C++ Real-Time Audio Programming with Bela

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Course topics

Programming topics

Working in real time
Buffers and arrays
Parameter control
Classes and objects
Analog and digital I/O
Filtering
Timing in real time
Circular buffers
State machines
MIDI
Block-based processing
Threads
Fixed point arithmetic
ARM assembly language

Today

Music/audio topics

Oscillators
Samples
Wavetables
Control voltages
Gates and triggers
Filters
Metronomes and clocks
Delays and delay-based effects
Envelopes
ADSR
MIDI
Additive synthesis
Phase vocoders
Impulse reverb

Lecture 16: MIDI part 2

What you'll learn today:

Handling the MIDI pitch wheel
Handling MIDI control change messages
Low-frequency oscillators and portamento

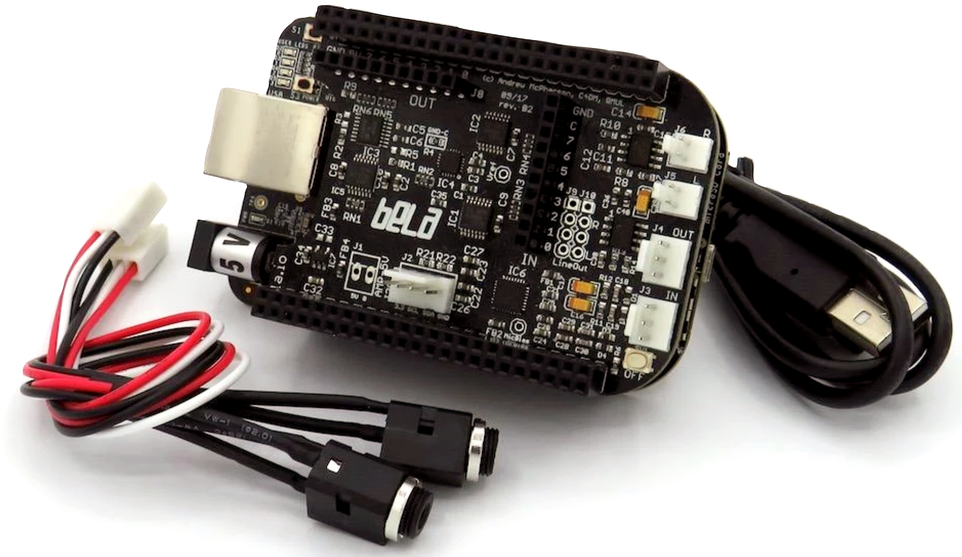
What you'll make today:

Analog-style monophonic MIDI synth

Companion materials:

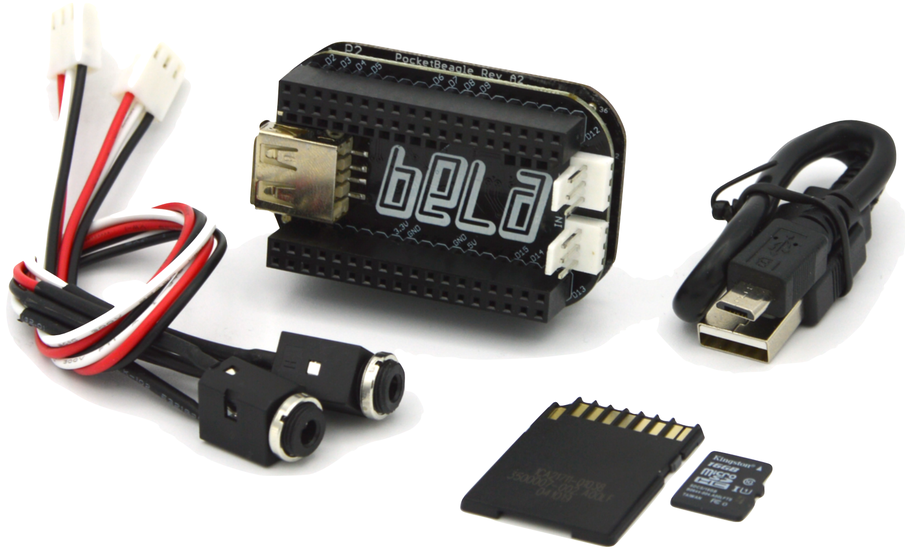
github.com/BelaPlatform/bela-online-course

What you'll need



Bela Starter Kit

or



Bela Mini Starter Kit

[shop.bela.io]

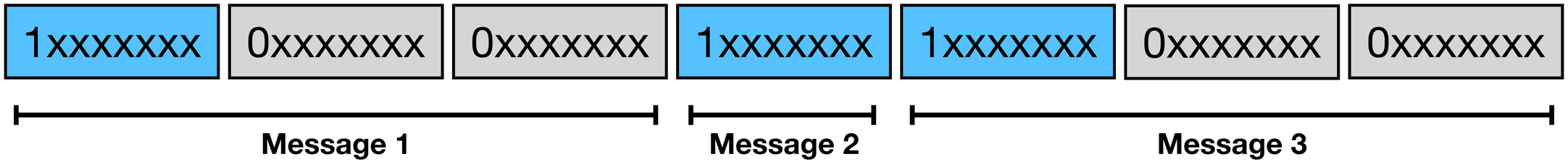
Also needed for this lecture:

or virtual keyboard software:

MIDIKeys (Mac)
vmpk (cross-platform)

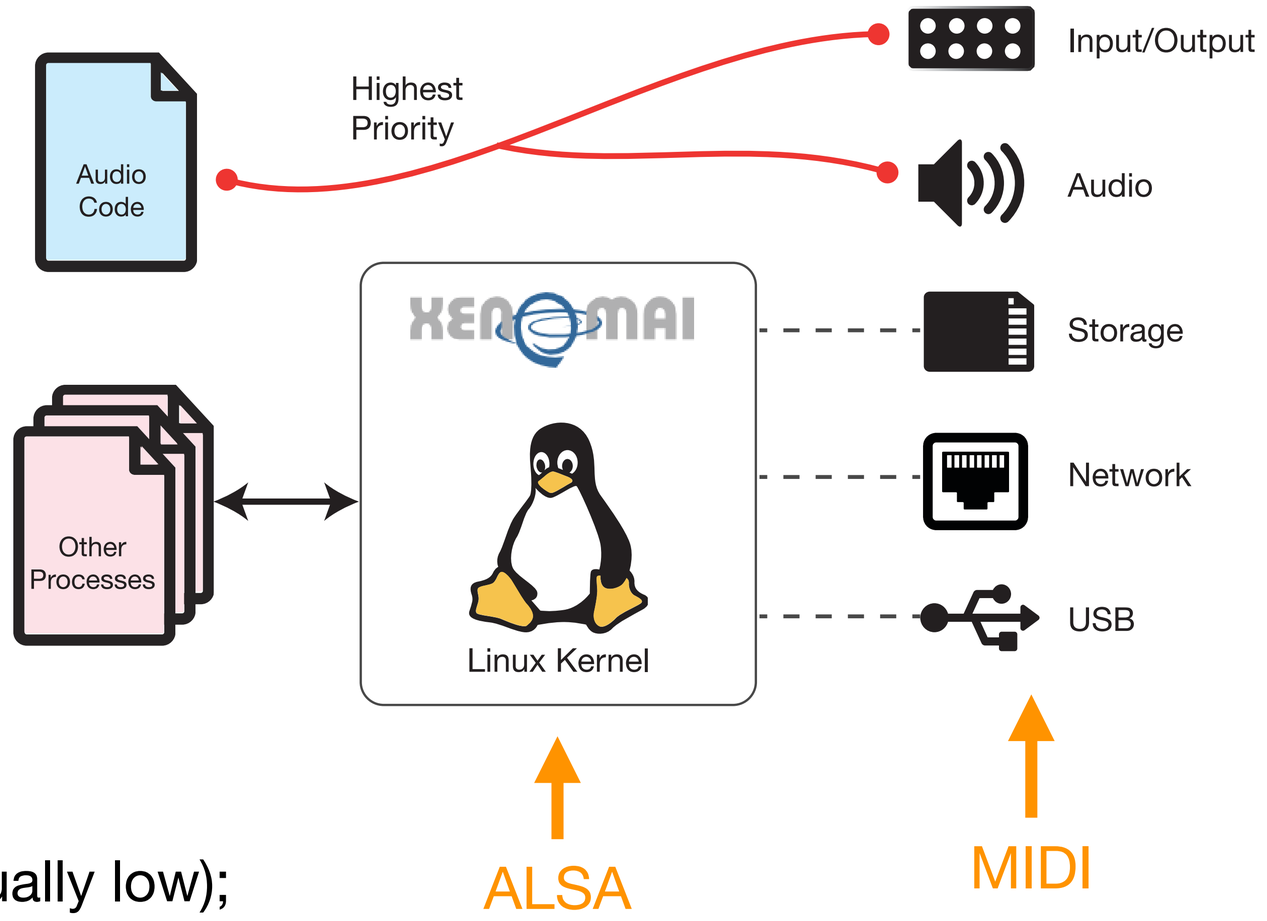
MIDI

- MIDI: Musical Instrument Digital Interface
  - Industry standard for connecting digital musical devices
  - First published in 1983, with minor updates since
  - Maintained by the MIDI Manufacturer's Association: http://midi.org
- The fundamental unit of MIDI is the message
  - A discrete packet of data, consisting of 1-3 bytes



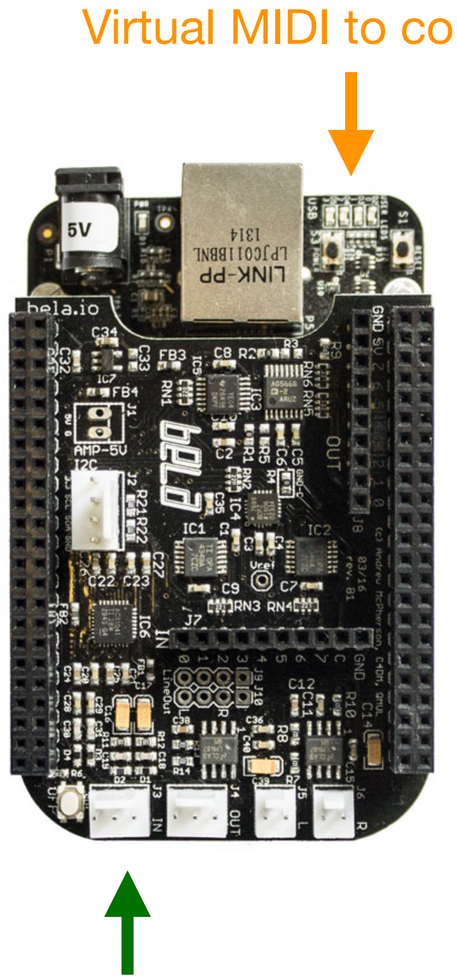
MIDI on Bela

- On Bela, MIDI uses ALSA (Advanced Linux Sound Architecture)
  - This is provided by the Linux kernel
- Advantage: compatibility
  - Any MIDI device that works on Linux works on Bela
  - All sources of MIDI data are treated equivalently (serial, USB, virtual ports)
- Disadvantage: real-time latency
  - ALSA cannot use the hard real-time priority of Bela's audio callback
  - We still need a way to pass data from the ALSA system to the Bela audio callback
  - Result: no latency guarantees (though usually low); latency could depend on other system load



MIDI on Bela: devices

- There are two common ways of using MIDI on Bela
  - Hardware MIDI devices
    - Connect these by USB to the host port on Bela
  - Bela as virtual MIDI device
    - Bela appears as a MIDI device to the host computer
    - Can exchange MIDI messages back and forth with the computer
- In your code, each MIDI device is specified by a device name (or port name)
  - The virtual device is usually `hw:0,0,0`
  - The first connected USB device is usually `hw:1,0,0`
  - To see connected devices, run `amidi -l` on the Bela console



MIDI on Bela: API (option 1)

- Bela provides an API that wraps the ALSA system
- To use it:
  1. Include `Midi.h`
  2. Make a global `Midi` variable
  3. Initialise the settings in `setup()`
  4. Read/write the messages in `render()`

```
#include <Bela.h>
#include <libraries/Midi/Midi.h>

Midi gMidi;                                    // MIDI object
const char* gMidiPort0 = "hw:1,0,0";           // Port name

bool setup(BelaContext *context, void *userData)
{
    // Initialise the MIDI device
    gMidi.readFrom(gMidiPort0);
    gMidi.writeTo(gMidiPort0);
    gMidi.enableParser(true);
    return true;
}

void render(BelaContext *context, void *userData)
{
    // At the beginning of each callback, look for available MIDI
    // messages that have come in since the last block
    while(gMidi.getParser()->numAvailableMessages() > 0) {
        MidiChannelMessage message;
        message = gMidi.getParser()->getNextChannelMessage();

        // Check message types and decide what to do with each one
        if(message.getType() == kmmNoteOn) {
            // Note on
        }
        // etc.
    }

    // Now calculate the audio for this block
}
```

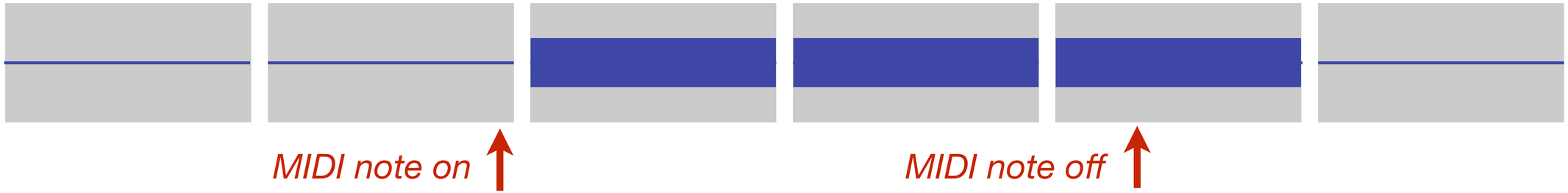
MIDI on Bela: API (option 2)

- You can also use a separate MIDI callback function
  - The system calls your function whenever MIDI data comes in
  - MIDI output is handled separately
- To use it:
  - In `setup()`, tell the `Midi` object where to find your callback
  - In the callback function, read the incoming message
  - Up to you to pass any required data to `render()`, e.g. using global variables

```
#include <Bela.h>
#include <libraries/Midi/Midi.h>

Midi gMidi;                                  // MIDI object
const char* gMidiPort0 = "hw:1,0,0";         // Port name

void midiEvent(MidiChannelMessage message, void *arg);

bool setup(BelaContext *context, void *userData)
{
    // Initialise the MIDI device
    gMidi.readFrom(gMidiPort0);
    gMidi.writeTo(gMidiPort0);
    gMidi.enableParser(true);
    gMidi.setParserCallback(midiEvent, (void *)gMidiPort0);
    return true;
}

void midiEvent(MidiChannelMessage message, void *arg)
{
    // Check message types and decide what to do with each one
    if(message.getType() == kmmNoteOn) {
       // Note on
    }
    else if(message.getType() == kmmNoteOff) {
       // Note off
    }
    // etc.
}
```

MIDI on Bela: other considerations

- Remember: MIDI is fundamentally asynchronous with audio
  - It comes from a different hardware device, via a different thread
    - When you read the messages in `render()`, you're seeing everything that happened since the last block
    - You won't necessarily know exactly which audio frame the message was received at



- MIDI messages have persistent effects
  - When a message comes in, we start doing something and usually continue doing it until we receive another message
  - Examples:
    - A Note On message starts some sound, which continues after the instant that the message comes in
    - Control Change or Pitch Wheel messages will affect current and future notes on that channel
  - This implies that we need to remember what happened before (e.g. with global variables)

MIDI note number

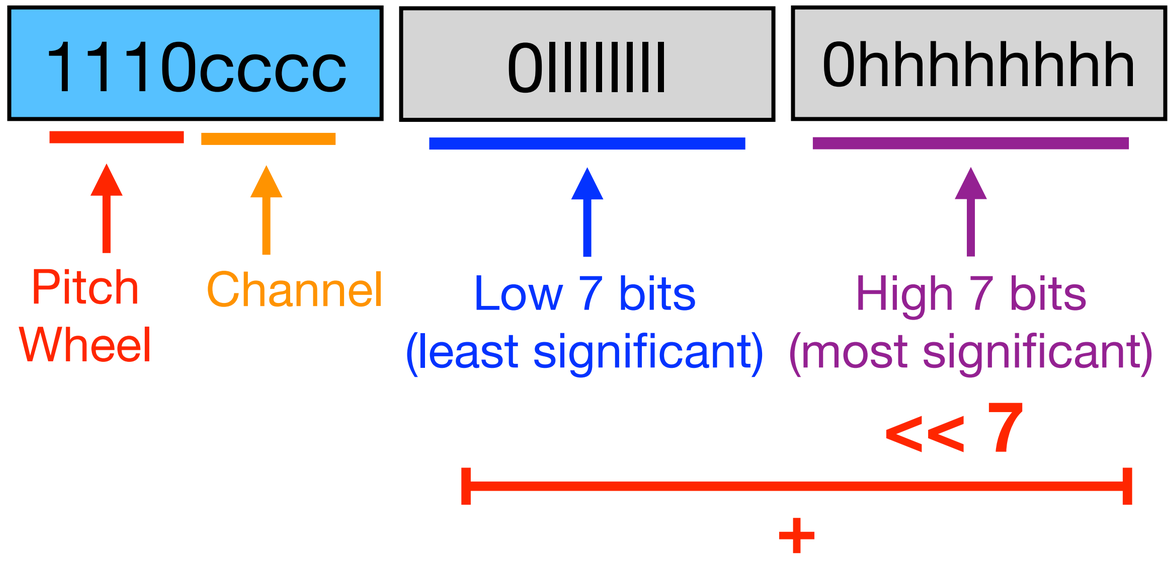
- MIDI note numbers uniquely indicate each key of the keyboard
  - Numbered sequentially from low to high
  - By definition, middle C is note number 60
    - It has frequency 261.63Hz
  - The A above middle C is note number 69
    - It has frequency 440Hz (a commonly used reference, sometimes called "A440")

- How should we write the formula to go from MIDI note number to frequency?
  - For a note number *N*, how do we calculate number of semitones above A440? *N* - 69
    - Number of octaves? (*N* - 69) / 12
  - If note 69 corresponds to $f_{ref} = 440\text{Hz}$ how do we calculate the frequency for note N?

$$f_{out} = 440 \cdot 2^{\frac{N-69}{12}}$$ *(MIDI note number to frequency)*

Implementing MIDI pitch wheel

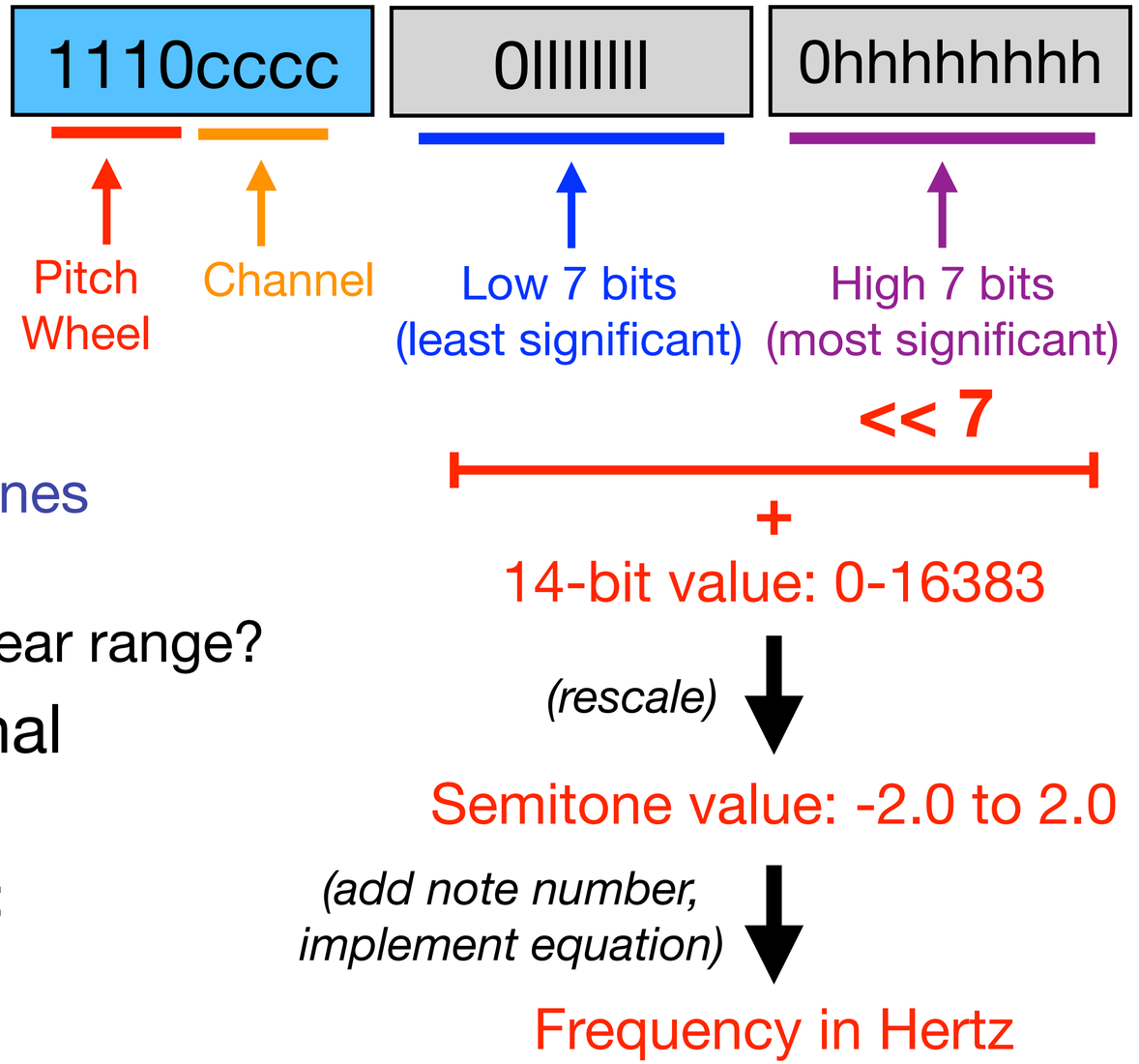
- Pitch Wheel messages create a relative change in frequency
  - A change compared to where that note number would normally be tuned
- To calculate the oscillator frequency, we always need both of:
  - The note number of the most recent Note On message
  - The value of the most recent Pitch Wheel message
  - We receive one message at a time, which means we have to remember the other one!
- Pitch Wheel messages are 14 bits (0 to 2^{14}-1), split over two data bytes
  - Our first task is to reconstruct the 14-bit value
  - Use the bit shift operator `<<` to shift the MSB left by 7 bits (i.e. multiply by 2^7)
  - Then add the two values together



Implementing MIDI pitch wheel

- Once we have the 14-bit value, convert it to a bend in semitones
  - The 14-bit value ranges from 0-16383
  - The centre value is 8192: this corresponds to no bend
  - A value of 0 corresponds to -2 semitones
  - A value of 16383 corresponds to +2 semitones
    - Though these ranges are adjustable
  - What function could we use to rescale a linear range?
- Finally, add the bend value to the original note number
  - Then convert the sum to a frequency using:

$$f_{out} = 440 \cdot 2^{\frac{N-69}{12}}$$

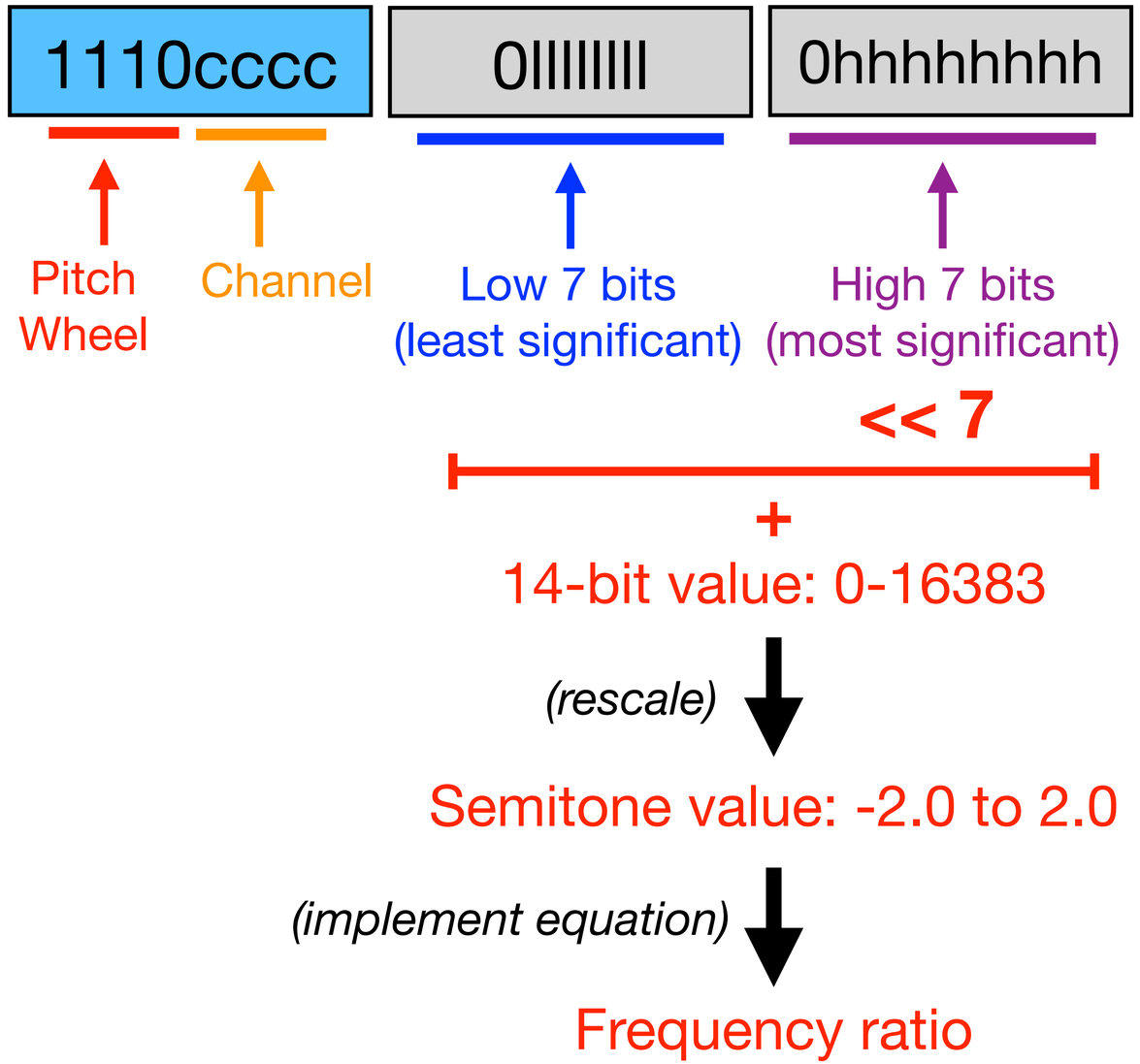


Implementing MIDI pitch wheel

- Alternatively: convert the pitch bend directly into a frequency ratio
  - Store the frequency f_{note} of the MIDI note elsewhere

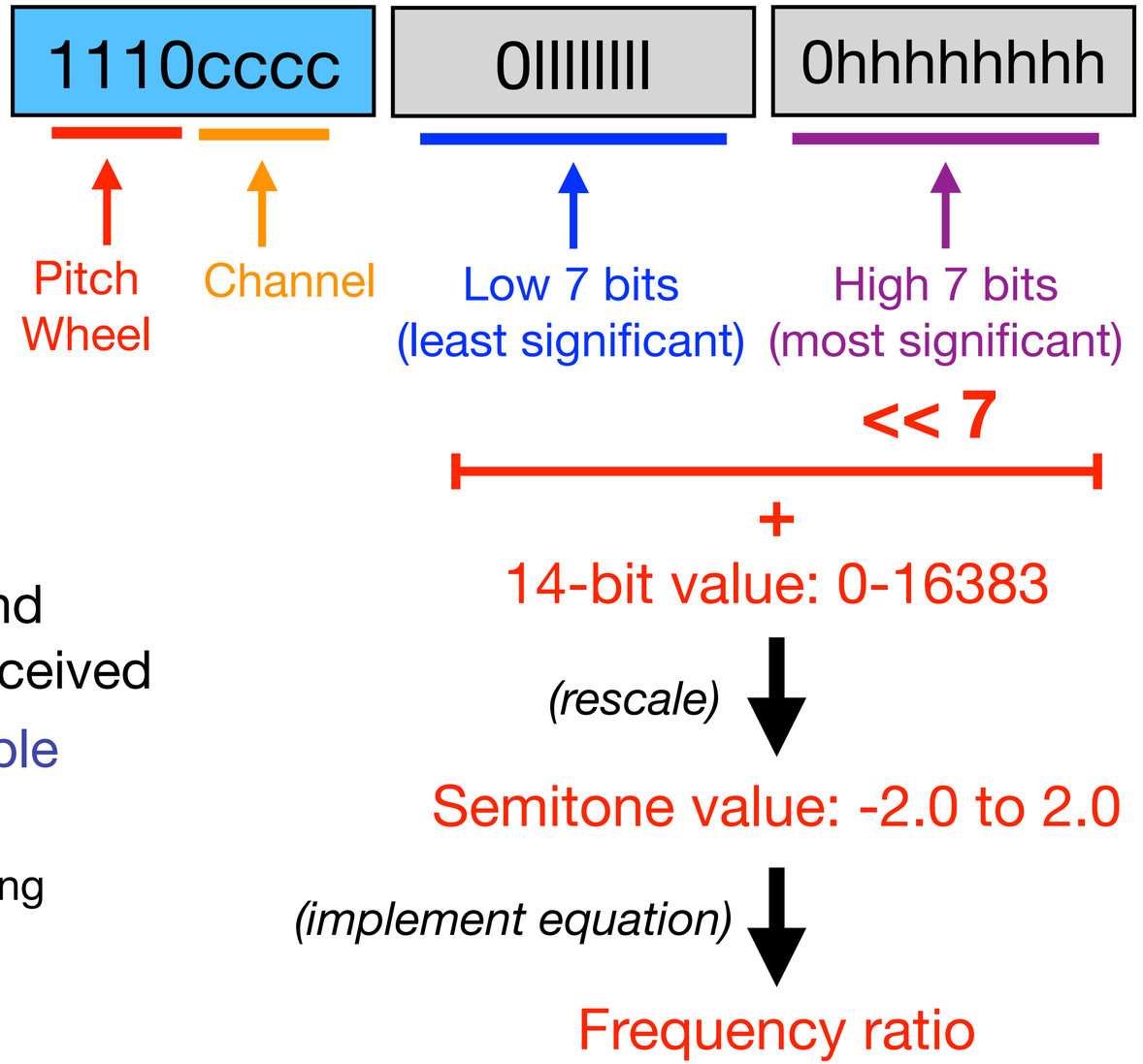
$$f_{out} = f_{note} \cdot 2^{\frac{N}{12}}$$

  - Multiply the two values together to get the final frequency
  - We'll take this approach for reasons we'll see later



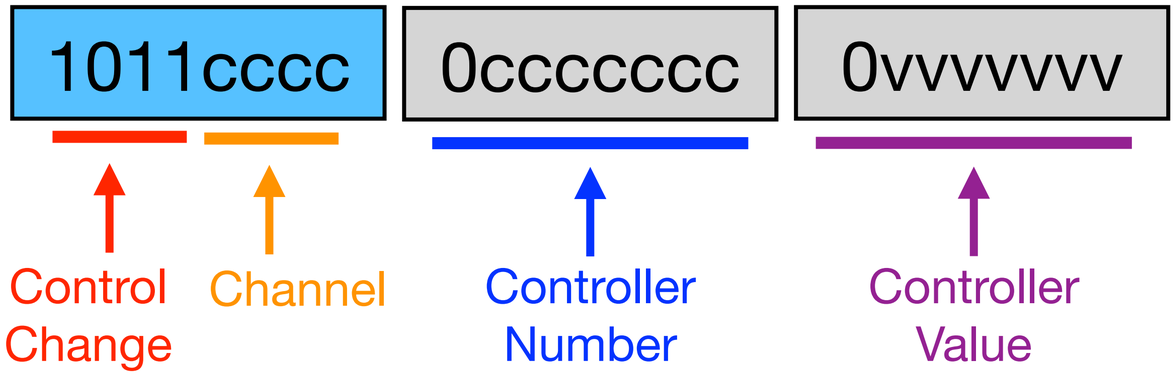
Implementing MIDI pitch wheel

- Task: using the midi-pitchwheel example, implement the pitch wheel
  - In `midiEvent()`, add a new `if()` statement looking for a message of type `kmmPitchBend`
  - Get the two data bytes from the message (see how it's done for `kmmNoteOn`)
    - Convert the two bytes to a single 14-bit number
  - Write a new function called `pitchWheel()` and call it when the `kmmPitchBend` message is received
  - Store the frequency ratio in a new global variable called `gPitchBendRatio`
    - In `render()`, calculate the final frequency by multiplying the note frequency by this value



MIDI control change messages

- Control Change
  - Status byte begins with 1011 (hexadecimal 0xB)
  - Indicates that a controller changed value
  - Controllers in MIDI might be dials, sliders, pedals, breath controllers, etc.
    - They produce a continuous value (0-127) which affects all notes on the channel
  - 2 data bytes: controller number, value
  - Controller numbers are standardised in the MIDI specification
    - e.g. CC1 = modulation wheel; CC7 = volume; CC11 = expression; CC64 = damper/sustain pedal
    - Controllers 120-127 are used for special functions on the channel, e.g. CC123 = all notes off
- Like all MIDI messages, the effect is persistent
  - When you receive a Control Change message, you'll need to keep track of its effect
  - Typically, rescale the range: from 0-127 to an appropriate range for the specific control



Multiple oscillators

- On analog synths, it's common to use 2 or more oscillators for a single voice
  - The oscillators are tuned nearly, but not exactly, to the same frequency
  - Slight detuning results in beat frequencies according to the mathematical relationship:

$$\sin(x) + \sin(y) = 2\sin(\frac{x+y}{2})\cos(\frac{x-y}{2})$$

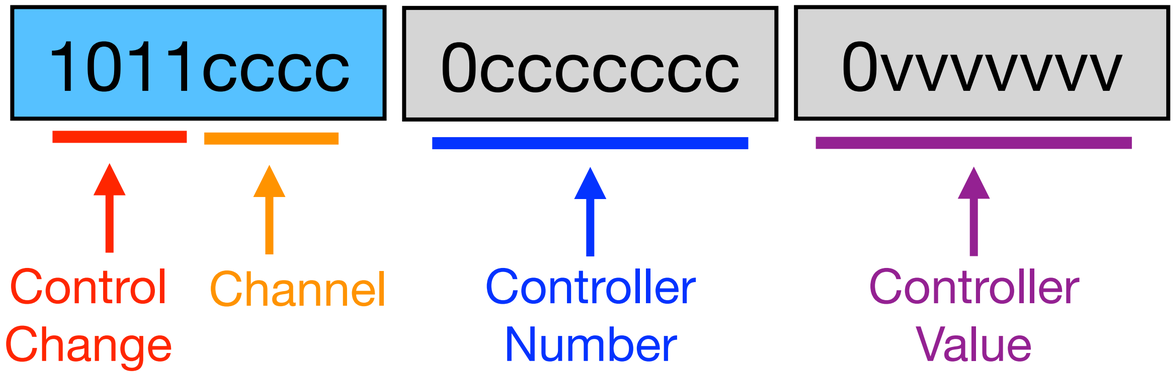
- We will use two controls to adjust the oscillator frequencies:
  - One for setting the centre frequency of both oscillators
    - Based on MIDI Note On messages, like before
  - One for changing the detuning (the slight difference between the oscillators)
    - We will implement this with a MIDI Control Change message
  - If the centre frequency is *f* and the detuning amount is *r*, we should have:

$$f_1 = (1+r)f \qquad f_2 = (1-r)f$$

    - In this case, *r* = 0 corresponds to no detuning (both oscillators the same frequency)

MIDI control change messages

- Task 1: in project midi-pitchwheel, implement two detuned oscillators
  - Replace the `Wavetable` object `gOscillator` with a two-element array
  - Initialise both oscillators in `setup()`
    - You don't have to recalculate the table
  - Declare a global variable `gDetuning` which holds the detuning amount
    - Try a default value of **0.002** for a good effect
  - In `render()`, set the frequency of both oscillators using the detuning amount
  - Mix both oscillator outputs together before applying the filter
- Task 2: use a MIDI control change to change the detuning ratio
  - Choose a controller number based on your keyboard's controls
    - Look in the console when the project is running and you adjust a controller
  - In `midiEvent()`, look for messages of type `kmmControlChange`
    - If the controller number matches, rescale the range to be between **0-0.01**

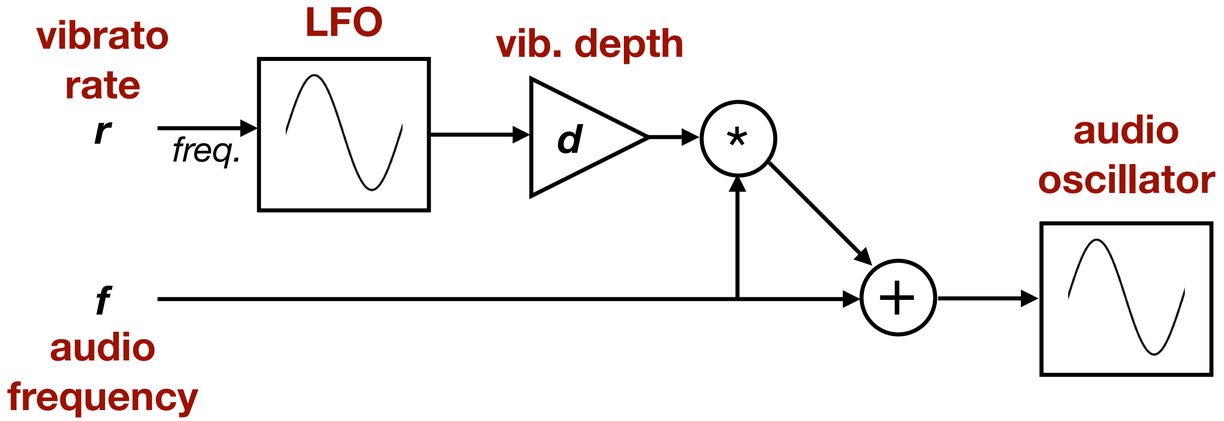


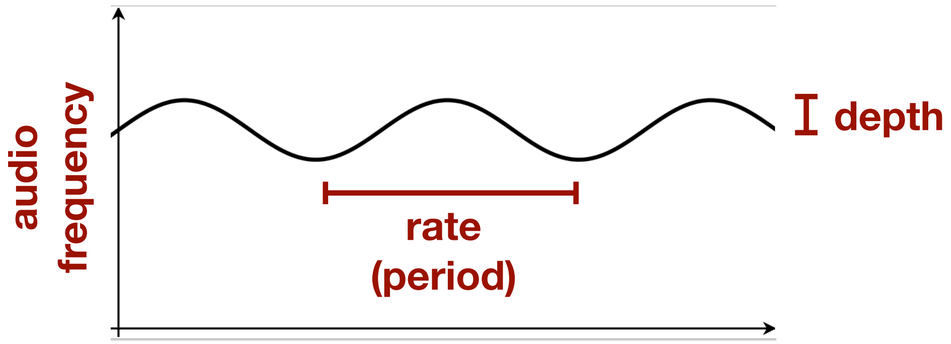
Modulation wheel

- In addition to the pitch wheel, most keyboards have a modulation wheel (“mod wheel”)
  - Introduced on the Minimoog in 1970 (before MIDI)
  - Unlike the pitch wheel which snaps back to centre, the modulation wheel stays in place
- The mod wheel can affect various parameters:
  - Filter cutoff frequency
  - Oscillator parameters (e.g. waveform)
  - Vibrato depth
    - Do this by change the amplitude of a low-frequency oscillator (LFO)
    - The LFO will then affect the oscillator frequency

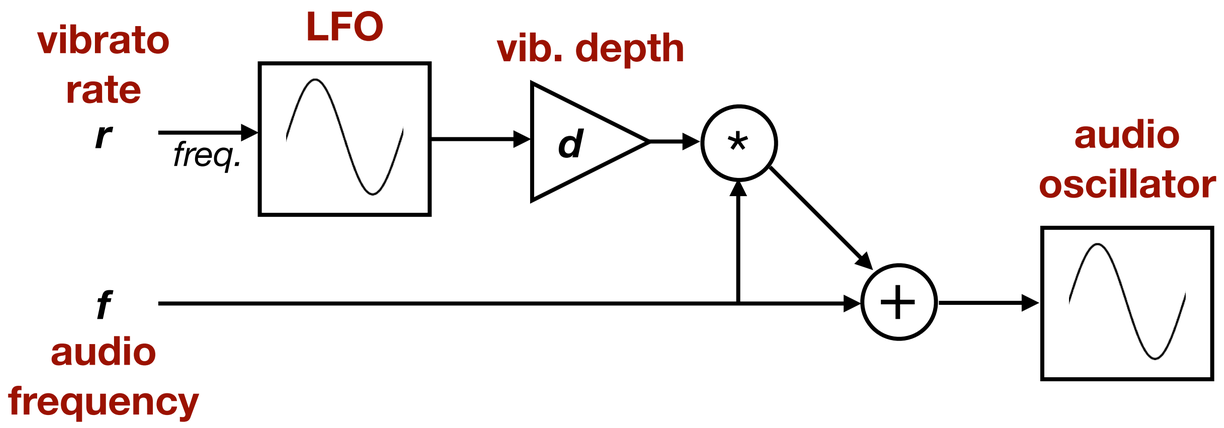
Low-frequency oscillators

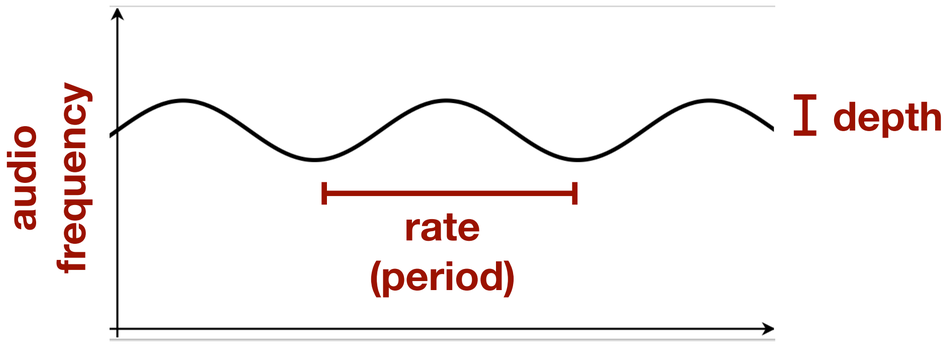
- We have seen oscillators (sine, sawtooth, wavetable) as audio sources
- In digital musical systems, oscillators are also often used as control signals
  - Typically these control signals will change more slowly than the audio waveform
  - Hence we refer to such oscillators as low-frequency oscillators of LFOs
- Example: Vibrato
  - Periodic modulation of frequency, typically changing at 3-6Hz (vibrato rate)
  - Typical amount of frequency variation ±0.5-3% (vibrato depth)
  - To implement: use an LFO to control the frequency of another (audio frequency) oscillator





Low-frequency oscillators

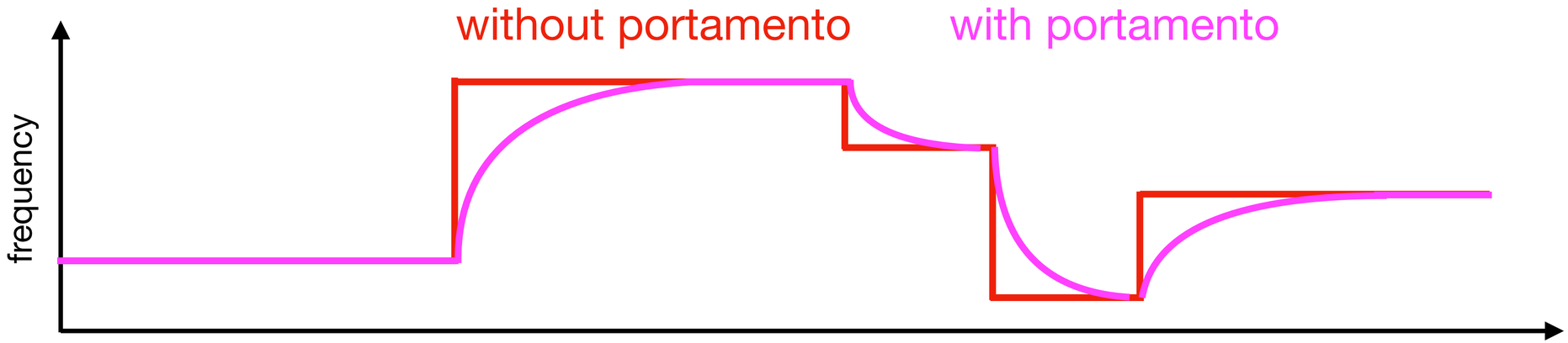




- Task 1: in midi-pitchwheel, use a `Wavetable` object to implement an LFO
  - In `setup()`, calculate a wavetable for a single sine wave (different than the current oscillators)
  - Set its default frequency to something low (e.g. 5Hz)
  - Use the output of the LFO to modulate the frequency of the main oscillators
- Task 2: make the vibrato depth controllable with the mod wheel
  - The mod wheel produces a MIDI control change message with a controller number of 1
  - Range of values is 0-127. Need to rescale to a suitable range of vibrato depth (e.g. 0-0.05)
  - Optionally add another MIDI controller to adjust vibrato speed (range 1-10Hz)

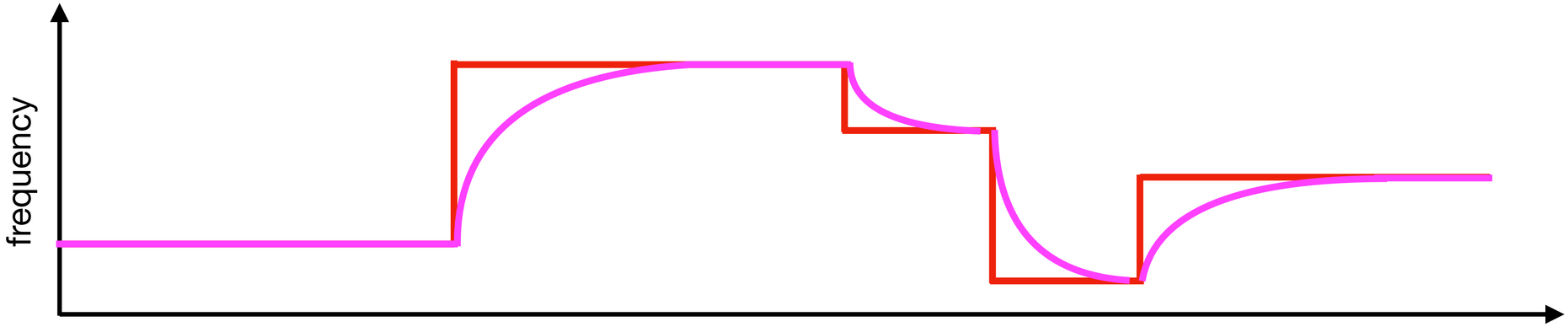
Portamento

- Portamento is a musical effect where the pitch moves gradually, rather than abruptly, from one note to the next:



- It is commonly found on analog synths, where the effect can be achieved by putting a low-pass filter on the pitch CV
  - Lower cutoff frequency → slower change in pitch → more pronounced portamento
- Equivalently, we can use an exponential segment to change frequency every time the MIDI note changes
  - Use the `ExponentialSegment` class from Lecture 14

Portamento implementation



- Task: in the midi-pitchwheel project, add portamento to the note frequency
  - Use the `ExponentialSegment` class (already included in the project)
  - Two possible approaches:
    1. Use `ExponentialSegment` to control the current centre frequency (not including pitch/mod wheels)
    2. Use `ExponentialSegment` to control the current (fractional) MIDI note number
  - Add a new MIDI control change message to adjust the portamento time
    - This will affect the time passed to the `ExponentialSegment::rampTo()`

Keep in touch!

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More resources and contact info at:

learn.bela.io/resources