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 15: MIDI part 1

What you'll learn today:

Introduction to the MIDI protocol
Handling MIDI Note On and Note Off messages
Keeping track of multiple notes

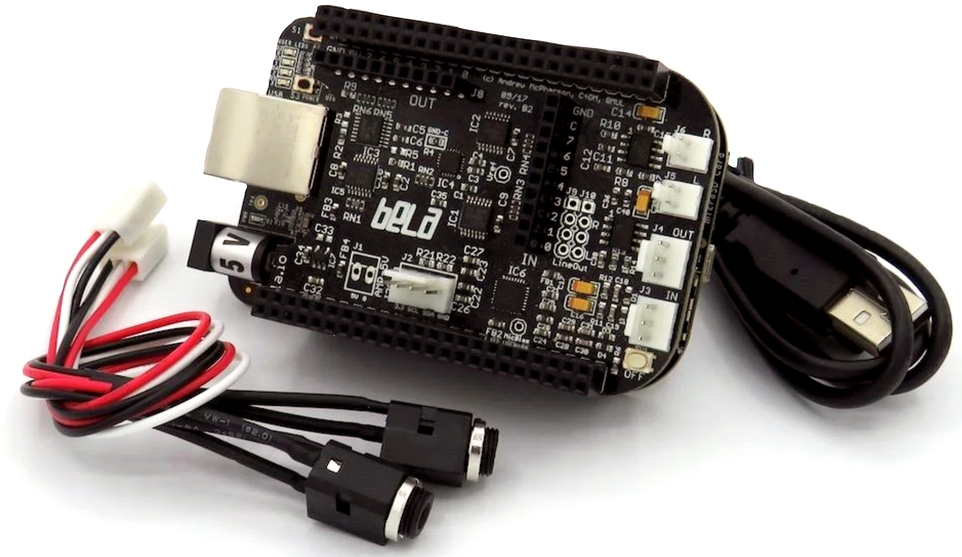
What you'll make today:

Monophonic MIDI synth with ADSR envelope

Companion materials:

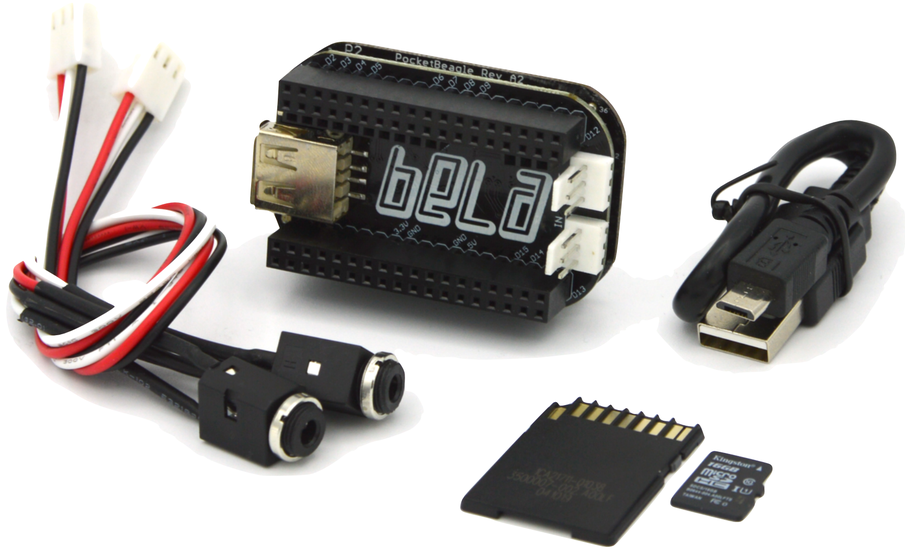
github.com/BelaPlatform/bela-online-course

What you'll need



Bela Starter Kit

or



Bela Mini Starter Kit

[shop.bela.io]

Also needed for this lecture:

or virtual keyboard software:

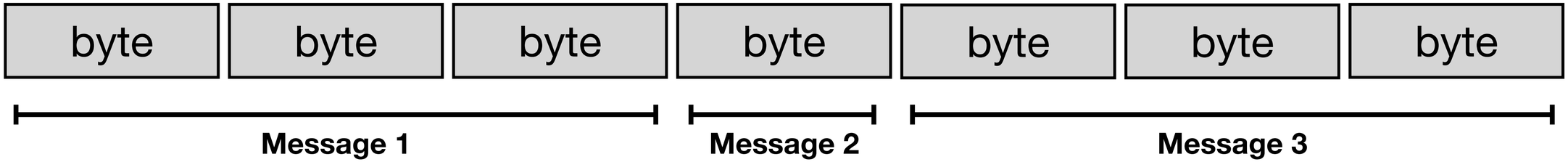
MIDIKeys (Mac)
vmpk (cross-platform)

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
- Several common MIDI transport layers
  - Serial: 31250 bps, 5-pin DIN cables, one cable for each direction
  - USB
  - Bluetooth
  - Virtual ports between software applications

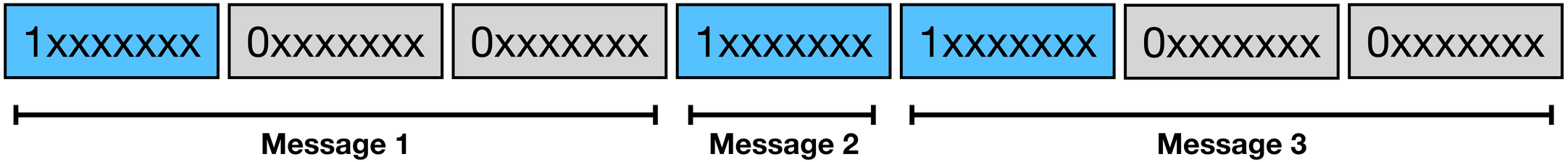
MIDI messages

- The fundamental unit of MIDI is the message
  - A discrete packet of data, consisting of 1-3 bytes



- The challenge is understanding which bytes group together
  - On a serial port, the contents of the byte are the only information we have
  - No external signals to tell us which bytes group with which others
- MIDI therefore uses the high bit of each byte to signal the start of a message
  - The first byte of each message has a 1 in the high bit; the others have a 0

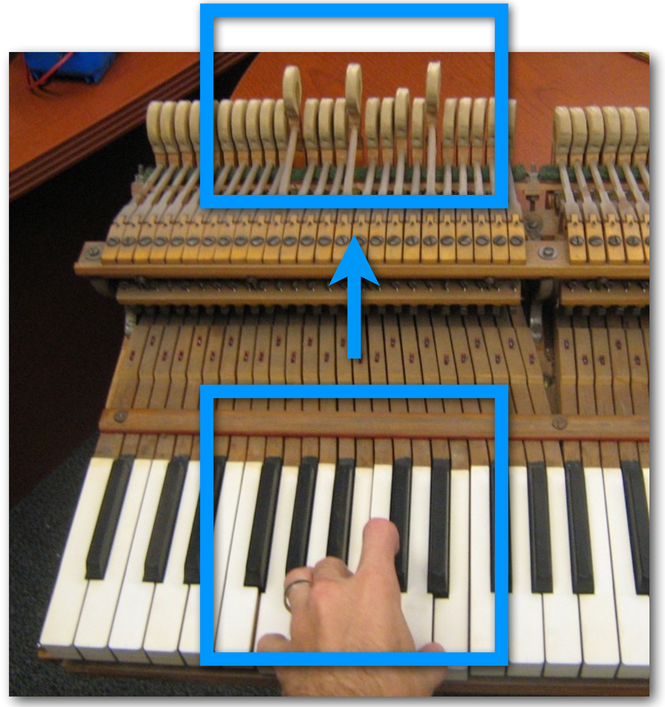
MIDI messages

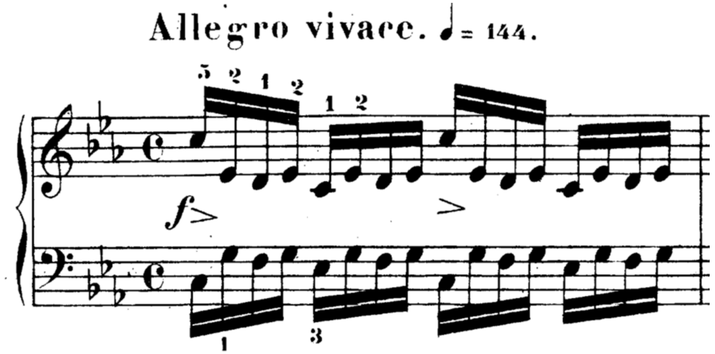


- The first byte of each message is called the status byte
  - The high bit is set to 1
  - The other 7 bits tell us what kind of message it is
- The remaining bytes are called data bytes
  - The high bit is set to 0
  - The data is held in the other 7 bits
  - For this reason, many MIDI messages have 7-bit resolution (values 0 to 127)
  - The number of data bytes is defined by the message type
- More details on MIDI messages:
  - https://www.midi.org/specifications-old/item/table-1-summary-of-midi-message

The musical assumptions of MIDI

- MIDI was designed with keyboards and western music in mind
  - It makes many assumptions about how music is organised
  - Captures many salient aspects in very little information, at the cost of generality
- The fundamental unit of MIDI is the note
  - Notes have a discrete onset and a discrete release
    - Happens at a particular instant in time
    - We'll sometimes hear the word "trigger" used to describe note events
  - Note onsets have a velocity
    - Analogy to the speed of a key press
    - Often related to volume
  - Note releases can also have a velocity
    - Analogy to speed of key release
    - In practice, this field is rarely used





Note On	
Note #	Velocity

Note Off	
Note #	Velocity

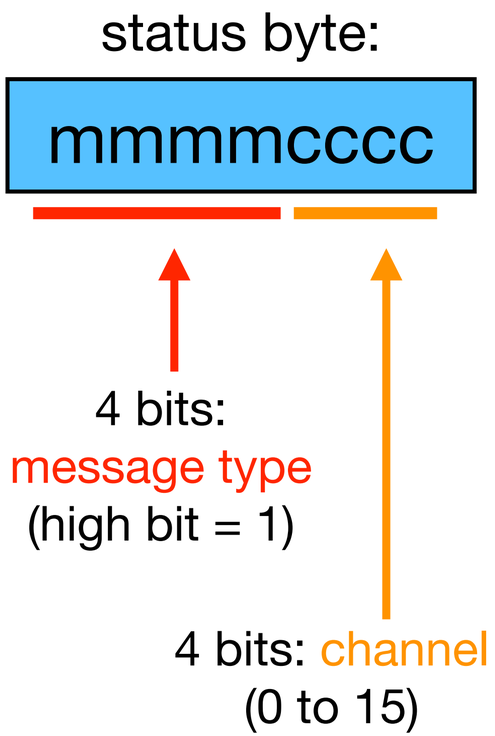
The musical assumptions of MIDI

- Notes are characterised by their note number
  - There are 128 note numbers (from 0 to 127)
  - Every key on the keyboard has a unique note number
    - This is agreed across all MIDI devices
  - By convention, middle C on the piano is note 60
    - That means the 88-key grand piano has note numbers 21 to 108
  - Notes are numbered by semitone
    - i.e. sequentially by piano key
    - There are 12 note numbers per octave

- There are other types of messages providing continuous control
  - Many of these are organised around the capabilities of electronic synths
- Collectively, these messages describe the piano and western staff notation
  - MIDI can be applied to many other situations, but be aware of its biases!

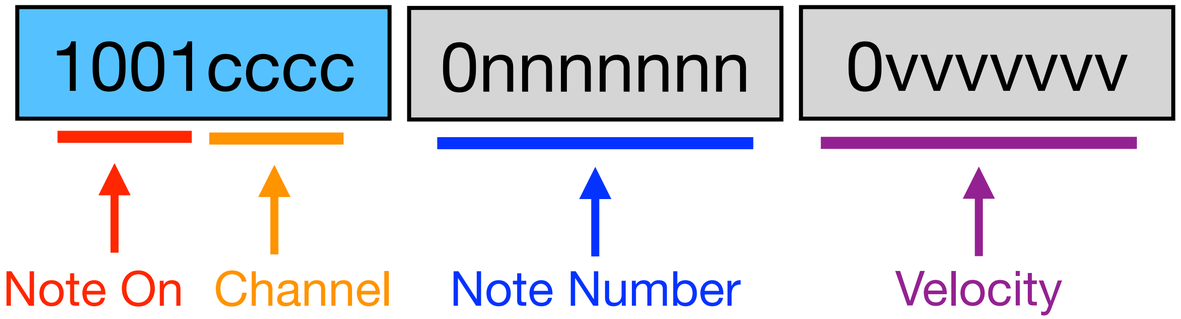
MIDI message types

- The MIDI 1.0 standard defines several types of messages
  - The status byte tells us the kind of message
  - Specifically, most message types are identified in the high 4 bits of the status byte
- MIDI messages can be sent on one of 16 channels
  - Different channels can be used to play different instruments at the same time, using a single MIDI cable
  - A single channel can have multiple notes, but other controls affect the whole channel
  - The channel is typically identified by the low 4 bits of the status byte
    - Values of 0 to 15 within the byte (2^4 possible values)
    - By convention these are known as channels 1 to 16

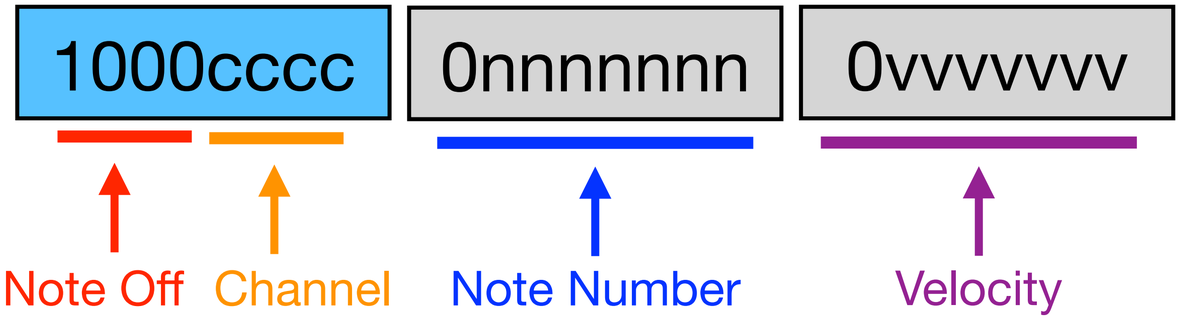


MIDI message types

- Note On
  - Status byte begins with 1001 (hexadecimal 0x9)
  - Indicates that a note started
    - e.g. a key was pressed
  - 2 data bytes: note number, velocity
    - In practice, usually related to frequency and amplitude
  - A Note On message with a velocity of 0 is the same as a Note Off message

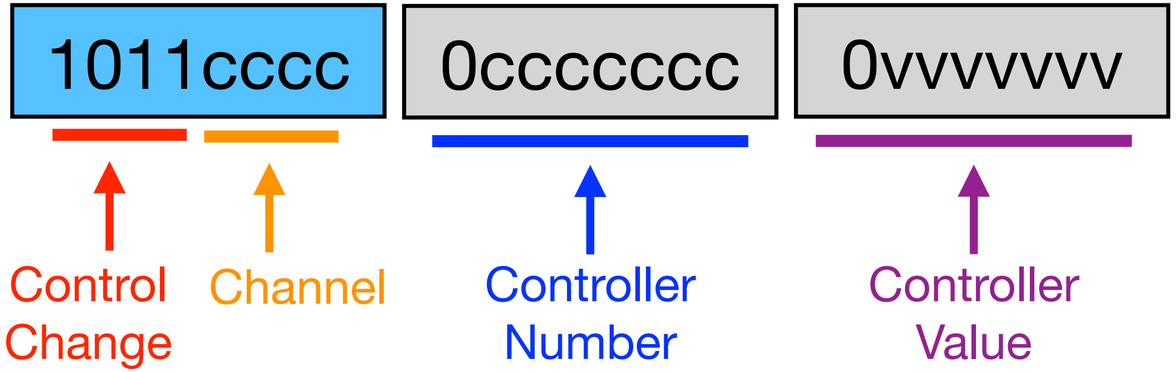


- Note Off
  - Status byte begins with 1000 (hexadecimal 0x8)
  - Indicates a note ended
    - e.g. a key was released
  - 2 data bytes: note number, velocity



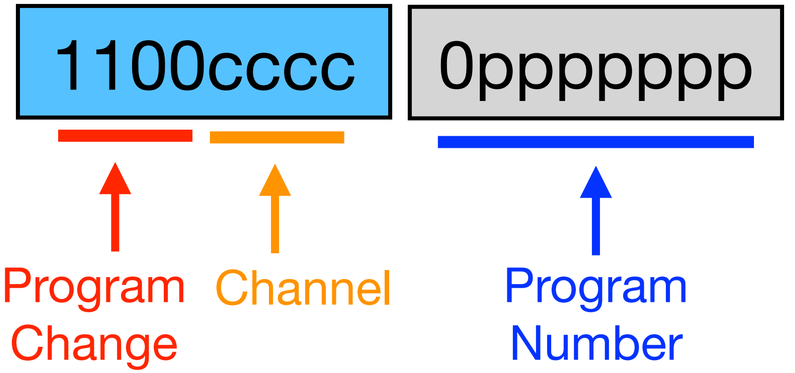
MIDI message types

- 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

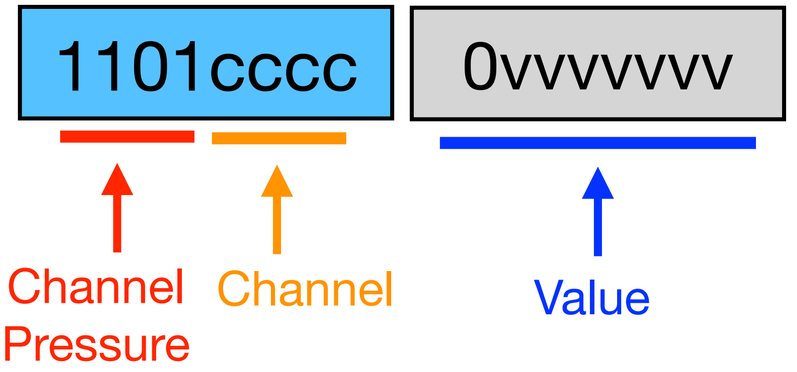


MIDI message types

- Program Change
  - Status byte begins with 1100 (hexadecimal 0xC)
  - Indicates that the synth should change program (preset or sound)
  - 1 data byte: program number

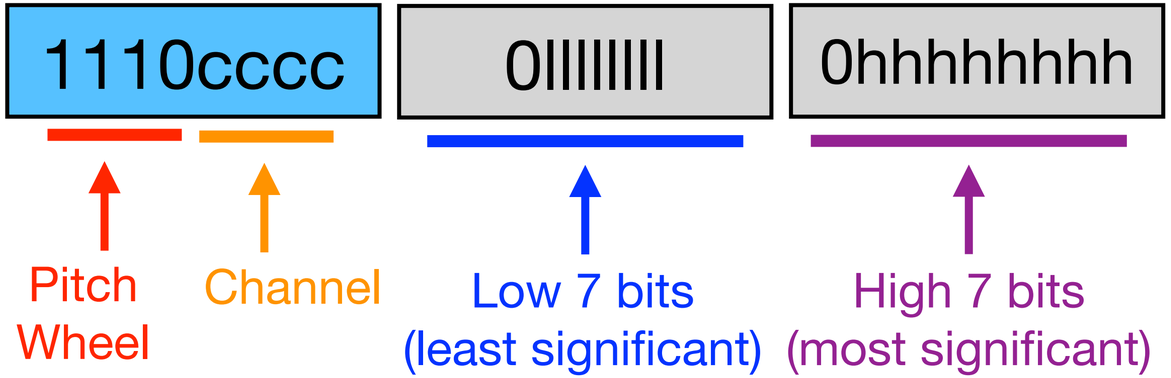


- Channel Pressure (aftertouch)
  - Status byte begins with 1101 (hexadecimal 0xD)
  - Some MIDI keyboards have a pressure sensor under the keys
    - Other types of MIDI controller could use different sensors for this purpose
  - This message reports the pressure value
    - Affects all notes on the channel
  - 1 data byte: pressure value



MIDI message types

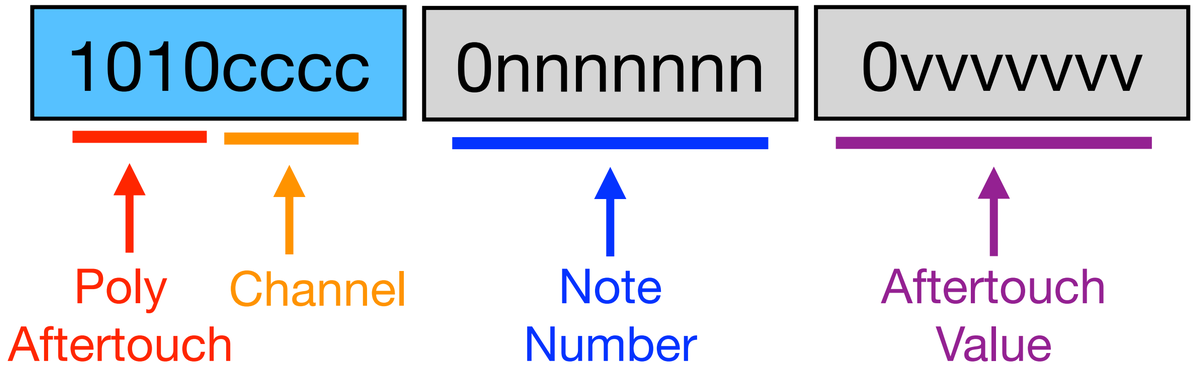
- Pitch Wheel
  - Status byte begins with 1110 (hexadecimal 0xE)
  - A control to bend the pitch of the notes up or down
  - First appeared in the Minimoog (1970)
  - The human ear is sensitive to frequency
    - We need more than 7 bits of resolution!
  - 2 data bytes: LSB and MSB
    - Each contains 7 bits, for a composite 14-bit value
    - 16384 (2^{14}) possible values
    - The centre value of the pitch wheel is 8192; higher or lower values bend the pitch up or down
  - By convention, the pitch wheel range is ±2 semitones (adjustable by other messages)



Minimoog (1970)

MIDI message types

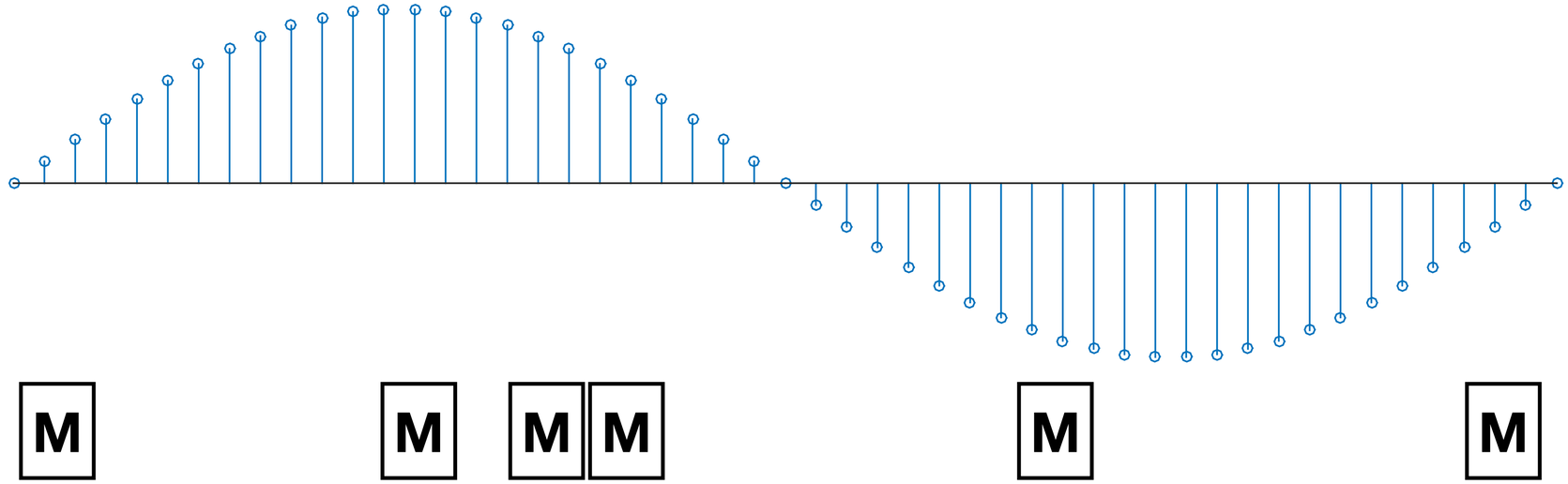
- Polyphonic Aftertouch
  - Status byte begins with 1010 (hexadecimal 0xA)
  - Like channel pressure, but a separate value for each key
  - Relatively few controllers support this
  - 2 data bytes: note number, value



- System Real-Time messages
  - Various messages beginning with 1111 (0xF) for controlling global settings of the device
- System Exclusive (SysEx)
  - A block of bytes beginning with 11110000 (0xF0) and ending with 11110111 (0xF7)
  - Used for manufacturer-specific messages, not supported by all devices
  - Variable length and meaning

MIDI and audio

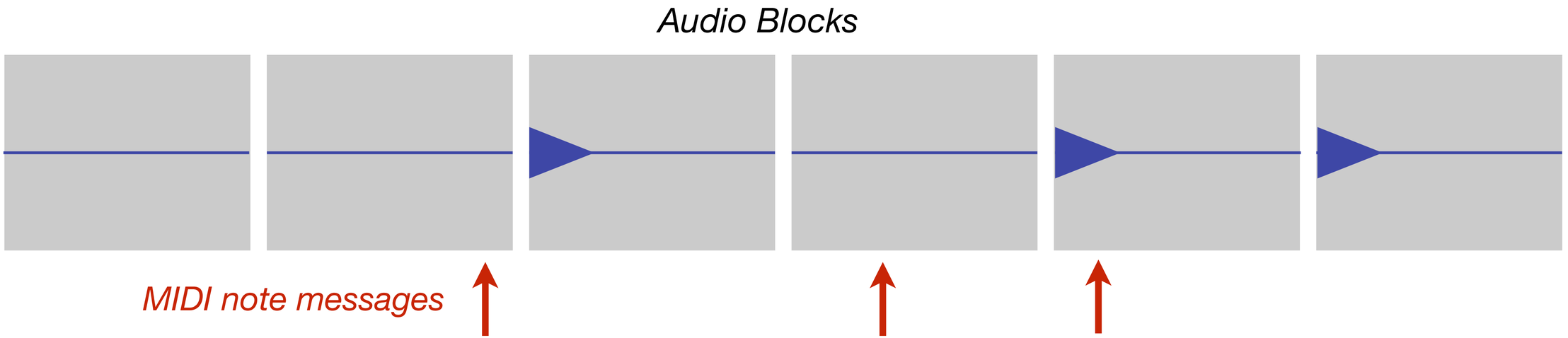
- Audio is a sampled signal
  - Has a regular sampling period, constant data rate, regular block size in real time



- By contrast, MIDI messages are sporadic events
  - Messages might arrive at any time (subject to overall limited bandwidth)
  - No regular sampling period, and no guarantee on alignment to audio frames
    - At minimum, we know that messages are sequential (one message finishes before the next begins)
- This sets up a familiar problem for real-time audio systems...

Jitter

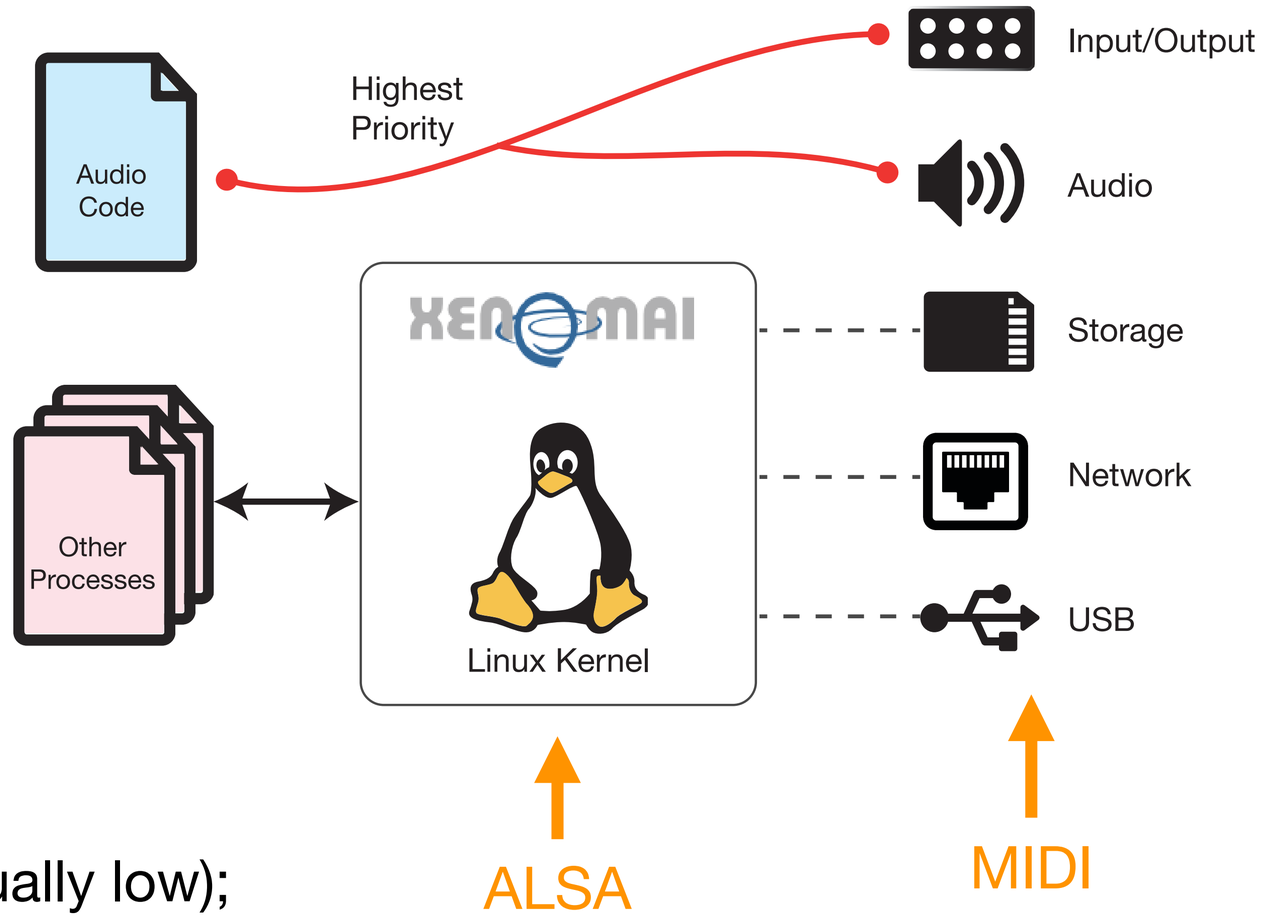
- Round-trip audio latency is usually constant
- MIDI-to-audio latency might vary randomly depending on the implementation
  - MIDI comes from a different hardware device, might be processed in a different thread
  - This variation in latency is known as jitter



- Unless we carefully plan otherwise, MIDI data processed at block intervals
  - Implication: larger block sizes mean more jitter
  - Possible alternative: strong timestamping of MIDI messages (requires hardware support)

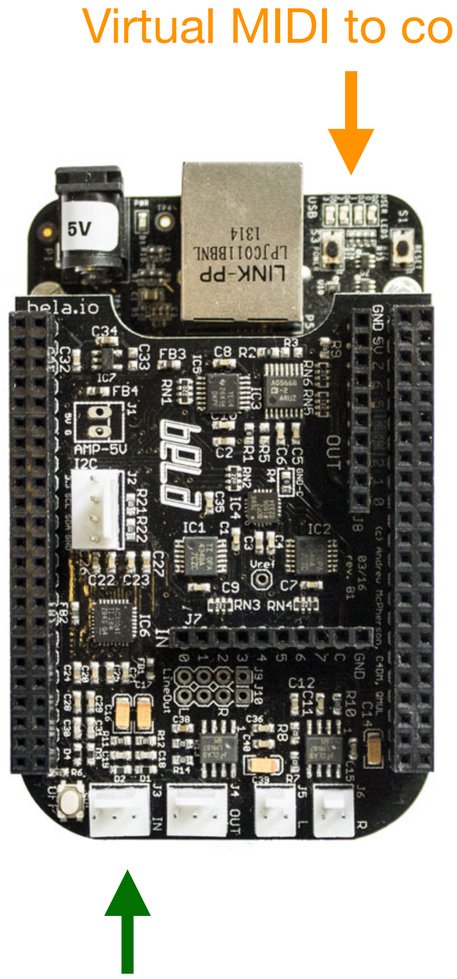
MIDI on Bela

- 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



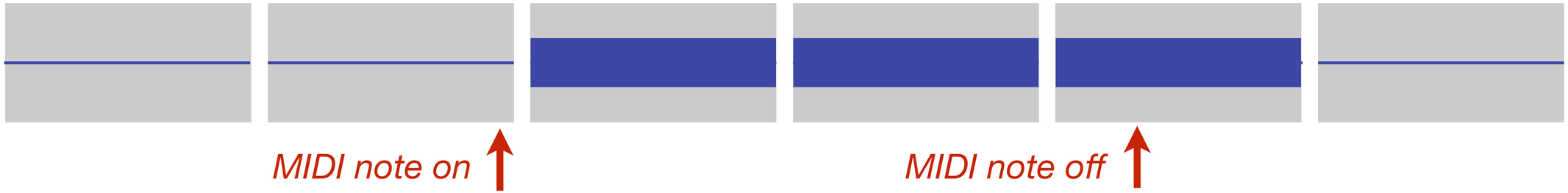
MIDI on Bela: API

- 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()`
- There is also an option to have a separate MIDI callback
  - The system calls your function whenever MIDI data comes in
  - See Bela example: `Communication/MIDI`

```
#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
}
```

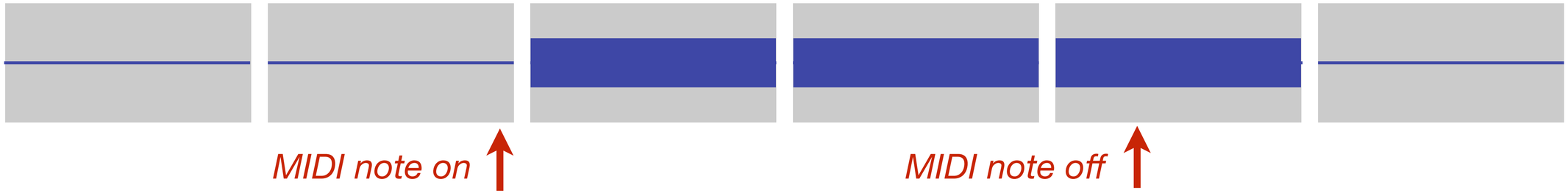
MIDI on Bela: other considerations

- 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)

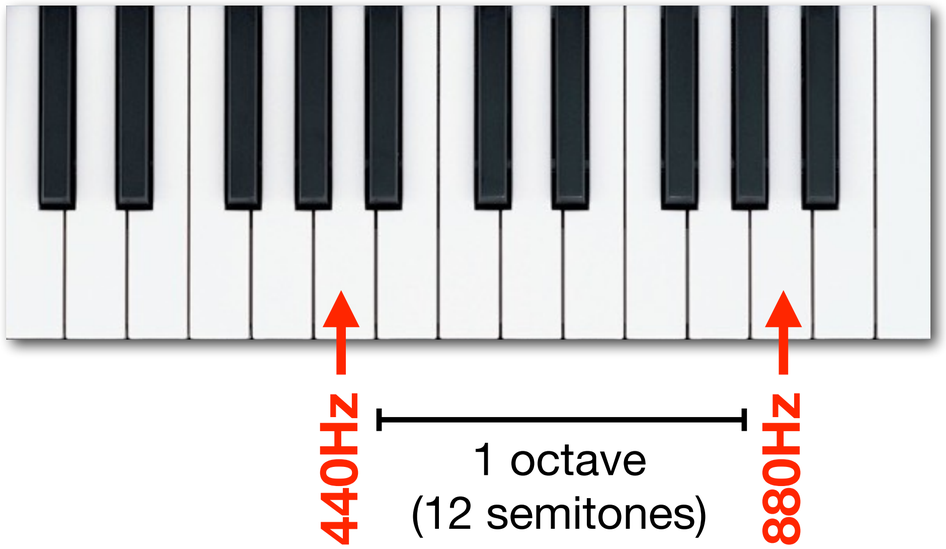
Making a MIDI synth

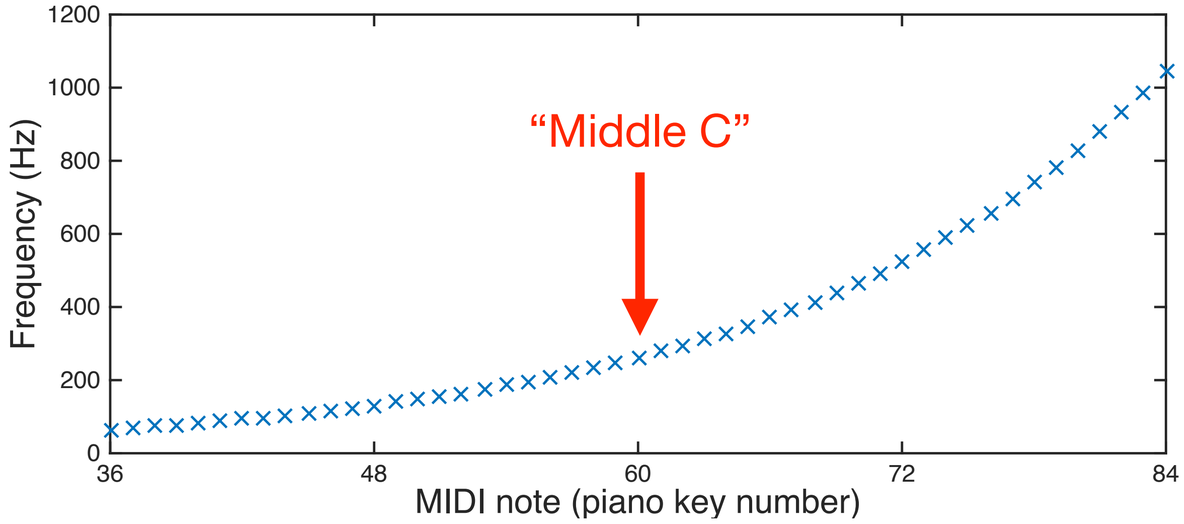


- When a Note On message arrives
  - Start generating sound for that note
    - If the sound has continuous sustain, keep generating it until we get a Note Off message
    - If the sound has a fixed length (e.g. percussion), generate it for the indicated length then stop
  - Convert the note number to a frequency
  - Optionally, set the amplitude (and/or other parameters) based on the velocity
    - Not all synths work this way: classic analog synths often do not have velocity control
- When a Note Off message arrives
  - Stop generating sound for that particular note
    - We'll look soon at how to handle multiple simultaneous notes

Review: frequency and pitch

- The perceived pitch of a sound is related to its frequency
- Pitch perception also operates on a logarithmic scale
  - Musical intervals are defined as frequency ratios
    - An octave is a 2:1 ratio; a perfect fifth is 3:2, a fourth is 4:3, etc.
  - To get from frequency to notes on a keyboard, we need a logarithmic calculation
  - However, by convention, this calculation is different from decibels





From musical pitch to frequency

- In audio synthesis, we often want to convert from pitch ("note") to frequency
  - We want a linearised scale: an increment of *x* is always the same musical interval
  - On analog synths, a common standard is 1V/octave
    - i.e. the control signal going up 1V makes the pitch go up by an octave (what happens to the frequency?)
- Given a reference frequency f_{ref} and an input *V* measured in octaves:
  - $f_{out} = f_{ref}2^{V}$ *(octaves to frequency)*
  - What if *V* was measured in semitones instead? (12 semitones to the octave)
    - How do I convert from semitones to octaves?
  - $f_{out} = f_{ref}2^{V/12}$ *(semitones to frequency)*

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)*

Building a basic MIDI synth

- Tasks: using the midi-sinetone example
  1. Implement MIDI note to frequency conversion for Note On messages

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

     - Sound can play all the time for now
     - Fill in the `noteOn()` function
  2. Mute the sound when a Note Off is received
     - Fill in the `noteOff()` function
  3. Implement velocity mapping to amplitude
     - Use a decibel scale where velocity 1-127 maps from -40dB to 0dB

$$A_{dB} = 20\log_{10}(A_{linear}) \quad \longleftrightarrow \quad A_{linear} = 10^{\frac{A_{dB}}{20}}$$

Monophony and polyphony

- There are two general approaches to musical synthesisers:

Monophonic

- One note at a time, no matter how many keys are pressed
- Only need one oscillator, one amplitude envelope, one filter etc.
- Early analog synths worked this way

Polyphonic

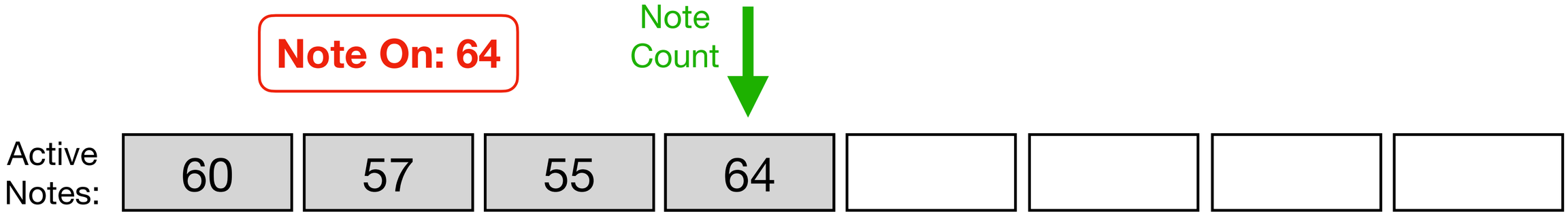
- Multiple notes at a time
- Closer to the familiar piano
- Each note has its own independent oscillators, filters, envelopes etc.
- There might be a maximum polyphony
- Some later analog synths and many digital ones work this way

Monophonic synths

- One note at a time seems easy: but which note?
  - The MIDI keyboard might still generate multiple notes
  - Typically, a monosynth uses the most recent note it receives
  - Our example has worked this way so far
- What happens when there are multiple notes active, and one note goes off?
  - In our simple example, the synth went silent: this isn't what we want
  - We would want it to revert to another note that was still held down
- Need a way to remember multiple key presses, in order of arrival
  - Play the most recent note, but remember the earlier ones
  - When the most recent note releases, go back to the one before
  - Only when all the notes release should the synth go silent

Remembering note order

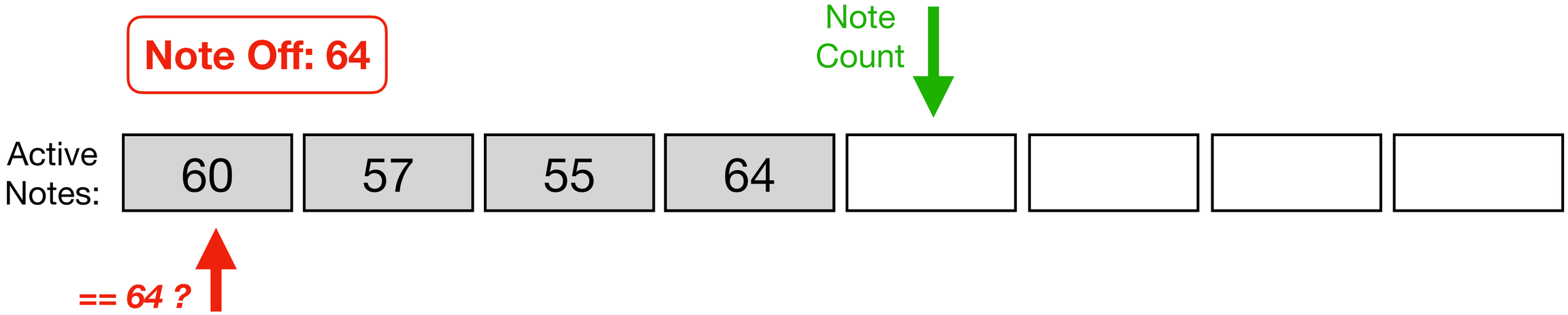
- We need two things to remember multiple key presses
  1. Array of currently active notes
     - This does not necessarily mean our synth is polyphonic: just that we remember which keys are held
     - Oldest notes occupy the earliest slots in the array
  2. Counter which keeps track of how many notes are in the array
     - Also doubles as a pointer to the first empty slot



- On receiving a Note On message:
  - Add the note number to the end of the array (at the location of the counter)
  - Increment the counter (which always points to the first empty slot)
  - Start the note as normal (set frequency, trigger envelope, etc.)

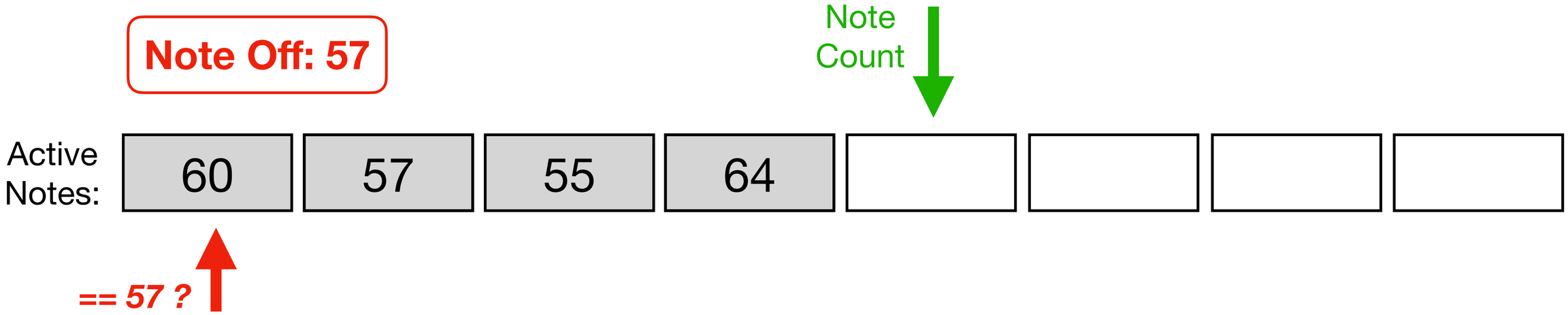
Remembering note order

- On receiving a Note Off message:
  - Step through the array and see if any of the elements match the note number
- If we find a match to the most recent note:
  - Remove it from the array, decreasing the count
  - Play the previous note (update oscillator frequency; might not retrigger the envelope)



Remembering note order

- On receiving a Note Off message:
  - Step through the array and see if any of the elements match the note number
- If we find a match to an older note:
  - Remove it from the array
  - Move back all the later elements, then decrease the count

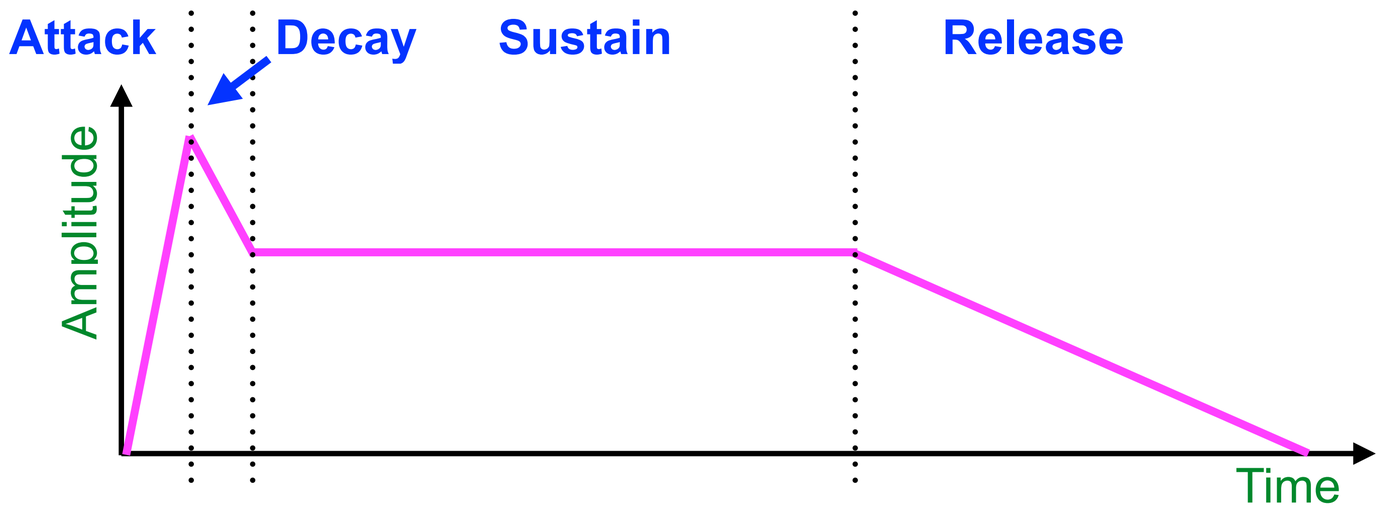


- If array becomes empty (count is 0), turn oscillator off

Note order task

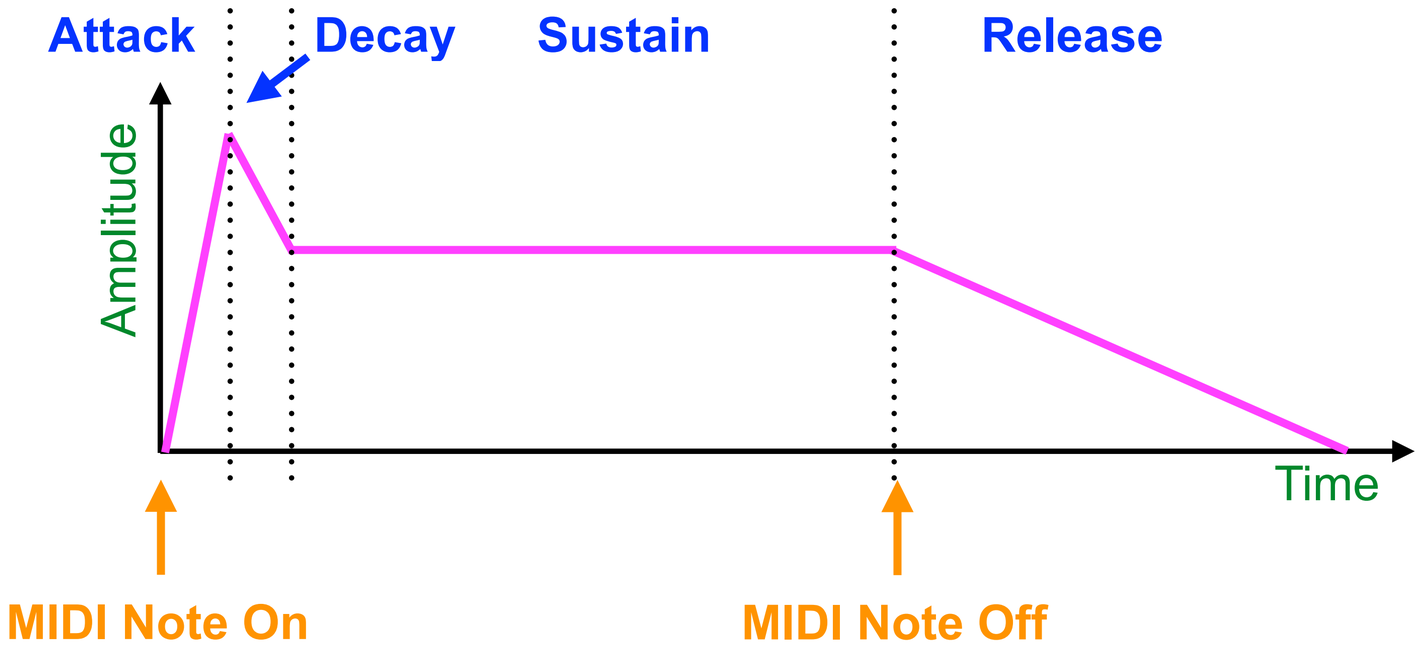
- Task: using the example midi-multinote
  - The code in `noteOn()` is already done for you, to add the most recent note to the array
  - Implement the code in `noteOff()` to keep track of multiple notes
  - When we get a note off message:
    - Check each element of the array to see if it matches the note number we just received
    - Remove that note from the array
    - If we removed the latest (last) element of the array, we will need to change the frequency
    - Move any later elements backward by one slot so the array doesn't contain any gaps
  - Variables are declared for you at the top of the file

ADSR envelopes



- Four phases (states) to an ADSR envelope:
  - Attack: level rises from 0 to maximum value (typically 1)
  - Decay: level drops from 1 to the sustain level (between 0 and 1)
  - Sustain: level remains constant at the sustain level
  - Release: level drops to 0 over a specified period of time
- The segments are often linear, can also be exponential

MIDI with ADSR



- Task: in project midi-adsr, use MIDI to control the ADSRs for amplitude/filter
  - All code to change is in `render.cpp`
  - Trigger the ADSRs in `noteOn()`
  - Release the ADSRs when the last note goes off in `noteOff()`
  - Process the ADSR values in `render()`, following Lecture 14

Gates and triggers

- In addition to control voltages (CVs), some synth modules are controlled by gates and triggers
  - Both are effectively digital signals, with only two states (on and off)
- A gate is a signal representing two states: open and closed
  - Usually, by convention, a positive voltage is open and 0V is closed
  - The ongoing value of the gate signal is what matters
- A trigger is a signal representing an instantaneous event
  - Used to begin envelopes, advance sequencers, and many other applications
- MIDI Note On messages might control both gates and triggers
  - The gate will indicate whether the synth is currently sounding
  - The trigger will create the attack phase of the ADSR envelope
- Task: in midi-adsr, make the ADSR trigger only on the first Note On received
  - Don’t retrigger the ADSR if a note is already sounding, just change the pitch

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