn_buf = synth_block(ps, framesPerBuffer);
```

This is buffer of framesPerBuffer mono audio samples, and must be written to the callback output buffer in interleaved form. That is, inside a loop of framesPerBuffer audio frames, write the Left and Right values to the callback output buffer for each audio frame.

synth.c

(15 Points) init_key()

In function

```
void init_key(Synth *ps, int new_key, double new_freq)
```

Set the following values in Synth to

```
f0 = new_freq;
fs = ps->samp_rate;
```

Initialize the values of the `Tone` array at index (`new_key-1`) to the values given below:

```
key = new_key; //from input argument
f0 = new_freq; //from input argument
phase_inc = 2*PI*f0/fs;
```

phase = 0.0;
attack_factor = ATTACK_FACTOR;
decay_factor = DECAY_FACTOR;
attack_amp = 1.0;
decay_amp = 1.0;

(40 Points) synth_block()

25 Points – basic synthesizer

In function

```
double *synth_block(Synth *ps, int framesPerBuffer)
```

Add code to synthesize the tones whose information is in the valid array elements of Synth. This is the main part of the assignment.

Check for cmd

As the first block of code in the `synth_block()` function, check if the cmd is set, that is, if cmd > 0. If so, then call function

```
execute_cmd(ps, local_cmd);
```

and reset `cmd` (which is an atomic write)

```
ps->cmd = 0;
```

Simple synthesizer loop

- The synthesizer will have a loop that runs over `framesPerBuffer` frames, where a frame is the interleaved samples of all channels.
- Initialize the output value to zero

  ```
  double v = 0;
  ```
- Within this loop is a second loop that computes an output sample for each of the tones that are currently voicing. These tones are described in the first `num_keys` entries in the Tone structure array.
- If the phase_inc for that tone is greater than -1, that is if

  pt[n].phase_inc > -1

  Then compute the next tone sample value is computed using the expression

  ```
  v += FS_AMPL * sin(pt[n]->phase);
  ```

  where

  `v` is the output sample value. Use the "+=" operator since each tone sample sums into the output sample value.

  `pt[n]` is a pointer to index `n` of the `Tone` array

  After tone sample value Is computed, the its `phase` in incremented by the `phase_inc`.

  Note that, first, the `phase_inc` for all structures in the `Tone` array were initialized to zero, and the output value `v` was set to zero prior to entering the inner loop. Hence, initially, no tones will be generated by the processing loops.

You now have a complete synthesizer, which should compile and run.

15 Points – Add Exponential Attack and Decay

However, the synthesizer has two negative features. The first is that once a key is pressed, that tone plays forever, or until a next key is pressed or you exit the program. The second is that the tones start and stop playing as full-scale values. That is not very realistic, and furthermore, causes an audible "pop" when play starts and stops.

To remove the audible pop and make the synthesizer more realistic, add an "attack" and "decay" to the envelope of the synthesized tone. The envelope of a tone will have an

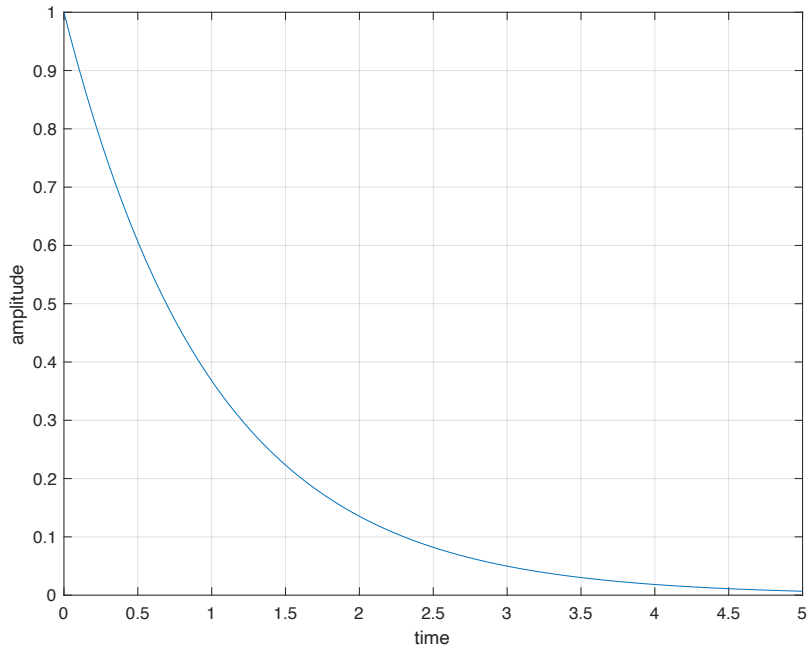
exponential attach and decay, you will can stop any tone whose amplitude decays below a specified level `DROP_LEVEL`, as defined in synth.h

Exponential Decay

An exponential decay is specified by

$$f(t) = e^{-\left(\frac{t}{\tau}\right)}$$

Where τ is the *time constant* and f(t) has the value 1.0 when t has the value 0, and the value 1/e = 1/(2.71828) = 0.368 when t has the value τ . A plot of f(t) for a time constant of 1.0 seconds looks like this:



This can be expressed as a function of n, the digital sample index as

$$f(n) = e^{-\left(\frac{n/Fs}{\tau}\right)}$$

Where Fs is the sampling frequency so that n/Fs is the sample-domain equivalent of t. This can be expressed as

$$f(n) = \left(e^{-\left(\frac{1/Fs}{\tau}\right)}\right)^n = (decay\_factor)^n$$

Hence, implementing an exponential decay consists of multiplying the output sample value by

$$(decay\_factor)^n$$

Where `n` is the sample frame index. This can be computed iteratively. Let

$$decay\_amp(n) = (decay\_factor)^n$$

Then

$$decay\_amp(n) = decay\_amp(n-1) * decay\_factor$$

where

$$decay\_amp(0) = 1.0$$

And the indexes are the sample index.

In our program, there is actually just `decay_amp` and `decay_factor`, where `decay_amp` is initialzed to 1.0 when a new key is pressed and, for each sample frame in the output

- the output value is multiplied by `decay_amp and`
- `decay_amp` updated as `decay_amp *= decay_factor`.
- The resultant `decay_amp` value is saved (in the Tone structure).

The value for `decay_factor` corresponding to a time constant of 1.0 seconds is given in the `synth.h` header file.

Exponential Attack

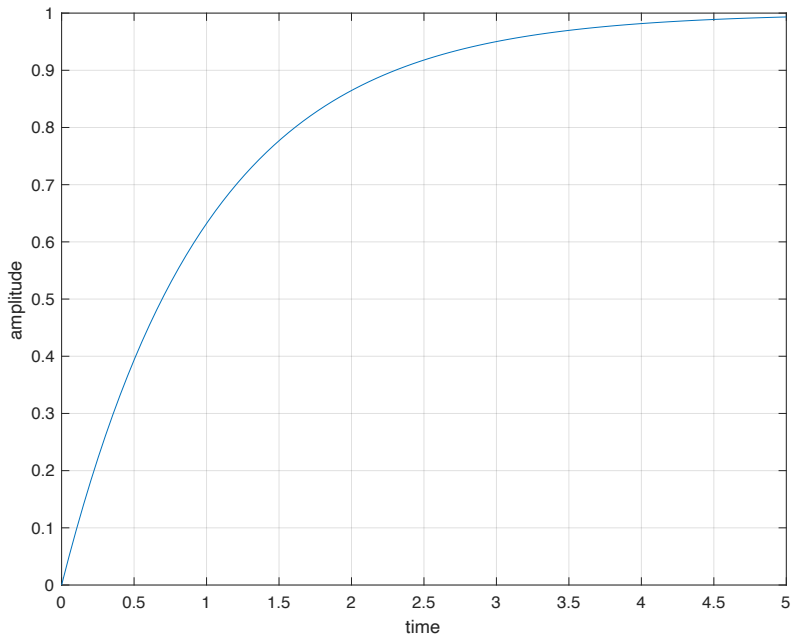
In a similar way, we can add an exponential attack to the tone amplitude

- An `attack_amp` value is initialized to 1.0 when a key is added to the key list (see `add_key()`, above)

However there is one important difference:

- the output value is multiplied by (`1 – attack_amp`)

This is a plot of (`1 – attack_amp`) for a time constant of 1.0 seconds:



However, a realist value for the attack time constant of e.g. a piano key is perhaps 10 ms, and a realistic decay time constant is 1.0 seconds.

The value for `attack_factor` corresponding to a time constant of 10 ms is given in the `synth.h` header file.

Finally, to apply both attack and decay time constants, simply multiply the output value by `(1 – attack_amp)` and `(decay_amp)`. At the key onset, the attack will dominate the decay, but will quickly reach a value near 1.0. As the tone rings out, the decay will dominate. This will produce a tone with an envelope like this:

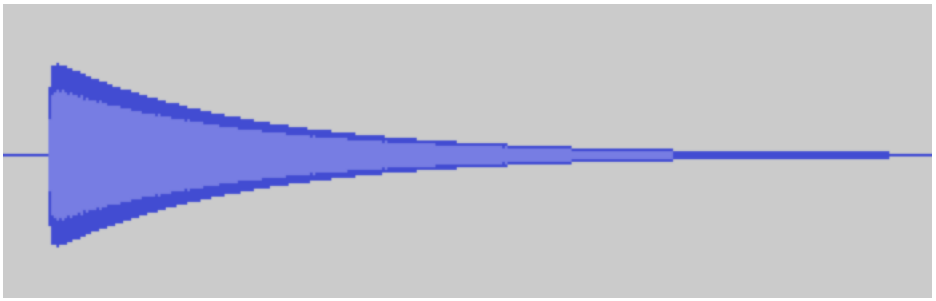
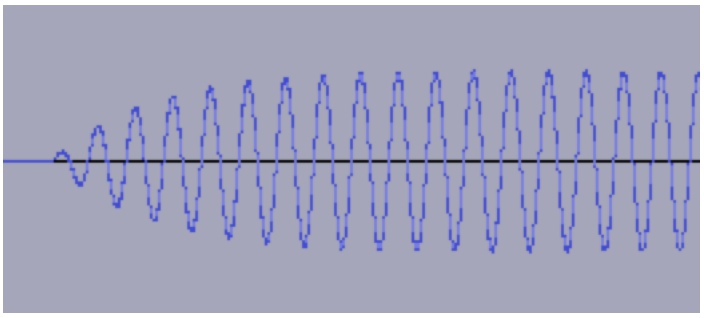


Figure – Note Waveform.

The exponential decay is clearly visible. The horizontal time scale for the plot is approximately 5 seconds. Notice that the tone drops to zero amplitude at one point. This is because the program stops the tone playout when the envelope falls below the `DROP_LEVEL`. Zooming in on the tone onset shows the attack, where the horizontal time scale is approximately 50 ms.



Attack and Decay Summary

So, you must add code that does the following:

- Inside the inner loop in `synth_block()`, multiply the tone output sample value by `(1 – attack_amp)` and `(decay_amp)`, and then update the `attack_amp` and `decay_amp` factors.
- At the end of the inner loop, add code that stops the tone playout if the envelope of the tone is (as measured by decay_amp) below some `DROP_LEVEL` (set to -60 dB in the `synth.h` header file). Stop the tone by setting
  `pt[n].phase = -1;`

(10 Points) – Waveform for Concert A

Set DB_WAV_OUT to 1 (true) as

```
#define DB_WAV_OUT          1
```

in **synth.h** and re-compile your program. This will cause all output from paCallback() to be written to file `test_file.wav.` Start the program and immediately hit Shift-F, which is Concert A or 440 Hz. After the note rings out, hit Space Bar to exit the program, which closes the WAV file. Use a DAW to edit the waveform so that it looks like the "Note Waveform" figure, above. Then revert back to

```
#define DB_WAV_OUT          0
```

and submit `test_file.wav` along with your code for `main.c` and `synth.c`.