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
Circular buffers
Timing in real time
State machines
MIDI
Block-based processing
Threads
Fixed point arithmetic
ARM assembly language

Today

Music/audio topics

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

Lecture 7: Digital I/O

What you'll learn today:

Digital inputs and outputs on Bela
Working with push buttons
Gates and triggers

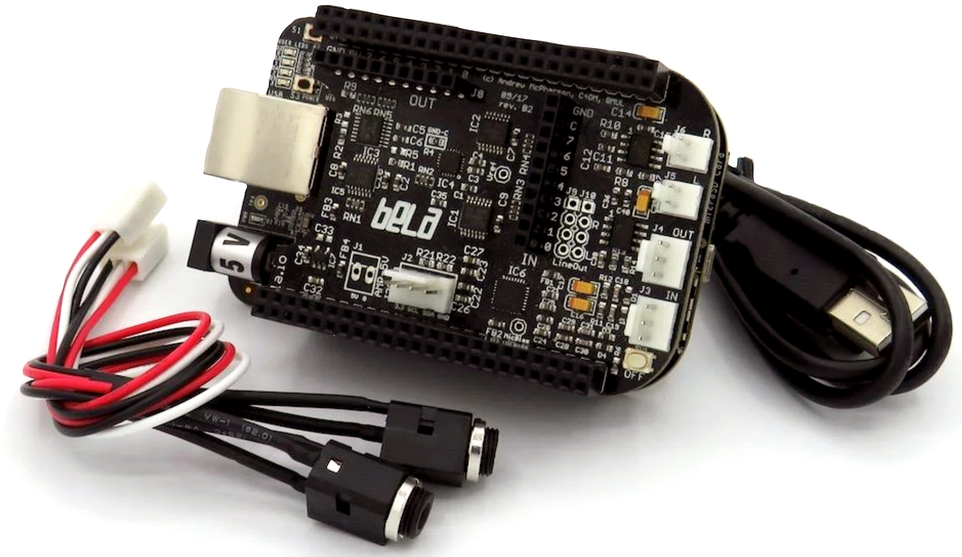
What you'll make today:

A noise generator and a step sequencer

Companion materials:

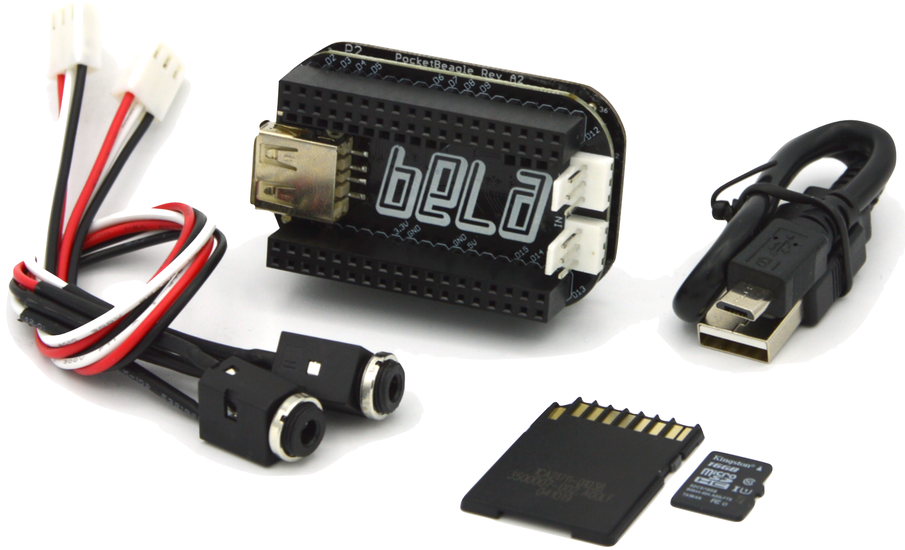
github.com/BelaPlatform/bela-online-course

What you'll need



Bela Starter Kit

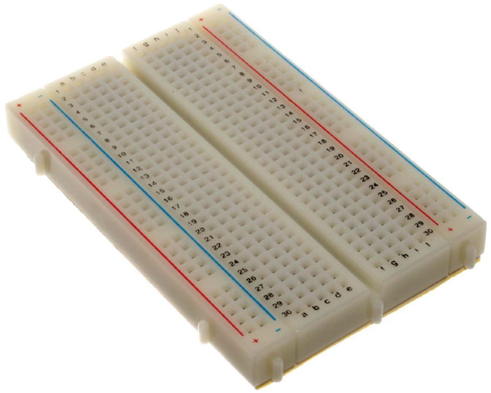
or

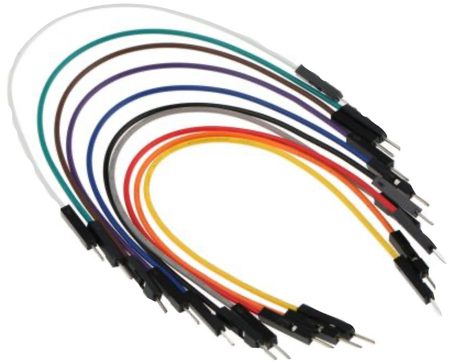


Bela Mini Starter Kit

[shop.bela.io]

Also needed for this lecture:



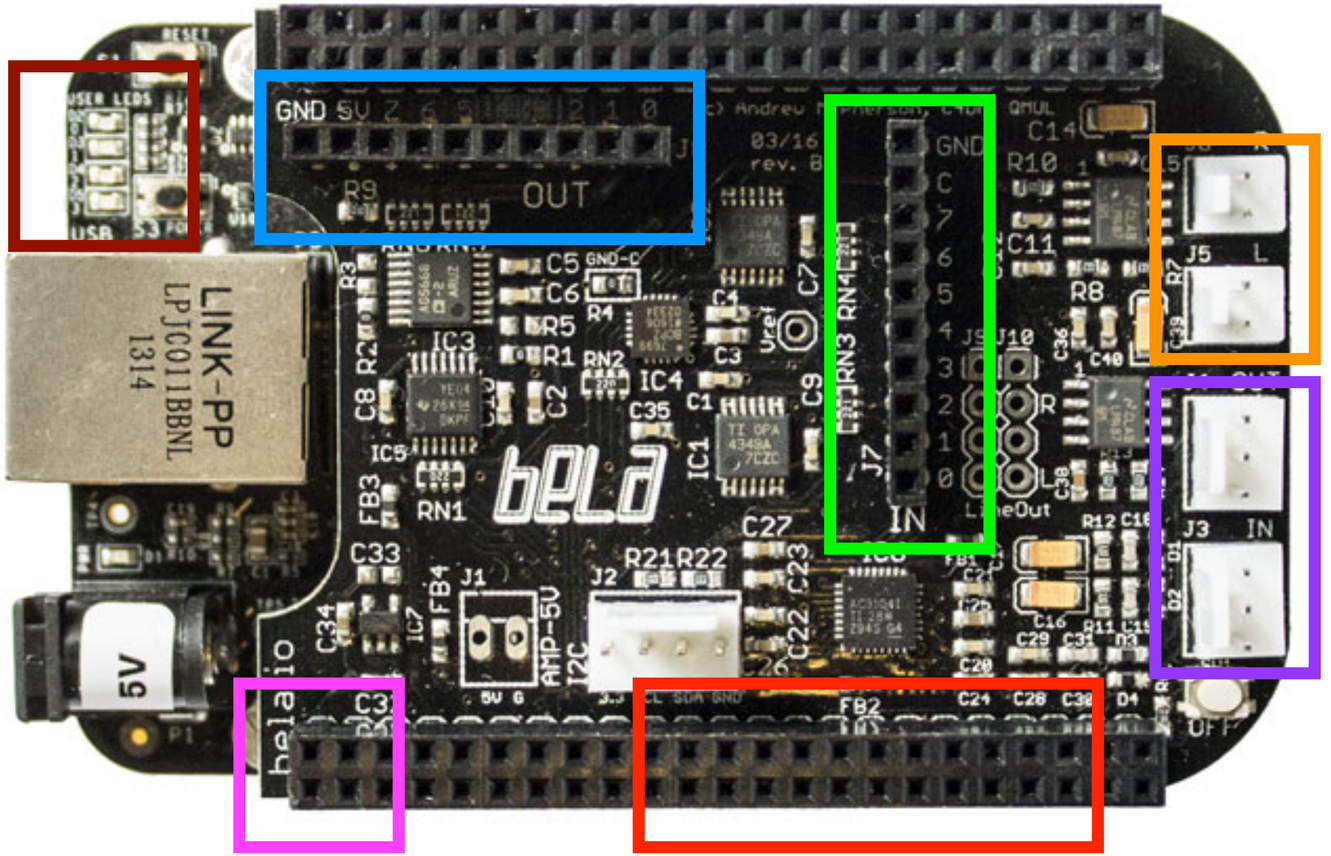


Bela hardware

Analog outputs

Analog inputs

USB to computer



R speaker

L speaker

Audio out (headphones)

Audio in

Power / Ground

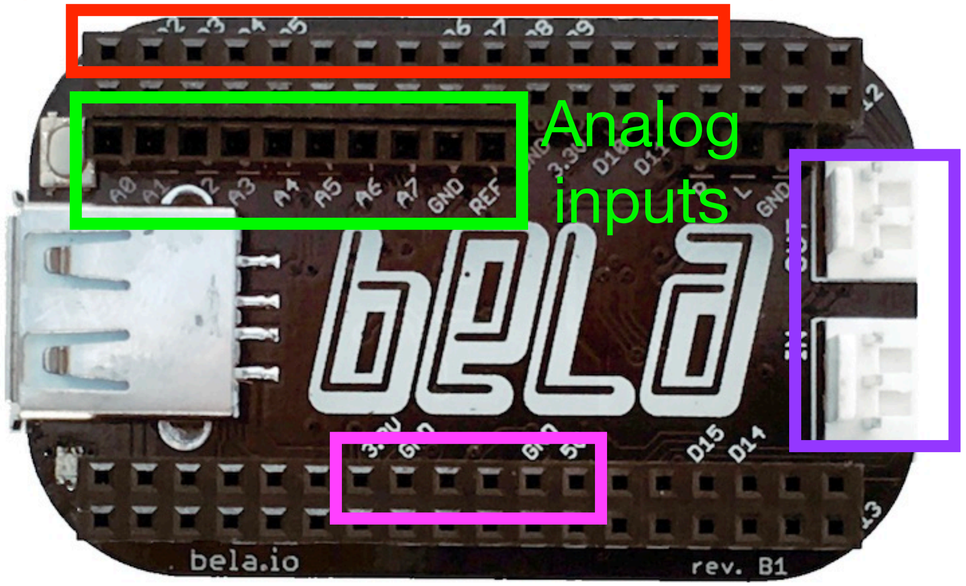
Digital inputs/outputs
(various locations around board)

Bela Mini hardware

Digital inputs/outputs
(various locations around board)

Analog inputs

USB to computer (below)



Audio out (headphones)

Audio in

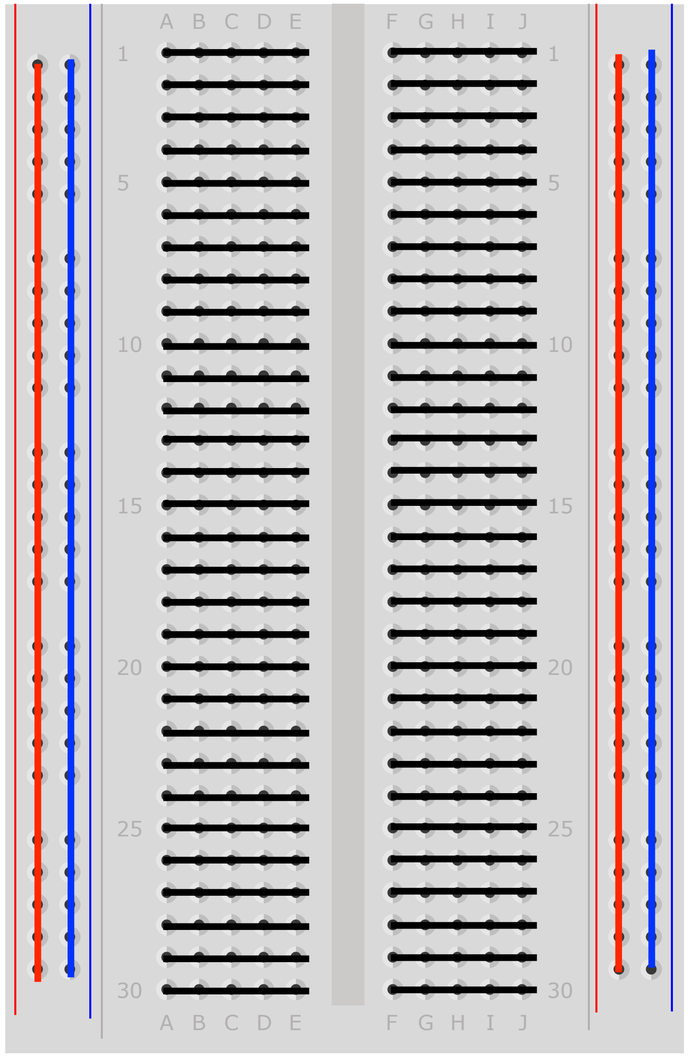
Power / Ground

Using a breadboard

Each column of 5 holes connects together...

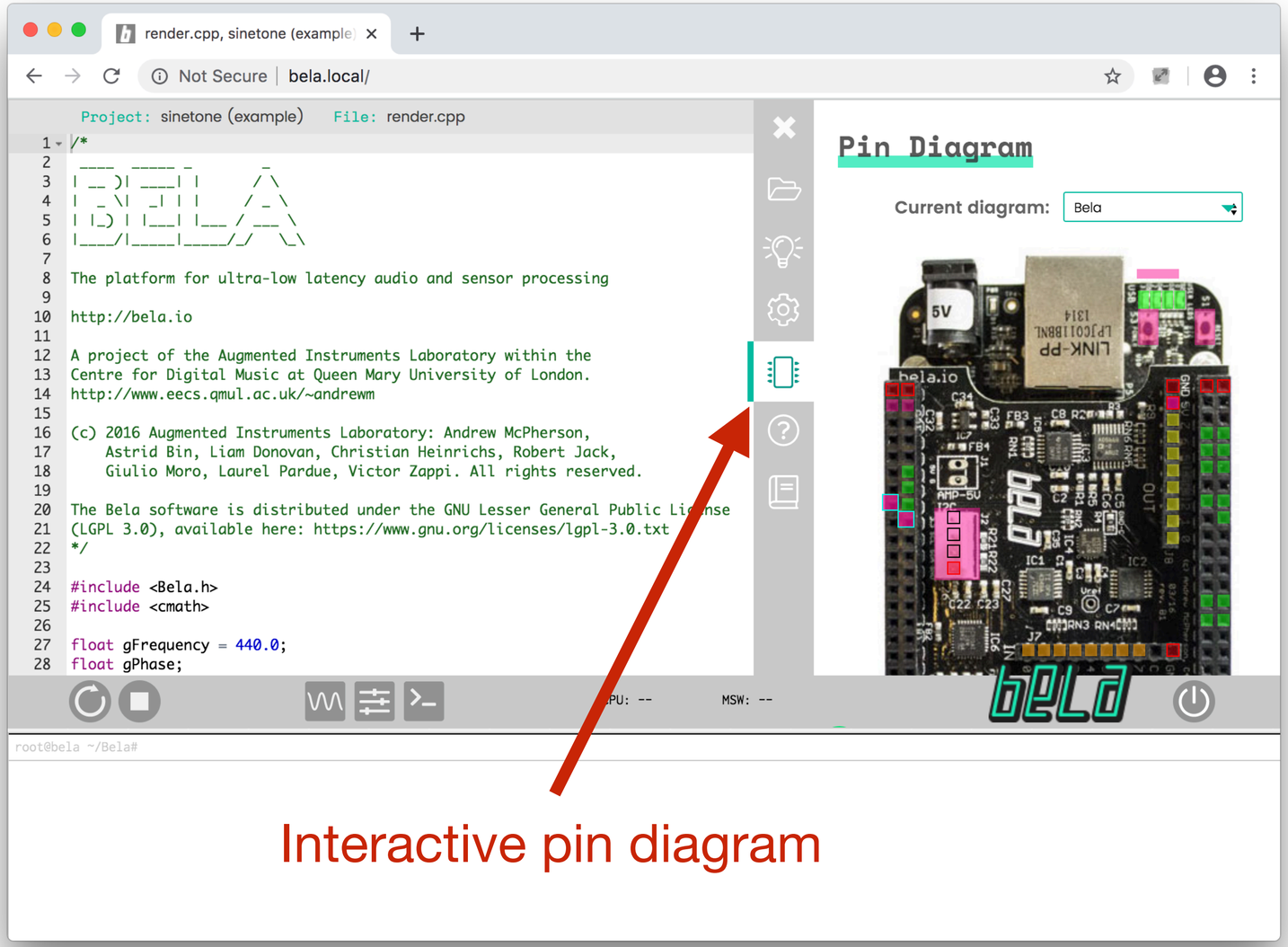
...but not across the break in the middle.

Long rows at the ends each connect together. Typically used for power and ground



Digital pin numbering

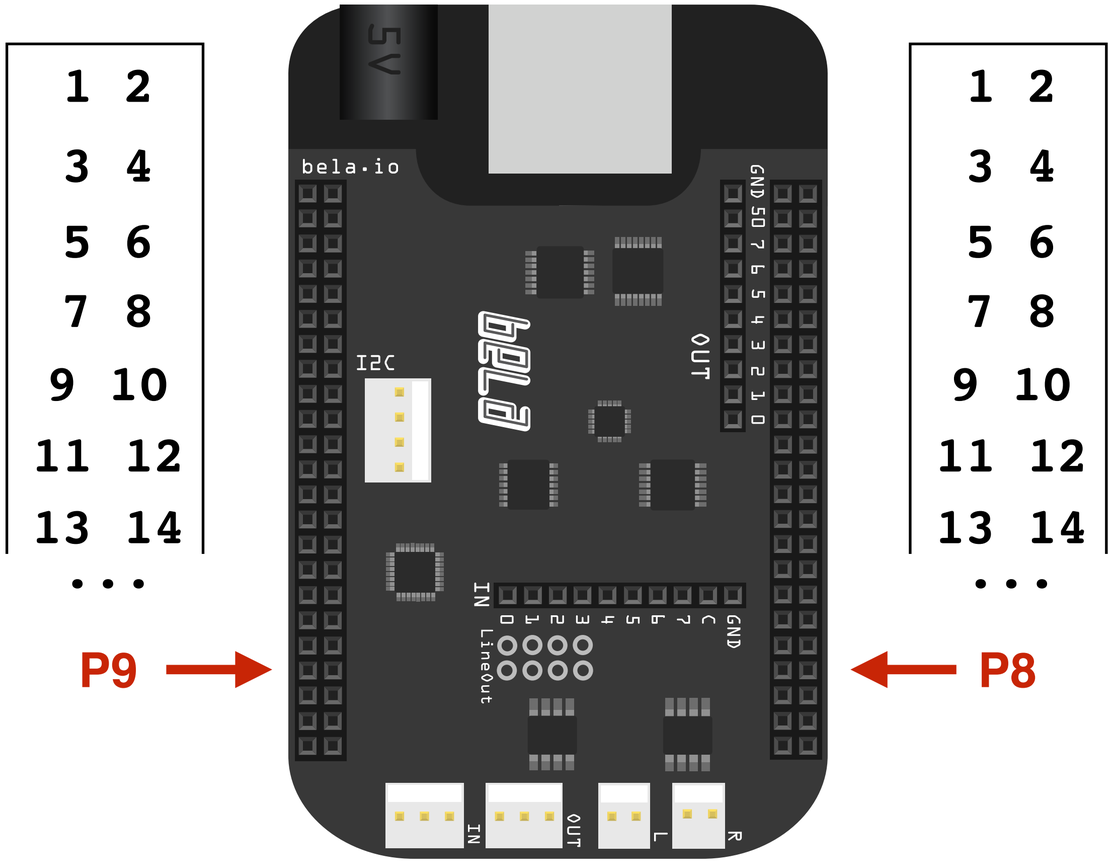
- You can always find the pinout for the digital I/O and other connectors in the IDE's Interactive Pin Diagram



Bela digital pin numbering

- 16 digital I/O pins are available on the P8 and P9 headers of the Bela cape
  - The names P8, P9 come from the BeagleBone Black
  - You can find what all the other pins do in the BeagleBone Black System Reference Manual:
    - https://github.com/beagleboard/beaglebone-black/wiki/System-Reference-Manual
  - Useful pins:
    - **Ground** on P8_1, P8_2, P9_1, P9_2
    - **3.3V** on P9_3, P9_4
  - Not all the pins are available to us

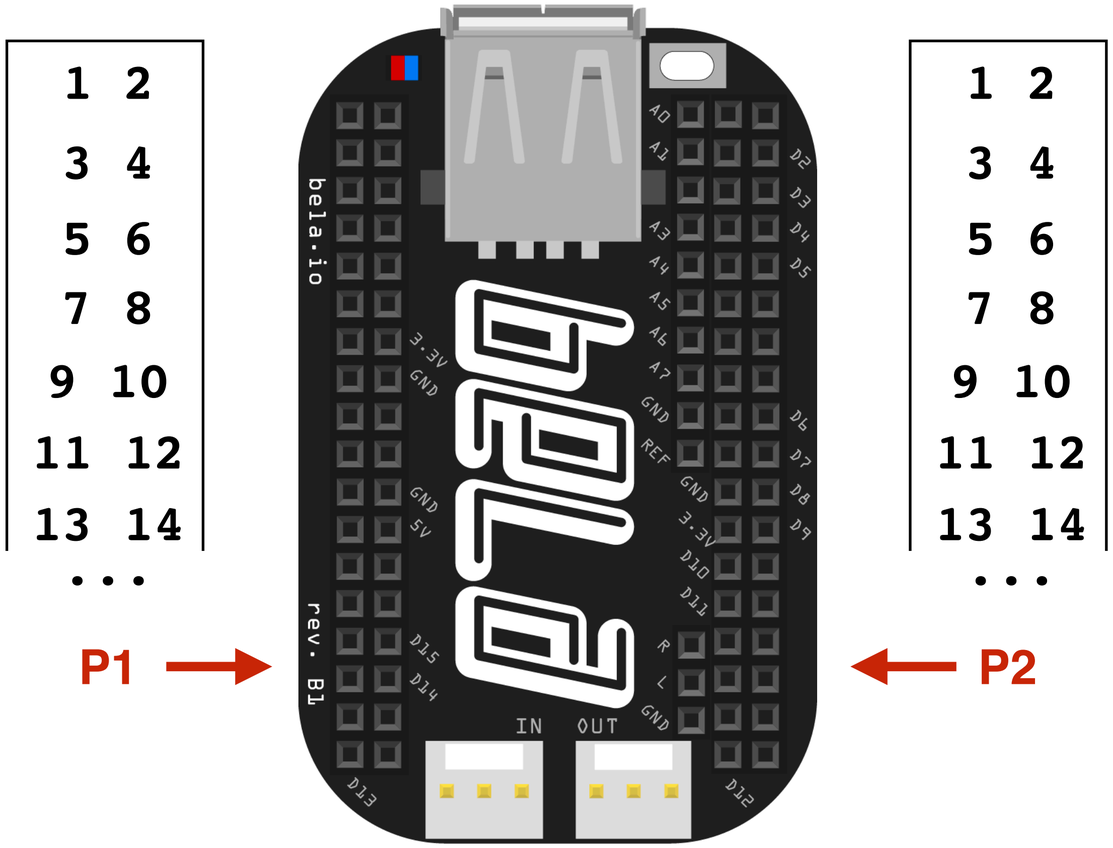
Important: NEVER use 5V with digital I/Os!



Bela Mini digital pin numbering

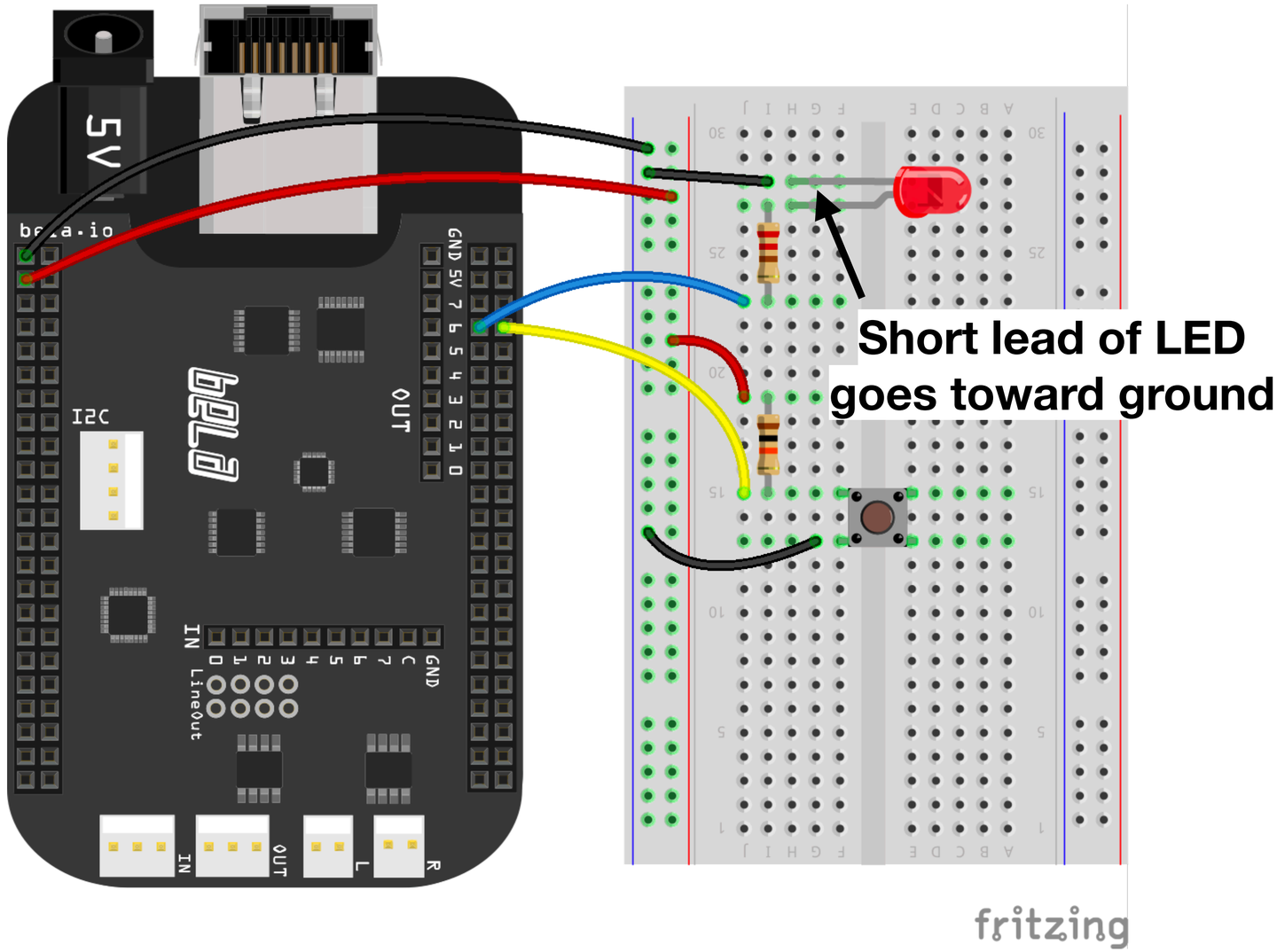
- 16 digital I/O pins are available on the P1 and P2 headers of the Bela Mini cape
  - The names P1, P2 come from the PocketBeagle
  - You can find what all the other pins do in the PocketBeagle System Reference Manual:
    - https://github.com/beagleboard/pocketbeagle/wiki/System-Reference-Manual
  - Digital and power pins are labelled on the Bela Mini cape
  - Not all the pins are available to us

Important: NEVER use 5V with digital I/Os!



Connect LED and button

- Connect the LED to digital pin 0
  - P8_7 on Bela
  - P2_1 on Bela Mini
- Connect the button to digital pin 1
  - P8_8 on Bela
  - P2_2 on Bela Mini
- Important: the button requires 3 wires and a resistor!
- Run the digital-io example from the companion materials



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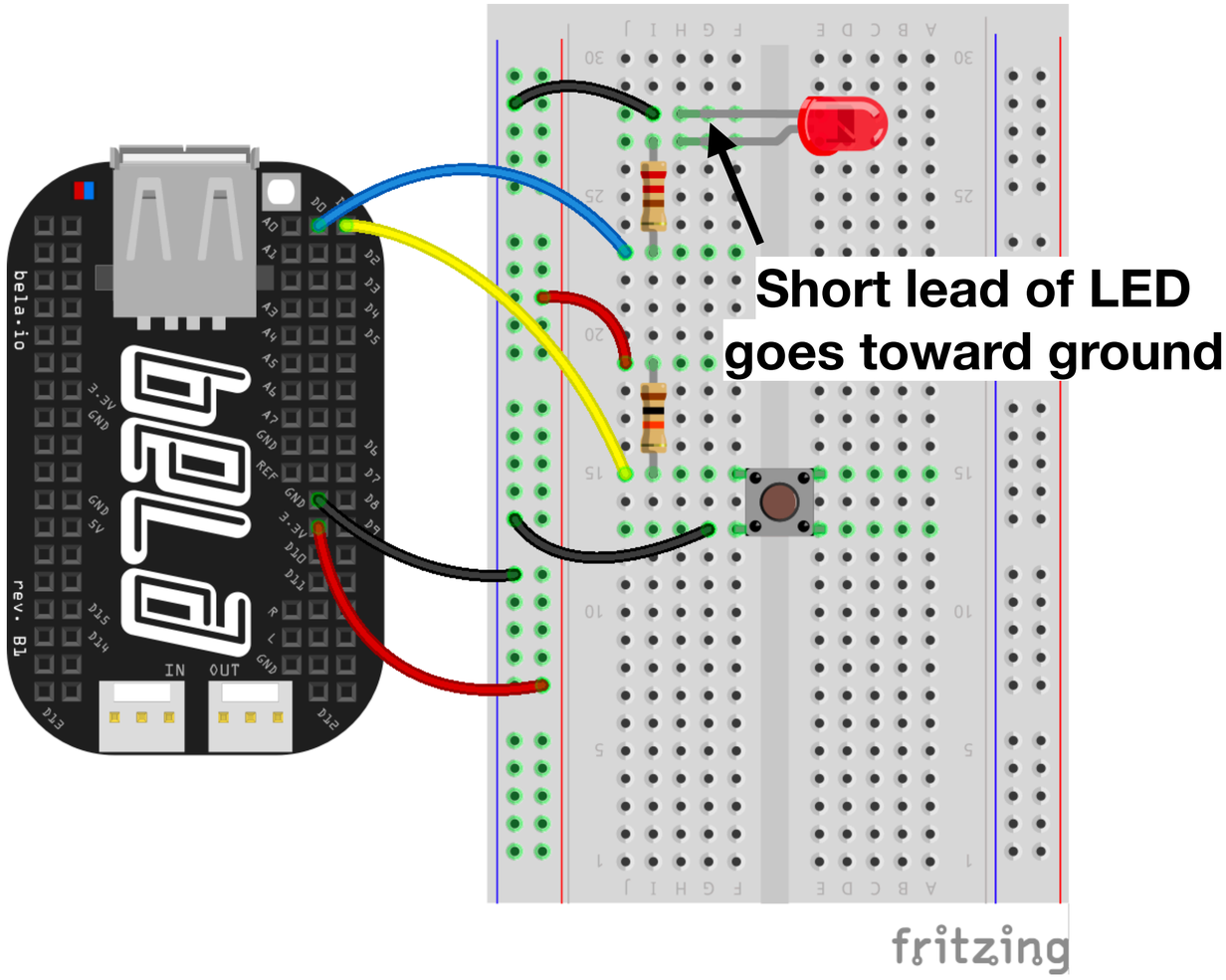


Digital I/O

- Digital input and output is sometimes called GPIO
  - General-Purpose Input and Output
- Digital I/Os have only two levels (“logic levels”)
  - High or Low, 1 or 0 - which on Bela corresponds to 3.3V and 0V
- Digital inputs and outputs on Bela are sampled signals
  - 44.1kHz sample rate, just like audio
  - Unlike audio, the possible values are **only** 0 and 1 (nowhere in between)

```
int digitalRead(BelaContext *context, int frame, int channel);
void digitalWrite(BelaContext *context, int frame, int channel, int value);
```

Reference to the `BelaContext` structure, which holds the actual data we want

Which frame (i.e. sample) within the buffer to write

Which channel (e.g. 0, 1, ..., 15) to write

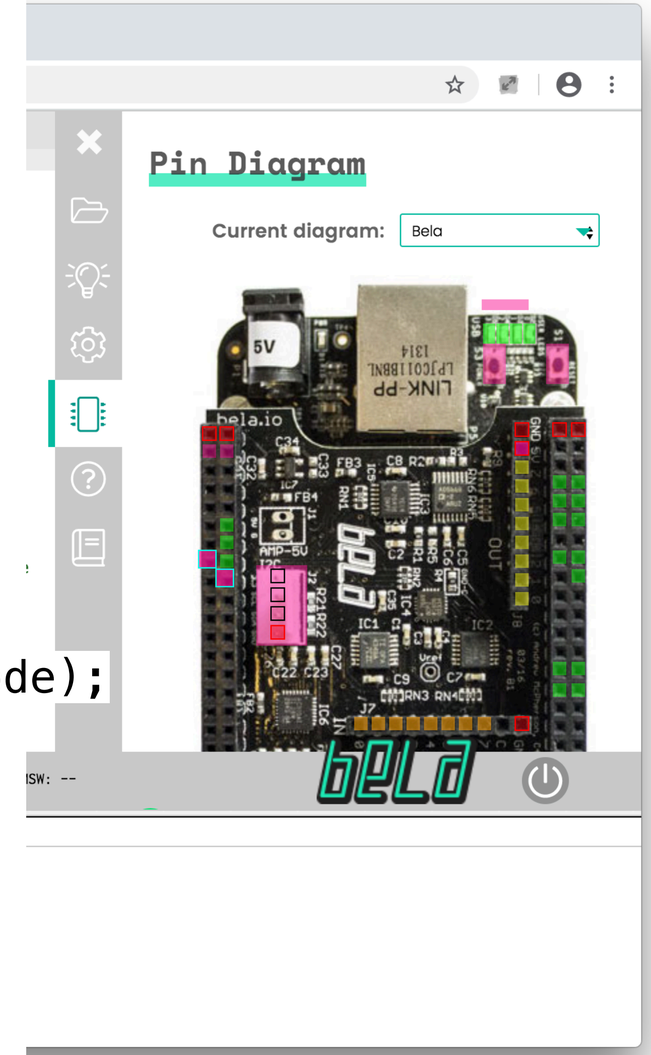
What value to write

Digital I/O

- Bela has only 16 digital pins
  - See the interactive pin diagram for where to find them
- How do we know which are inputs vs. outputs?
  - Any digital pin could be either!
  - We have to tell the system which way to set it
- All digital pins start as inputs by default
  - To change, we call a function:

```
void pinMode(BelaContext *context, int frame, int channel, int mode);
```

  - As with `digitalRead()` and `digitalWrite()`, this is set to take place at a particular frame
    - Note: like analog output, digital output has the functions `digitalWriteOnce()` and `pinModeOnce()`



Digital I/O code

```
// ***** Inside setup():
// Set the LED pin to be an output
pinMode(context, 0, kLedPin, OUTPUT);
// Set the button pin as an input. This isn't strictly needed but is recommended
pinMode(context, 0, kButtonPin, INPUT);
```

Set the pin directions at the beginning

Predefined constants

```
// ***** Inside render(), within the for() loop:
// Read the button
int status = digitalRead(context, n, kButtonPin);

// Check if the value was low
if(status == LOW) {
    // Low input means the button was pushed. Turn on the light and play the sound.
    // Generate white noise: random values between -1 and 1
    float noise = 2.0 * (float)rand() / (float)RAND_MAX - 1.0;
    out = noise * 0.1;
    digitalWriteOnce(context, n, kLEDPin, HIGH);
}
else {
    // Button wasn't pushed. Turn the LED off, no sound
    digitalWriteOnce(context, n, kLedPin, LOW);
}
```

Read the input and check its value

Write the output (3.3V)

Write the output (0V)

White noise

- White noise is a random signal with constant power spectral density
  - Equal energy at all frequencies
  - Compare to pink noise, red noise which have more power at lower frequencies
- We can make a digital white noise signal with a random number generator
  - Each sample is independent of the previous one, with a uniform distribution

```
float noise = 2.0 * (float)rand() / (float)RAND_MAX - 1.0;
```

Scale range to 0-2

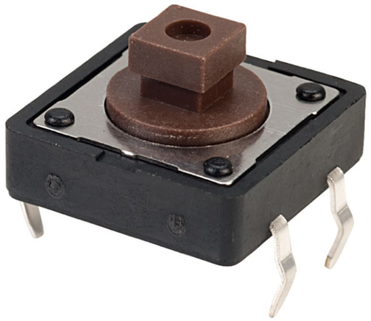
Random integer between 0 and `RAND_MAX` (see `stdlib.h`)

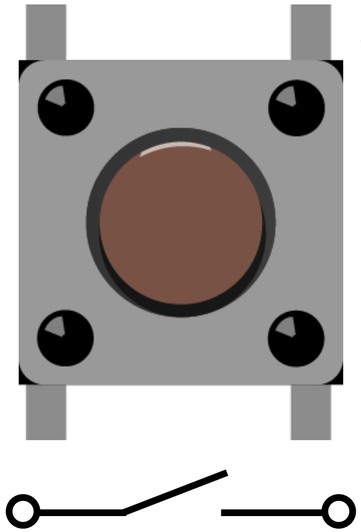
Maximum possible value for the random number: dividing by it normalises to 0-1

Rescale range to -1 to 1

How does the button work?

- Breadboard-style buttons are known as tactile switches
  - Extremely common in electronics, in both through hole and surface mount forms
  - Typically a normally open switch (connects only when button is pushed)

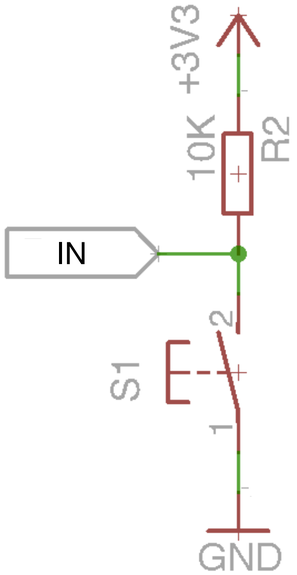




Why does it have 4 leads?

Just for mechanical stability

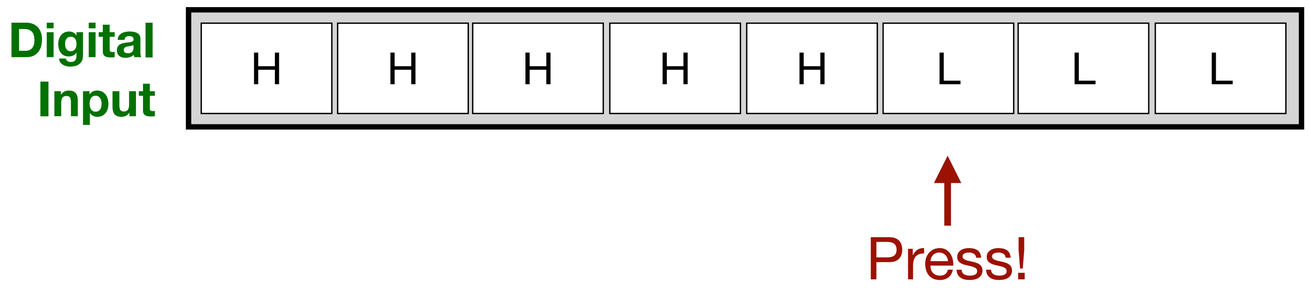
Important: the switch is between the **two adjacent pins on the same side**

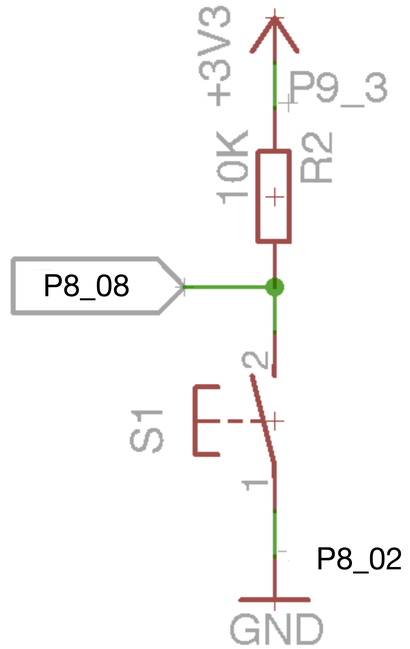


- To use the button, we need 3 wires a resistor:
  - When pushed, digital input connected to ground
  - When not pushed, resistor pulls input up to 3.3V

Detecting button presses

- How do we know if the button was held on any given frame?
  - `digitalRead()` will return... LOW
  - Be sure to compare to the wiring of your specific circuit!
- How do we know if the button was just now pressed?
  - i.e., how do we identify when a button press first begins?
  - Let's look at each successive frame of digital input:

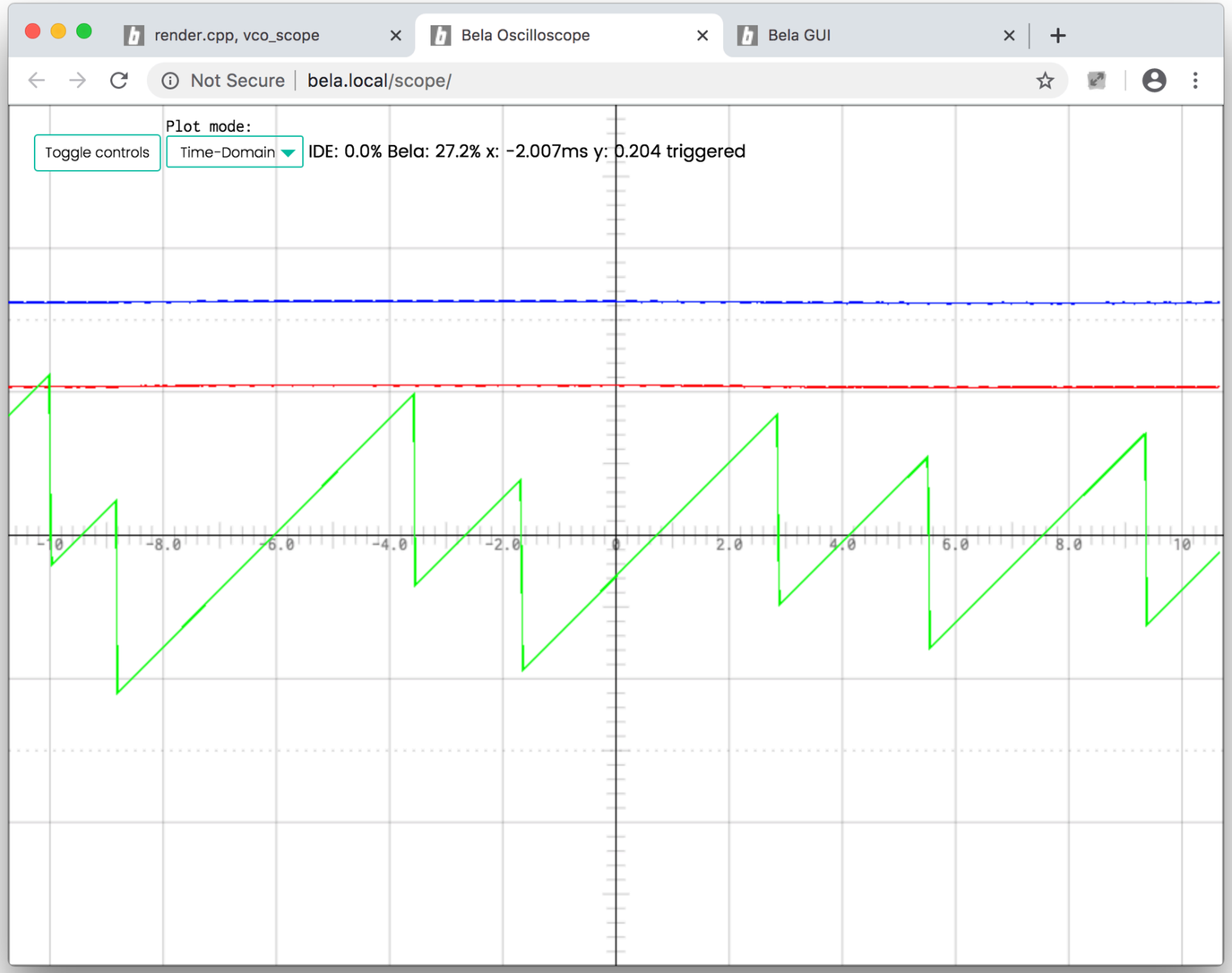




  - Condition is: previous value was high (= 1) and current value is low (= 0)
- This is known as edge detection

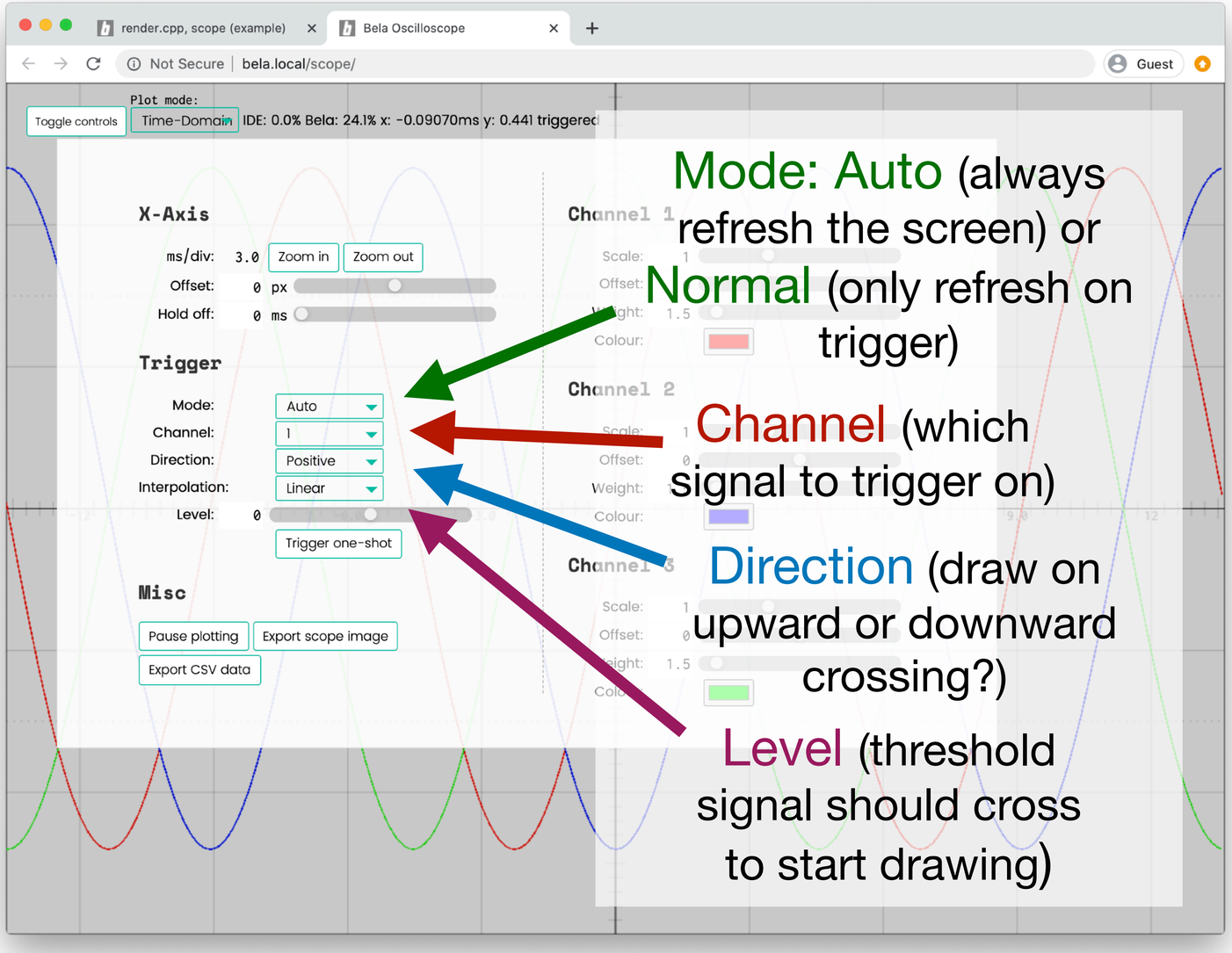
Oscilloscope

- Bela features an oscilloscope that runs in the browser
  - As the name "*oscillo-scope*" implies, a way of viewing oscillations (signals)
- Typical use of oscilloscope is an X-Y plot
  - Time on the X-axis
  - Amplitude on the Y-axis
- The scope can plot any signal made or used by your program
  - Not just I/O signals!



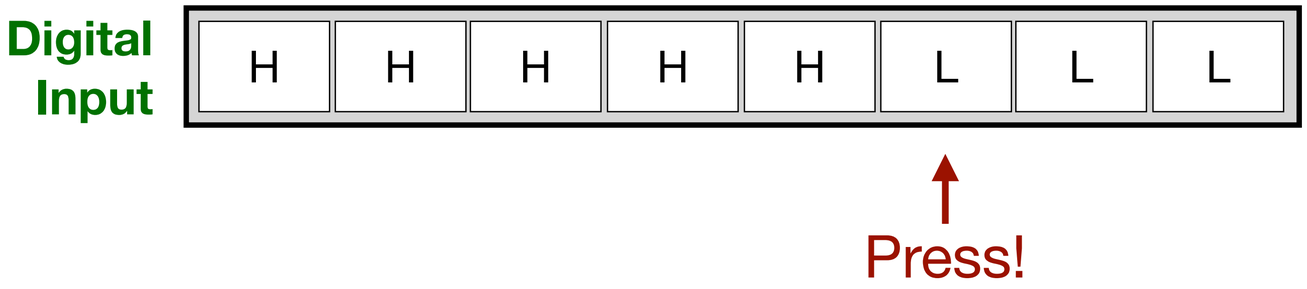
Oscilloscope controls: trigger

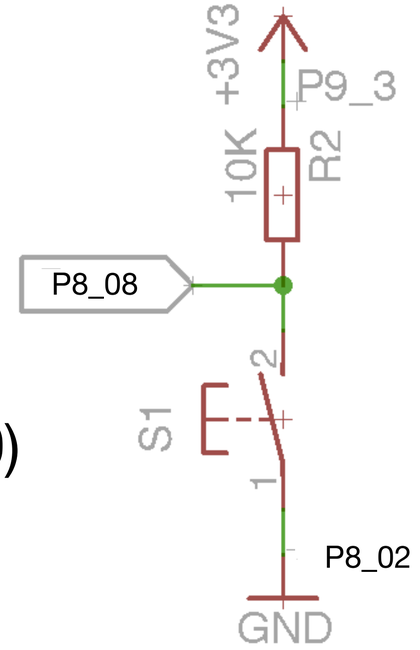
- Oscilloscopes show the signal in brief snapshots
  - One screenful corresponds to a limited window of time
  - To show the signal in real time, the scope regularly refreshes the screen with new time windows
- To keep the picture still, what do we need to do?
  - Start drawing at the same phase in the waveform each time
  - This is what the trigger does: sets where and how the screen starts drawing



Button as trigger

- Once again: how do we know if the button was just now pressed?
  - Let's look at each successive frame of digital input:





  - Edge detection: previous value was high (= 1) and current value is low (= 0)
- What do we mean by "previous value", and how do we find it?
  - Value of the digital input on the frame (sample) before this one
  - We need to remember the previous value by storing it in a global variable
  - That way, our next time through the loop in `render()`, we will have the old value alongside the current one

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
  - The transition (or edge) is what we care about - usually the edge from low to high
- In the digital-io example, we built a gate with the button
  - Pushing the button opens the gate so we can hear the noise
- Next, let's build a project using the button as trigger!

Step sequencer

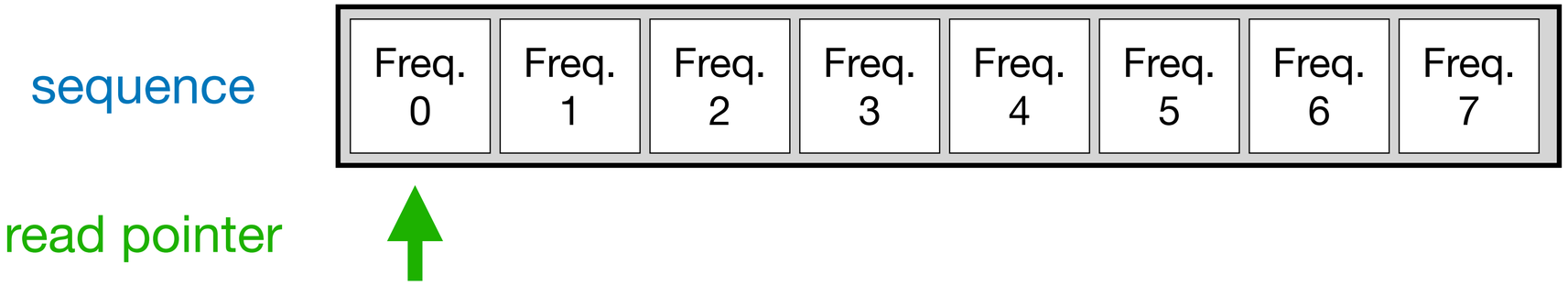
- A step sequencer plays a set pattern of notes in a loop
  - Step sequencers commonly store patterns of 8 or 16 notes
  - Every time it receives a trigger, it advances to the next note
- For now, let's focus just on controlling pitch (frequency)
  - We could implement a step sequencer like this:

  - We store 8 frequencies in a buffer, and the read pointer keeps track of which one we are currently reading. That frequency then controls an oscillator.
  - Does this architecture look familiar?
  - Very similar to playing a wavetable!

Step sequencers and wavetables

- Task: in the step-sequencer example,
  - Store the previous value of the button in a global variable
  - Look for a falling edge (high-to-low transition) on the input, which is the trigger
  - When you receive this trigger, advance the read pointer, looping as needed
  - Once this works, turn the LED on and off for successive steps (e.g. on for even steps)

- For a step sequencer, our buffer holds frequencies (or more generally, CV values)
  - We move the read pointer only when we receive a trigger (i.e. a signal edge)



Edge detection code

- We need the current and previous state of the button:

```
// Last state of the button
int gLastButtonStatus = HIGH;

void render(BelaContext *context, void *userData)
{
    for(unsigned int n = 0; n < context->audioFrames; n++) {
        // [...]
        // Check for a button press to advance the sequence
        int status = digitalRead(context, n, kButtonPin);

        if(status == LOW && gLastButtonStatus == HIGH) {
            // Button was pressed - advance the sequence
            gSequencerLocation++;
            if(gSequencerLocation >= gSequencerBuffer.size())
                gSequencerLocation = 0;
        }

        gLastButtonStatus = status;
        // [...]
    }
}
```

global variable to hold previous state

so that the **next** time it holds last status

set `gLastButtonStatus` to current status

CV out (Bela only)

- As a final step, let's have our step sequencer output a CV
  - We'll use the analog output with a 1V/octave standard
- We already have the sequence stored as MIDI note numbers:

36 (C2)	**48** (C3)	**39** (E♭2)	**51** (E♭3)	**53** (F3)	**41** (F2)	**55** (G3)	**43** (G2)

  - We used this formula to convert to frequency: $f_{out} = 440 \cdot 2^{\frac{N-69}{12}}$
  - Let's convert MIDI notes to octaves with the lowest note (36) as a reference
  - How do we convert note number N to semitones above the reference? N - 36
  - Now how about octaves above the reference? (N - 36) / 12
- Task: add CV out to the step-sequencer example
  - *Hint: given that analog output range is 0-5V, what value do we have to write to get 1V?*

Keep in touch!

Social media:

@BelaPlatform

forum.bela.io

blog.bela.io

More resources and contact info at:

learn.bela.io/resources