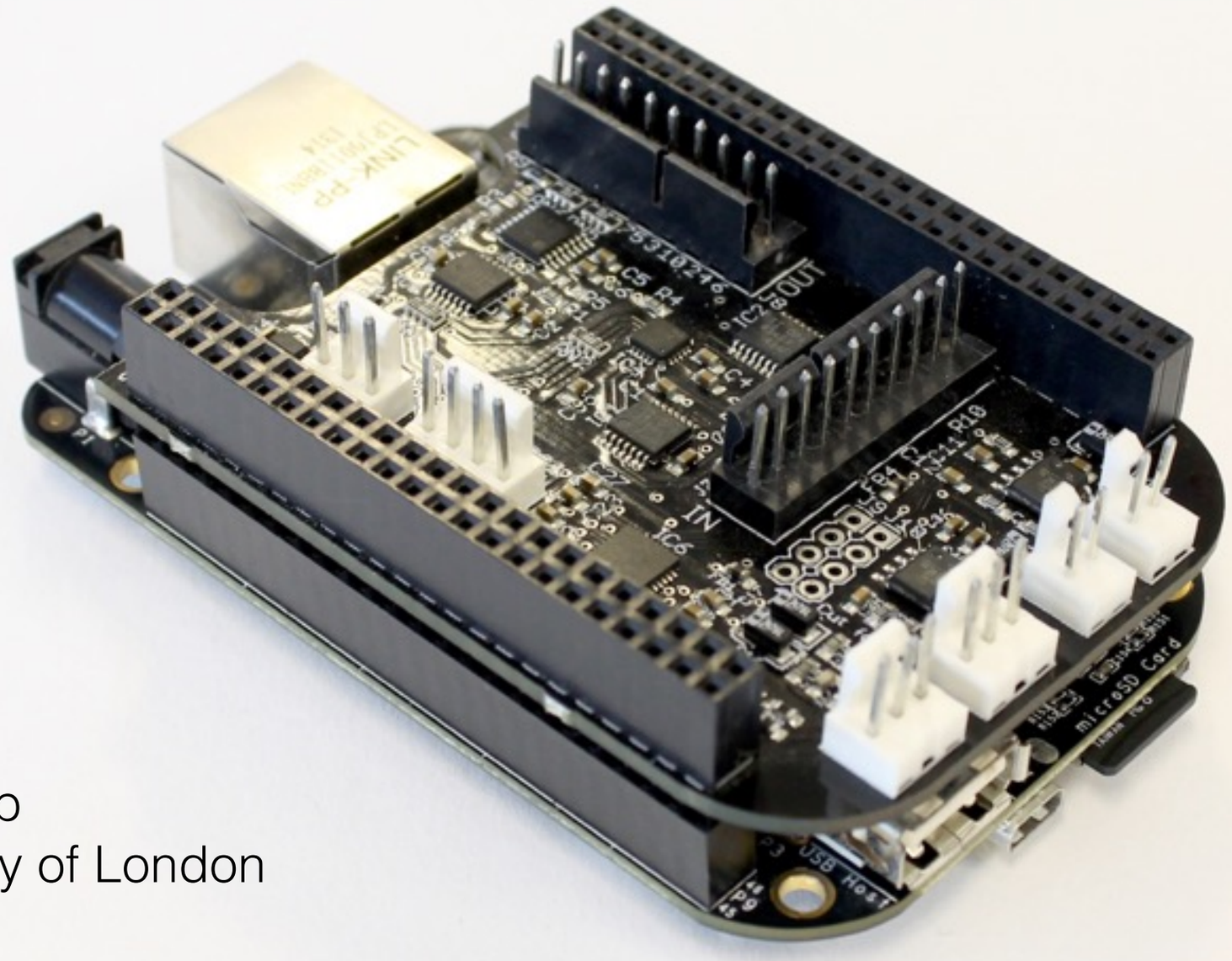
bela

Ultra-low latency audio and sensor processing on the BeagleBone Black



A project by
The Augmented Instruments Lab
at C4DM, Queen Mary University of London

http://bela.io

EPSRC
centre for digital music
Queen Mary University of London

How it started

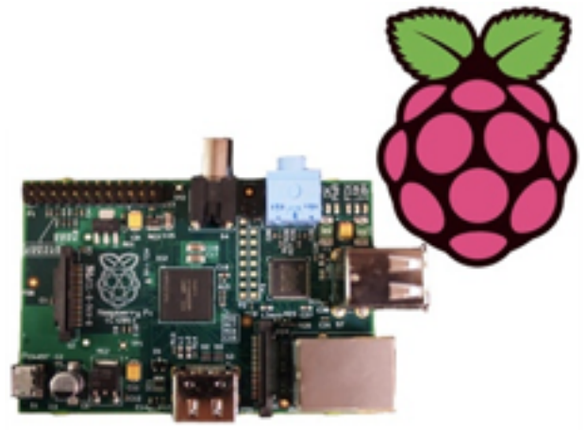
The Goal:

High-performance, self-contained audio and sensor processing

Already available platforms:

ARDUINO

- Easy low-level hardware connectivity
- No OS = precise control of timing
- Very limited CPU (8-bit, 16MHz)
- Not good for audio processing



- Reasonable CPU (up to 1GHz ARM)
- High-level hardware (USB, network etc.)
- Limited low-level hardware
- Linux OS = high-latency / underruns

- Fast CPU
- High-level hardware (USB, network etc.)
- Arduino for low-level
- USB connection = high-latency, jitter
- Bulky, not self-contained

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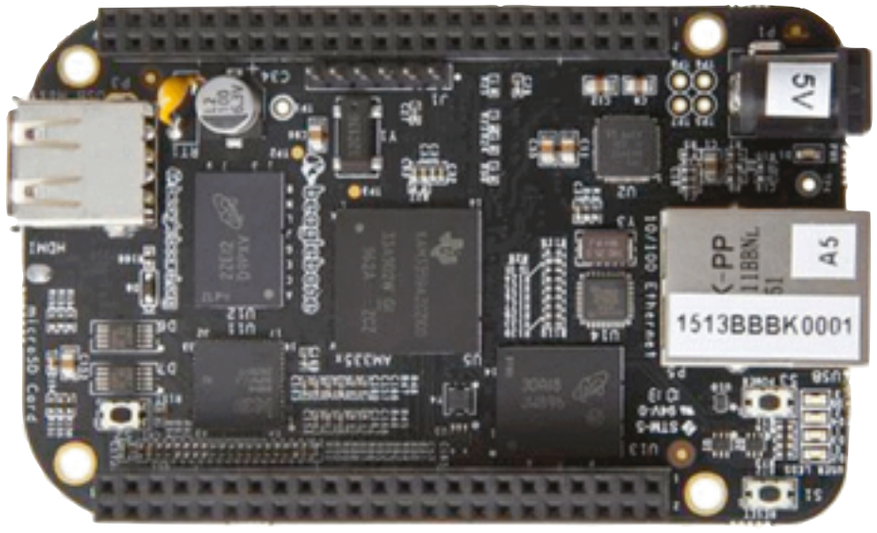
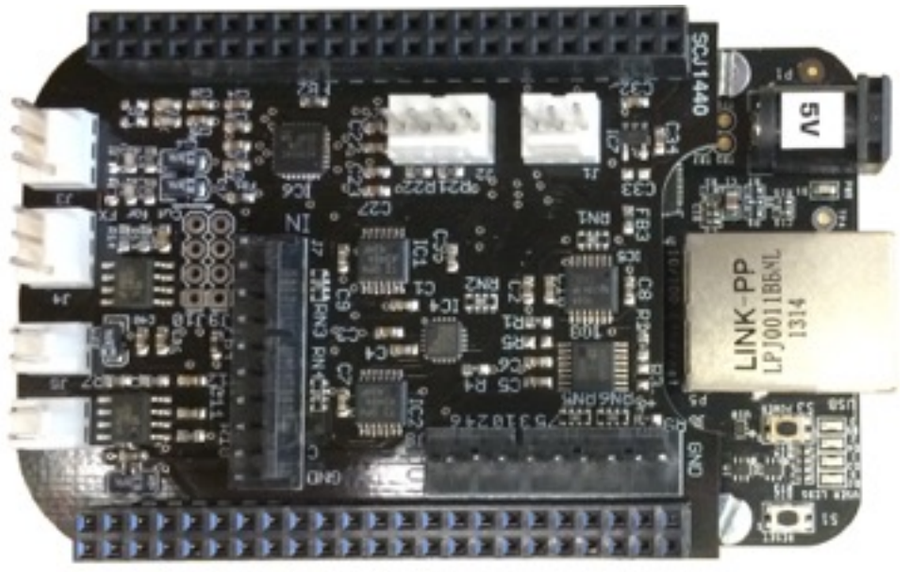
Hardware



BeagleBone Black

1GHz ARM Cortex-A8
NEON vector floating point
PRU real-time microcontrollers
512MB RAM



Custom Bela Cape

Stereo audio in + out
Stereo 1.1W speaker amps
8x 16-bit analog in + out
16x digital in/out

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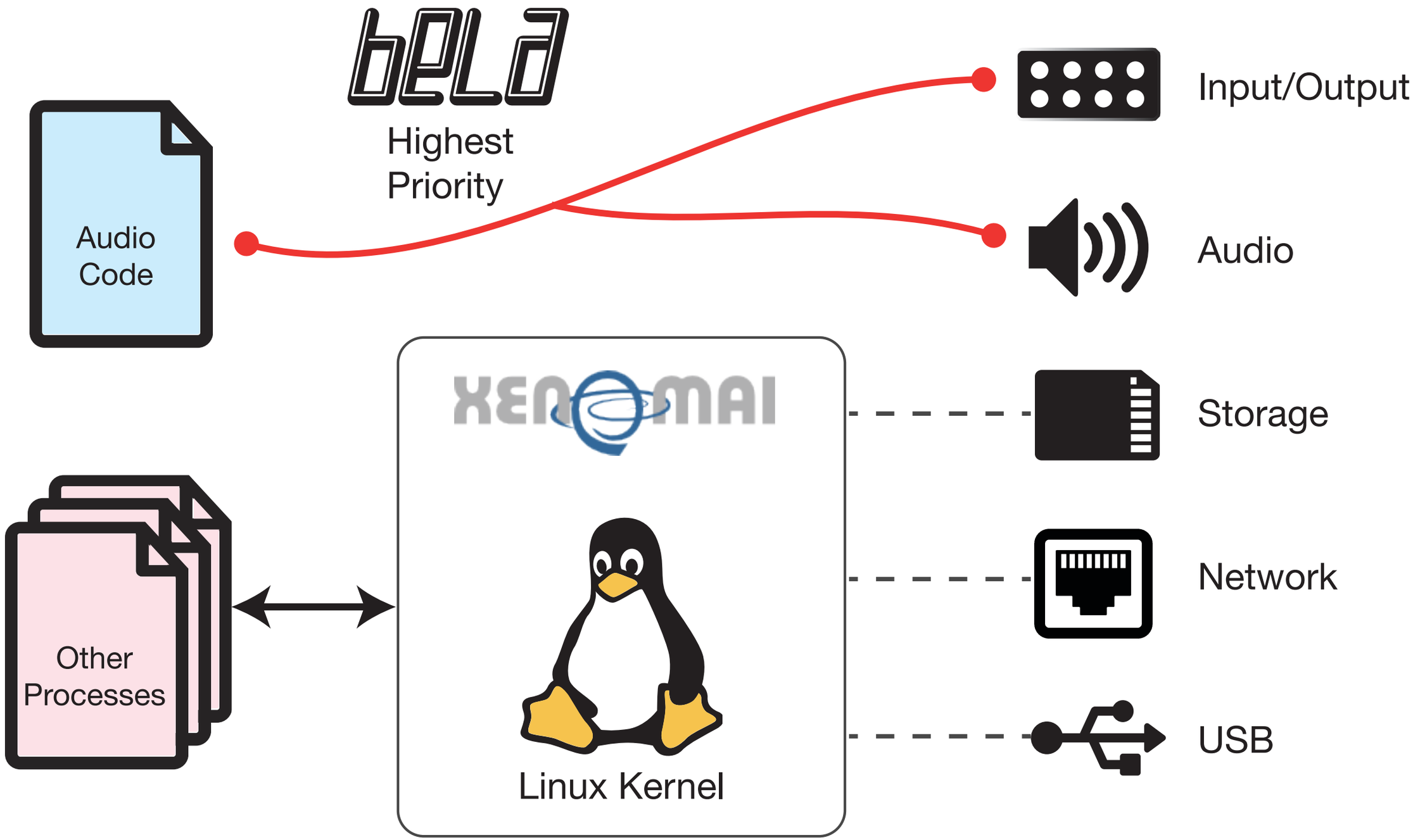
Features

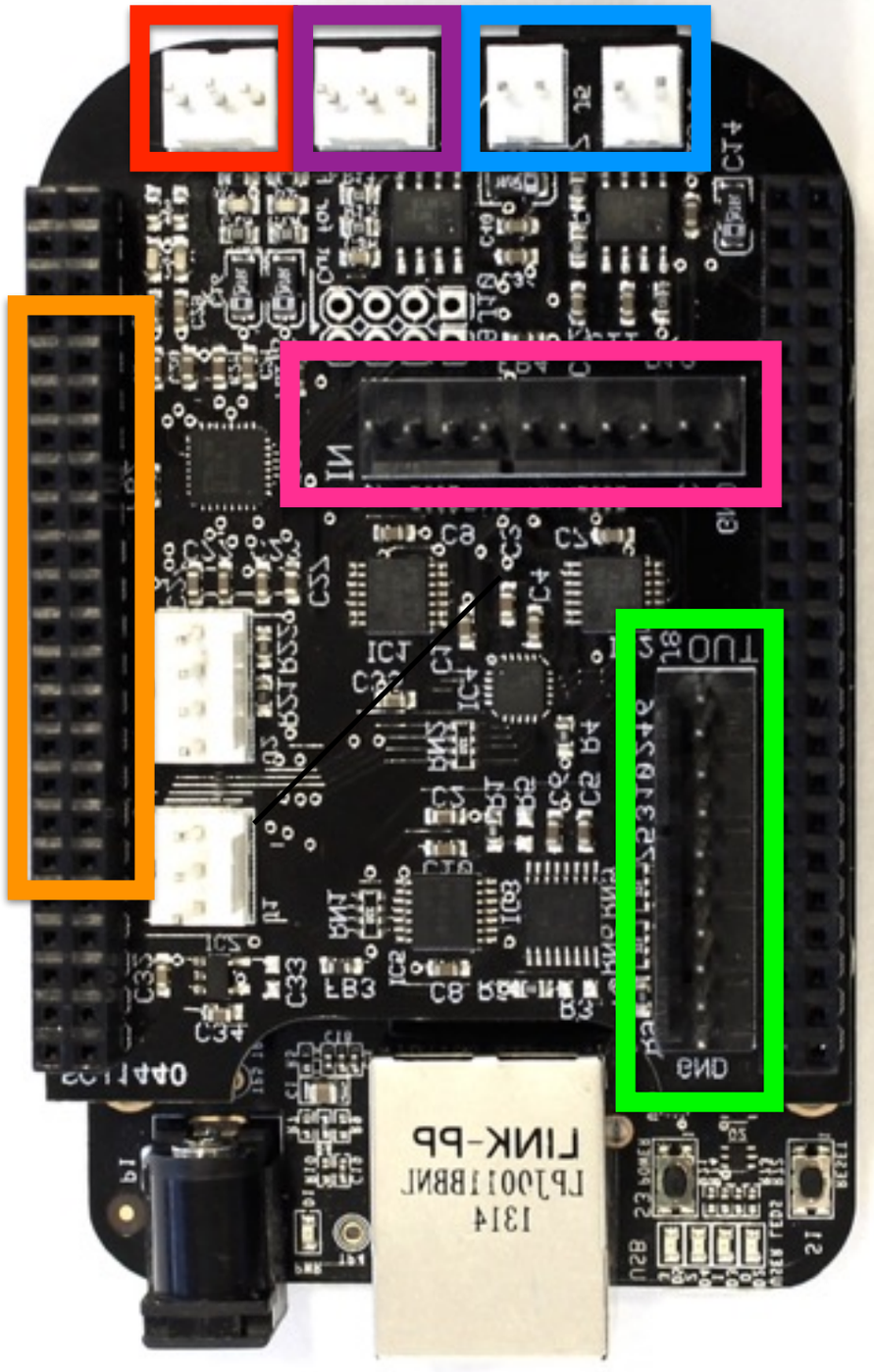
- **1ms round-trip audio latency** without underruns
- **High sensor bandwidth:** digital I/Os sampled at 44.1kHz; analog I/Os sampled at 22.05kHz
- **Jitter-free alignment** between audio and sensors
- **Hard real-time audio+sensor performance**, but full Linux APIs still available
- Programmable using **C/C++, Pd and Faust**
- Designed for **musical instruments and live audio**

How it works


bELa
Highest
Priority
Audio
Code
Input/Output
Audio
Storage
Network
USB
XENOMAI
Other
Processes
Linux Kernel

Xenomai remarks

- scheduler can preempt non-preemptable kernel operations
- audio-thread can be set at a higher priority than the Kernel
- mode switches into kernel mode need to be avoided in the audio thread:
  - disk I/O
  - socket
  - printf
  - pthread
  - available.notify_one(); triggers a mode switch



- **Speakers** with on-board amps
- **Audio Out**
- **Audio In**
- **16x digital I/O**
- **8x 16-bit analogue in (22.05kHz)**
- **8x 16-bit analogue out (22.05kHz)**

Find an interactive pin out diagram at http://bela.io/belaDiagram

Connected.

Embedded.

Fast.

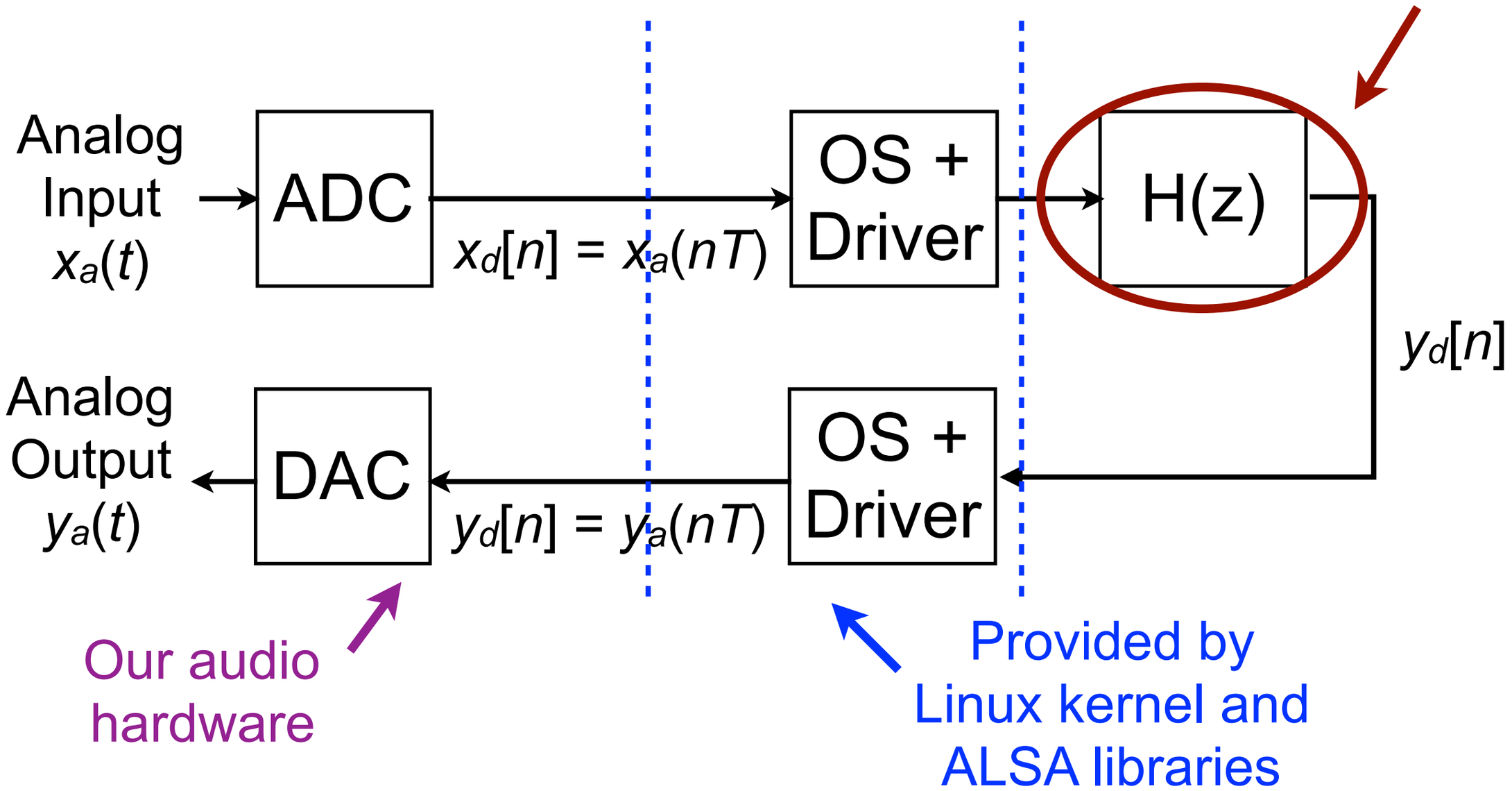
Easy to get started.

API introduction

- In **`render.cpp`**....
- Three main functions:
- **`setup()`**
  runs once at the beginning, before audio starts
  gives channel and sample rate info
- **`render()`**
  called repeatedly by Bela system ("callback")
  passes input and output buffers for audio and sensors
- **`cleanup()`**
  runs once at end
  release any resources you have used
- bela.io/code/embedded *Code docs*

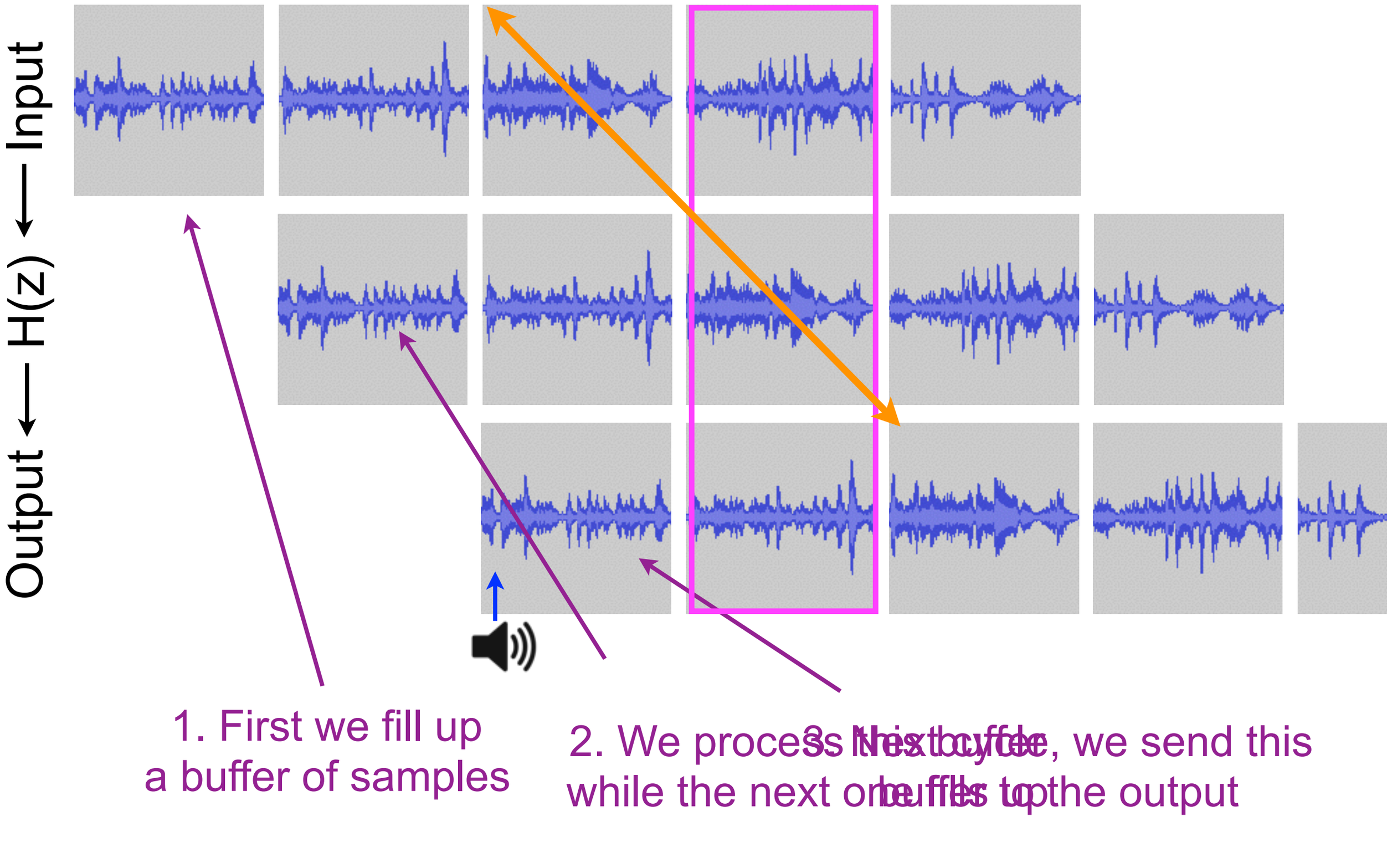
Latency

- Primary tradeoff for buffering: latency
  - There will be a delay from input to output
- Let's consider a full-duplex system (in and out)
  - Which are the sources of latency?



Buffering illustration

Total latency is 2x buffer length

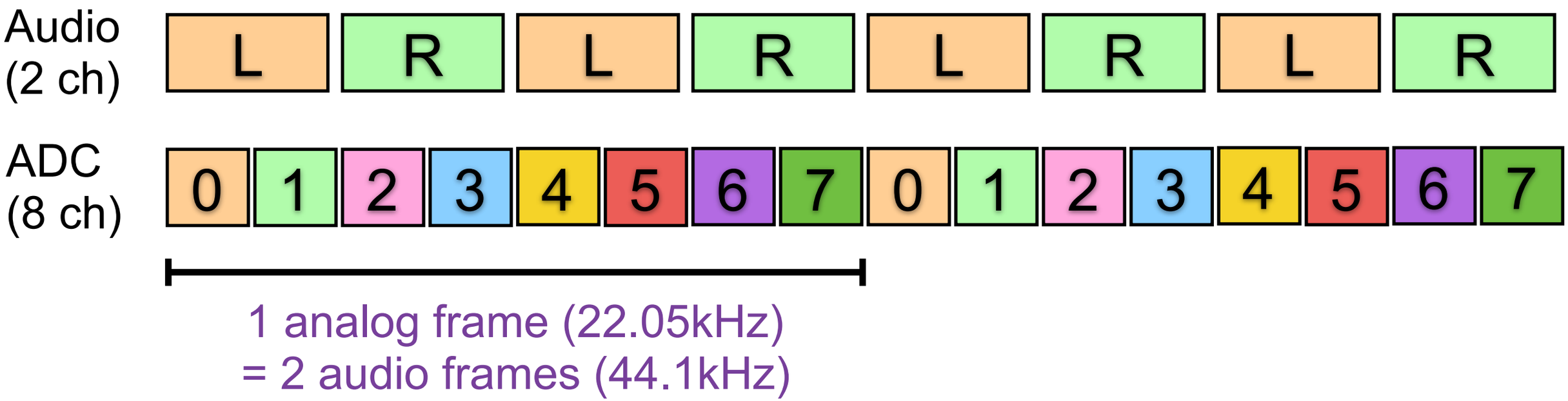


1. First we fill up a buffer of samples

2. We process this buffer while the next one fills up

3. Next cycle, we send this buffer to the output

Analog input data format



- Data type is `float`: just like audio
  - But range is 0.0 to 1.0
    - This is internally converted from raw values 0 to 65535
  - Compare this to audio, which is -1.0 to 1.0

Getting Started

Materials

1. **BeagleBone Black** (BBB)
2. **Bela Cape**
3. **SD card** with Bela image
4. 3.5mm headphone jack **adapter cable**
5. **Mini-USB cable** (to attach BBB to computer)
6. Also useful for hardware hacking: **breadboard**, **jumper wires**, etc.

Step 1

Install BBB drivers and Bela software

BeagleBone Black drivers:
http://bela.io/code/wiki --> Getting Started

Bela code (for later today):
http://bela.io/code/files --> Downloads --> bela_4-12-2015.zip

Bela code (in general):
http://bela.io/code --> Repository

Instructions:
http://bela.io/code/wiki --> Getting Started

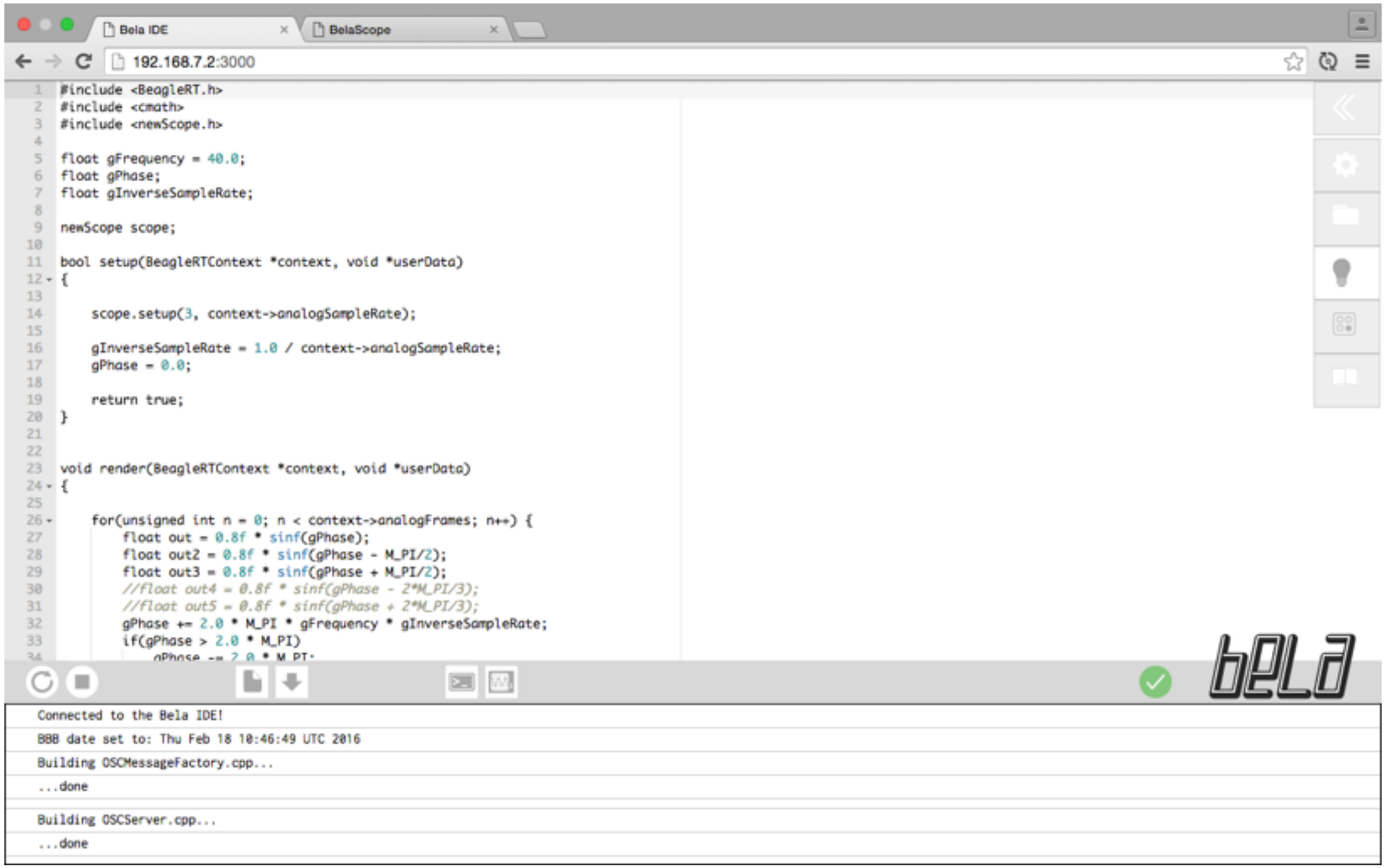
Step 2

Build a project

1. **Web interface**: http://192.168.7.2:3000
   Edit and compile code on the board
2. **Build scripts** (within repository)
   Edit code on your computer; build on the board
   No special tools needed except a text editor
3. **Heavy Pd-to-C compiler** (https://enzienaudio.com)
   Make audio patches in Pd-vanilla, translate to C and compile on board
4. **Libpd**
   Compile Pd patches without Heavy - access to more objects but not as fast, but good for prototyping
5. **Faust**
   Build online, export to C++, run on Bela

Access the IDE:

http://192.168.7.2:3000



Access the IDE:

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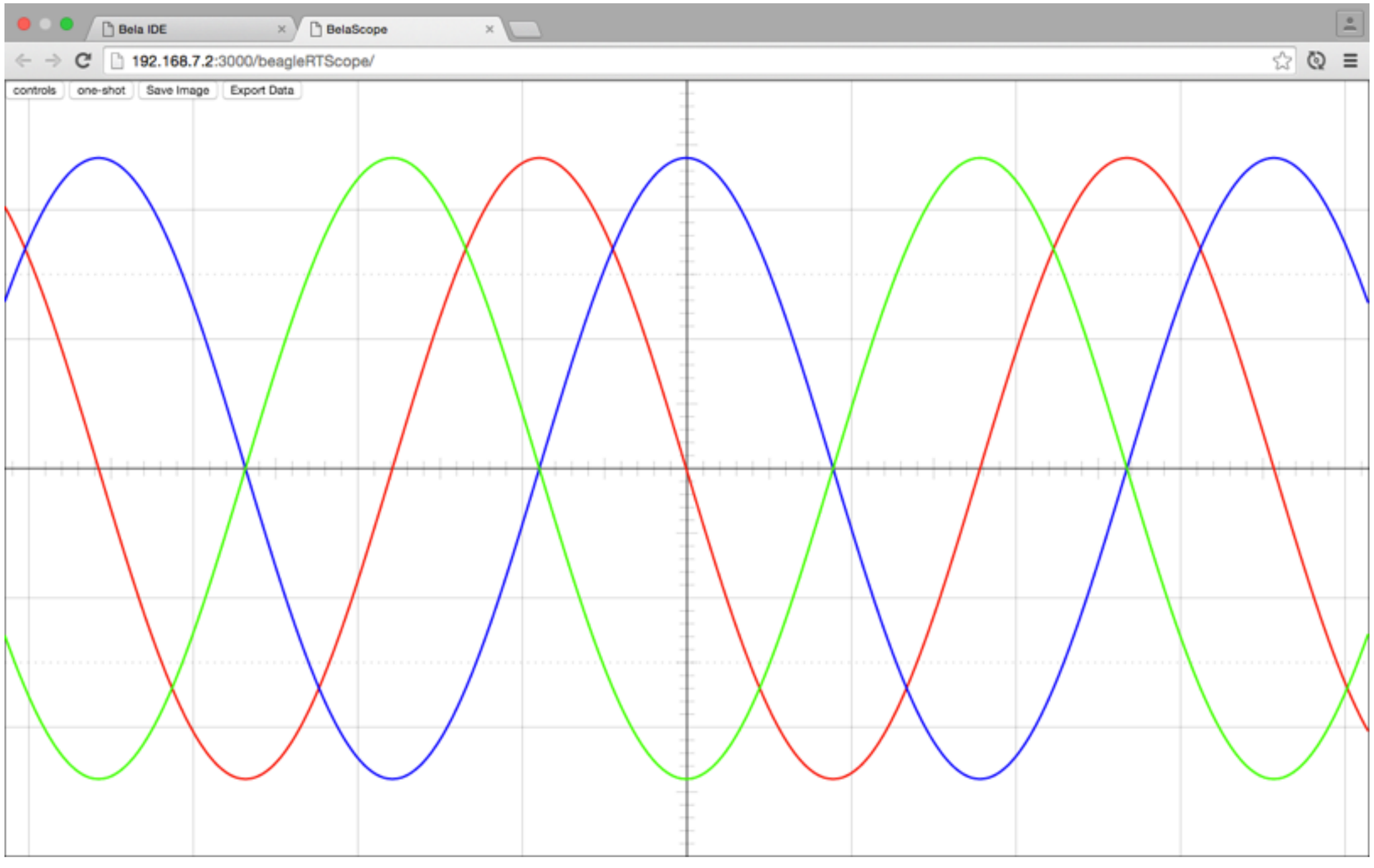
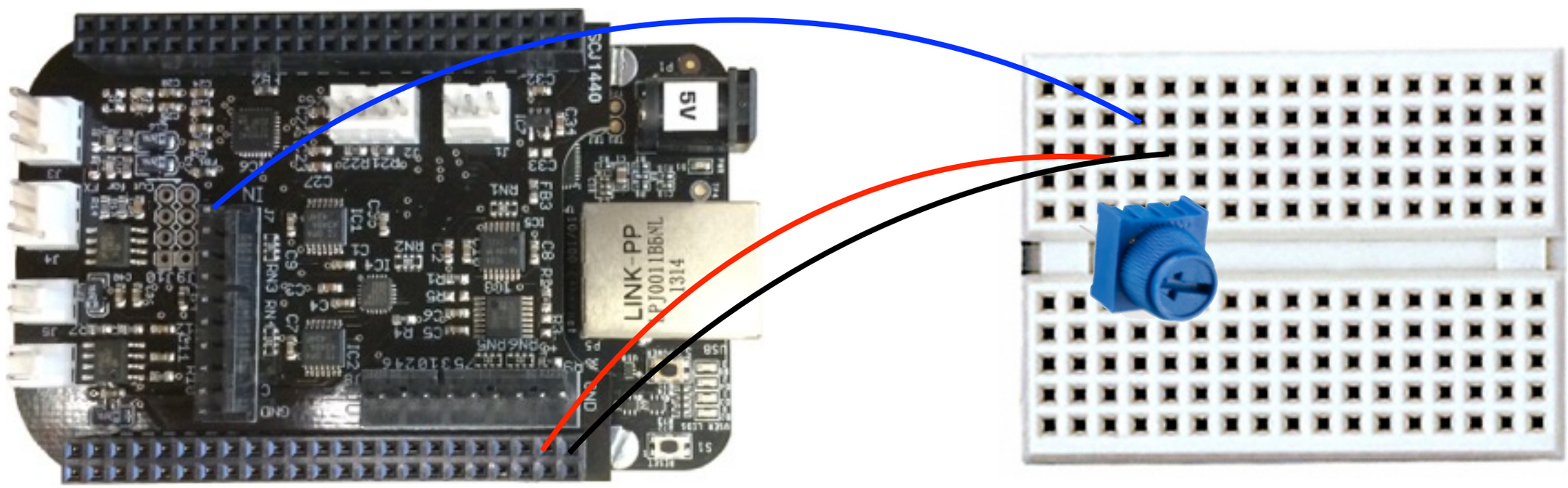


Connect a Potentiometer

a.k.a. a “pot” or knob

The pot has 3 pins
5V and GND on the outside
Bela analog in in the middle

analogue in 0



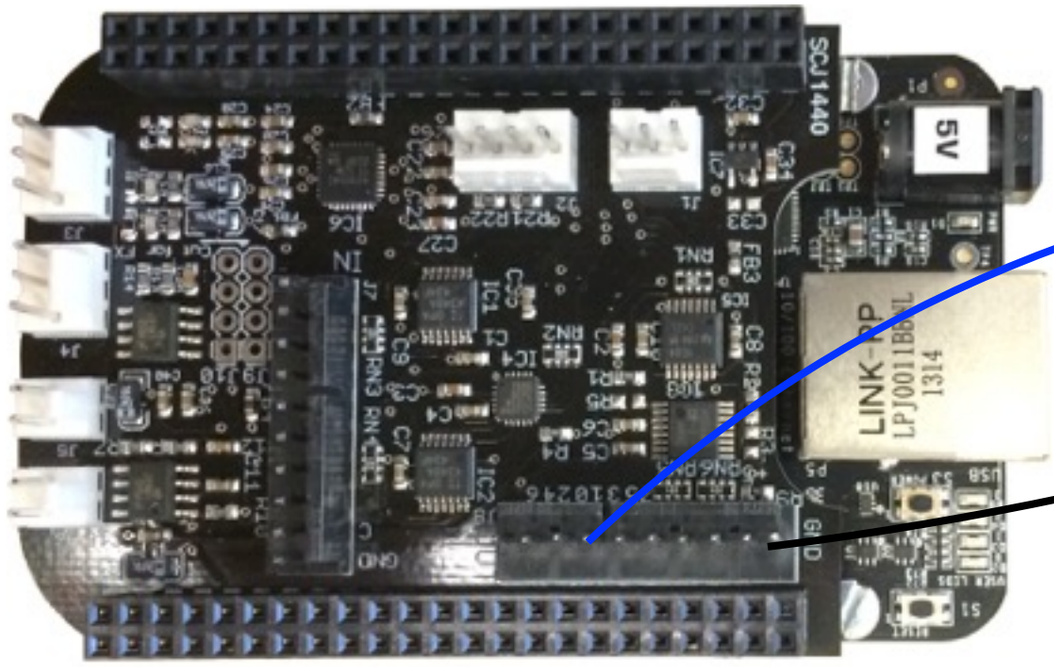
5V GND (ground)

Connect an LED*

* Light-Emitting Diode

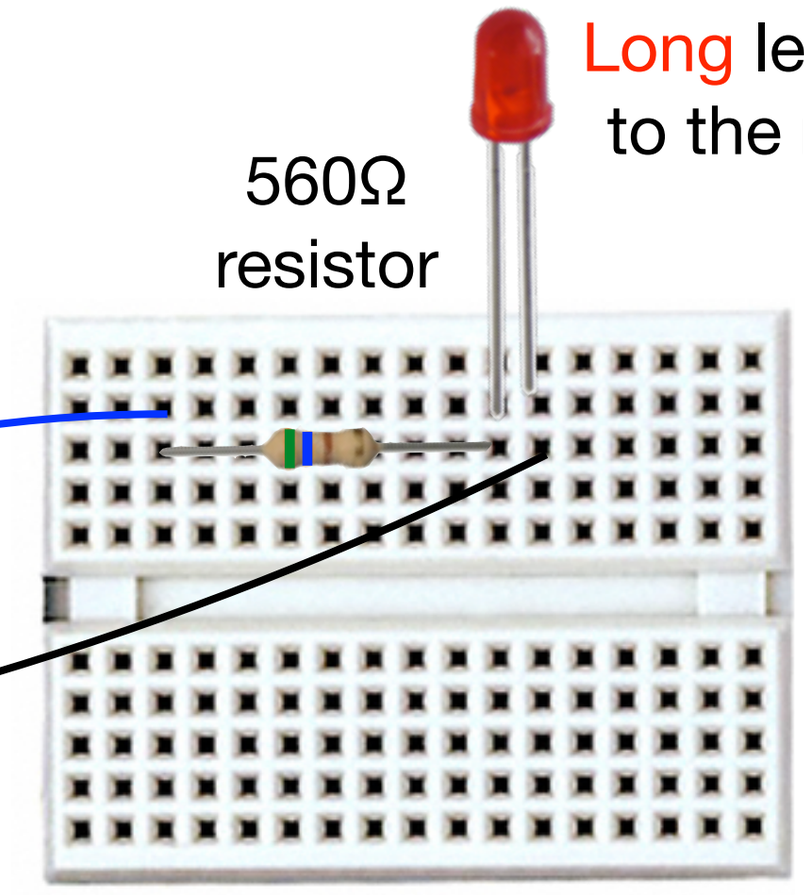
analog out 0

(note pinout:
6 4 2 0 1 3 5 7)



560Ω
resistor

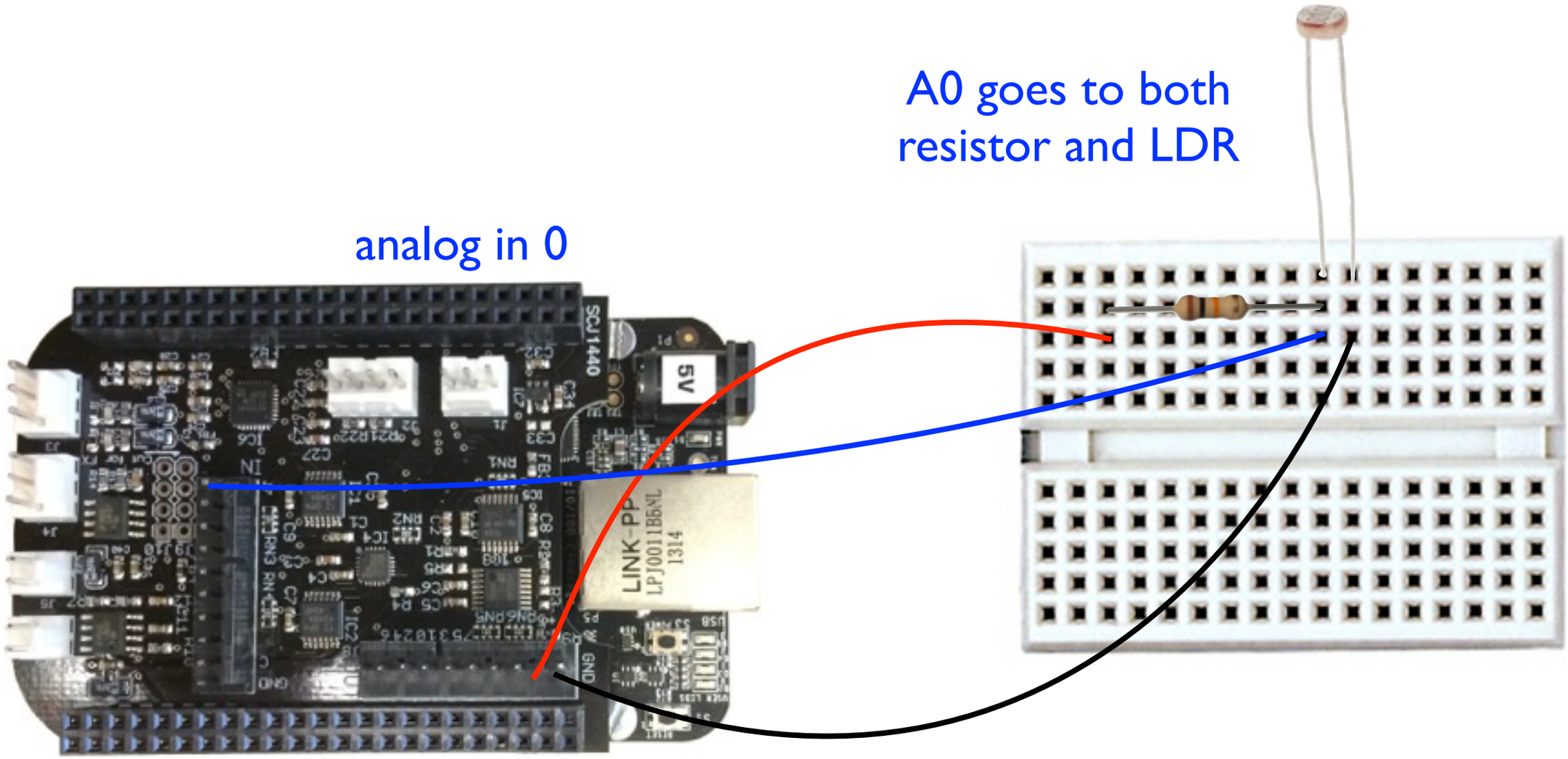
Long lead goes
to the resistor



GND (ground)

Connect a LDR/FSR*

* Light-Dependent Resistor / Force-Sensing Resistor



Analog input

```
float gPhase;
float gInverseSampleRate;           /* Pre-calculated for convenience */
int gAudioFramesPerAnalogFrame;

extern int gSensorInputFrequency;   /* Which analog pin controls frequency */
extern int gSensorInputAmplitude;   /* Which analog pin controls amplitude */

void render(BeagleRTContext *context, void *userData)
{
    float frequency = 440.0;
    float amplitude = 0.8;

    for(unsigned int n = 0; n < context->audioFrames; n++) {
        /* There are twice as many audio frames as matrix frames since
            audio sample rate is twice as high */
        if(!(n % gAudioFramesPerAnalogFrame)) {
            /* Every other audio sample: update frequency and amplitude */
            frequency = map(analogReadFrame(context,
                                n/gAudioFramesPerAnalogFrame,
                                gSensorInputFrequency),
                            0, 1, 100, 1000);
            amplitude = analogReadFrame(context,
                            n/gAudioFramesPerAnalogFrame,
                            gSensorInputAmplitude);
        }

        float out = amplitude * sinf(gPhase);

        for(unsigned int channel = 0; channel < context->audioChannels; channel++)
            context->audioOut[n * context->audioChannels + channel] = out;

        gPhase += 2.0 * M_PI * frequency * gInverseSampleRate;
        if(gPhase > 2.0 * M_PI)
            gPhase -= 2.0 * M_PI;
    }
}
```

This runs every other sample

Read the analog input at the specified frame

Map the 0-1 input range to a frequency range

Digital I/O

```
void render(BeagleRTContext *context, void *userData)
{
    static int count = 0; // counts elapsed samples
    float interval = 0.5; // how often to toggle the LED (in seconds)
    static int status = GPIO_LOW;

    for(unsigned int n = 0; n < context->digitalFrames; n++) {
        /* Check if enough samples have elapsed that it's time to
           blink to the LED */
        if(count == context->digitalSampleRate * interval) {
            count = 0; // reset the counter
            if(status == GPIO_LOW) {
                /* Toggle the LED */
                digitalWriteFrame(context, n, P8_07, status);
                status = GPIO_HIGH;
            }
            else {
                /* Toggle the LED */
                digitalWriteFrame(context, n, P8_07, status);
                status = GPIO_LOW;
            }
        }

        /* Increment the count once per frame */
        count++;
    }
}
```

This runs once per digital frame

Write the digital output at the specified frame

Bela and Faust

- Today: you will have to download the C++ file generated by the http://faust.grame.fr/onlinecompiler/ (after setting the -i flag), save it on your computer and target it with the build_project.sh script, as in:

```
/path/to/bela/repo/scripts/build_project.sh /path/to/faust/file/CppCode.cpp
```

```
freq = hslider("[1]Frequency[BELA:ANALOG_0]", 440,460,1500,1):smooth(0.999);
pressure = hslider("[2]Pressure[style:knob][BELA:ANALOG_4]", 0.96, 0.2, 2.0, 0.01):smooth(0.999):min(0.99):max(0.2);
gate = hslider("[0]ON/OFF (ASR Envelope)[BELA:DIGITAL_0]",0,0,1,1);
```

Queen Mary University of London

Help me with Supercollider

- We got it to work, thank to Dan Stowell at C4DM
- We run 120sinewaves for 55% CPU time.
- Can you make something useful with it?

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Bela and PureData

- https://docs.google.com/presentation/d/1DLCDUgZp0liaQhnO55uhOJ5iymbNMmDqPC_JyfTkAaE/
- Nice URL, uh?

Interested to pre-order a kit?

65£ for a cape + SD card

Delivery: July

http://bit.ly/1eKffsL

Stay tuned! Join the announcement list at

http://bela.io

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