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 13: State machines

What you'll learn today:

Structure and uses of state machines
Debouncing buttons
Hysteresis

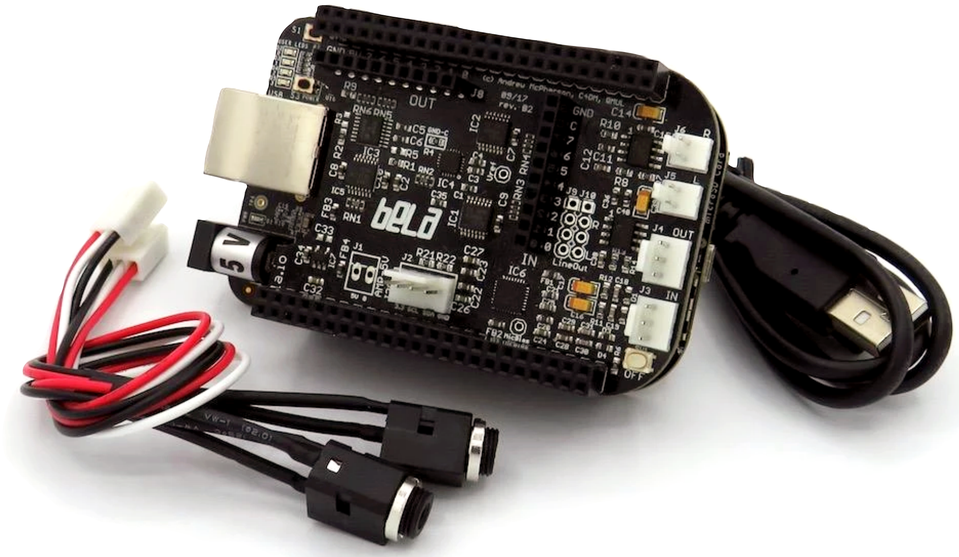
What you'll make today:

Metronome which marks the bar lines, button debouncer

Companion materials:

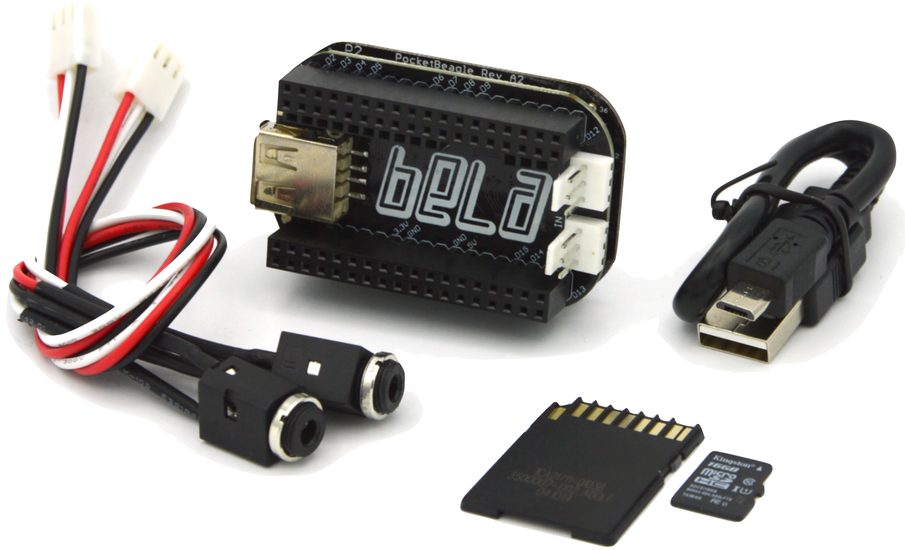
github.com/BelaPlatform/bela-online-course

What you'll need



Bela Starter Kit

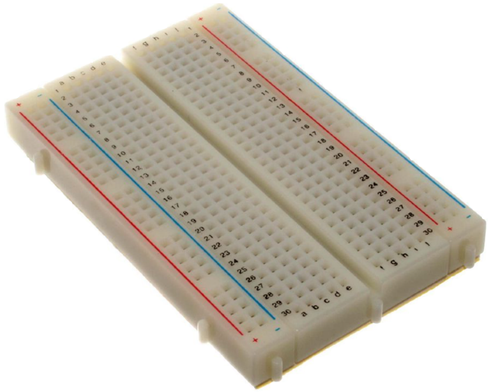
or

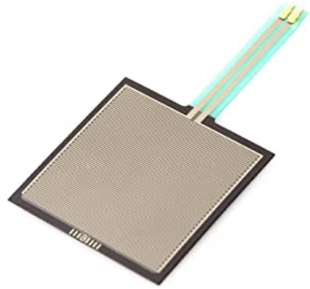


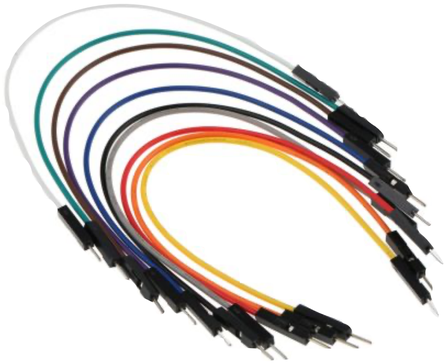
Bela Mini Starter Kit

[shop.bela.io]

Also needed for this lecture:

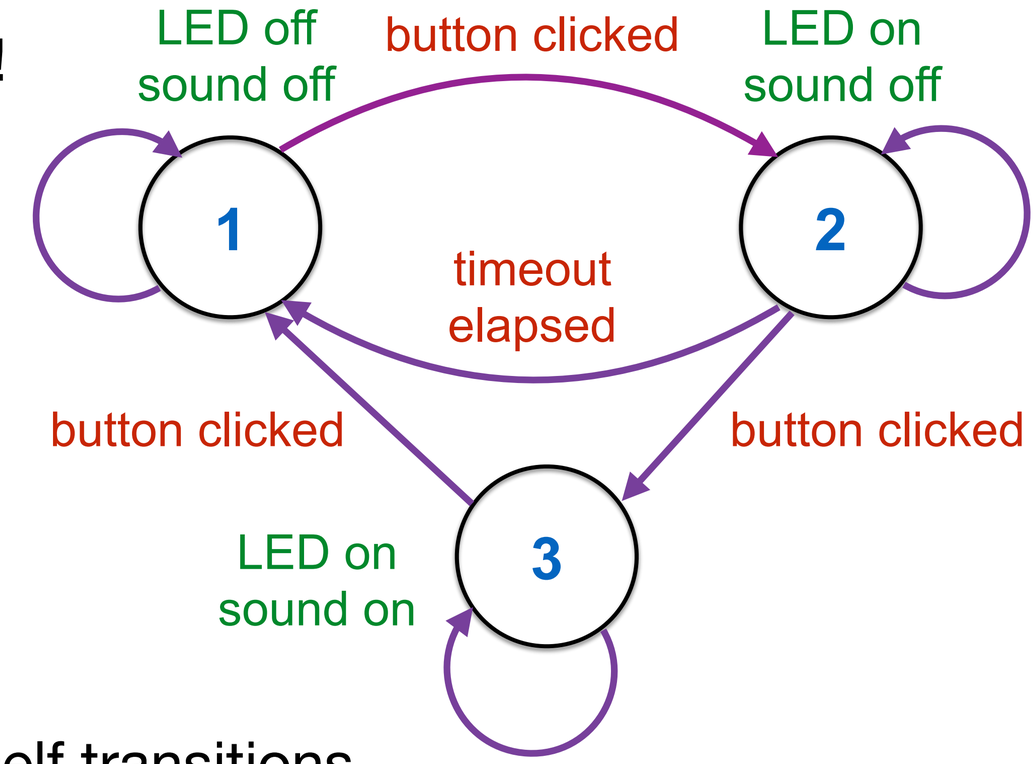






State machines

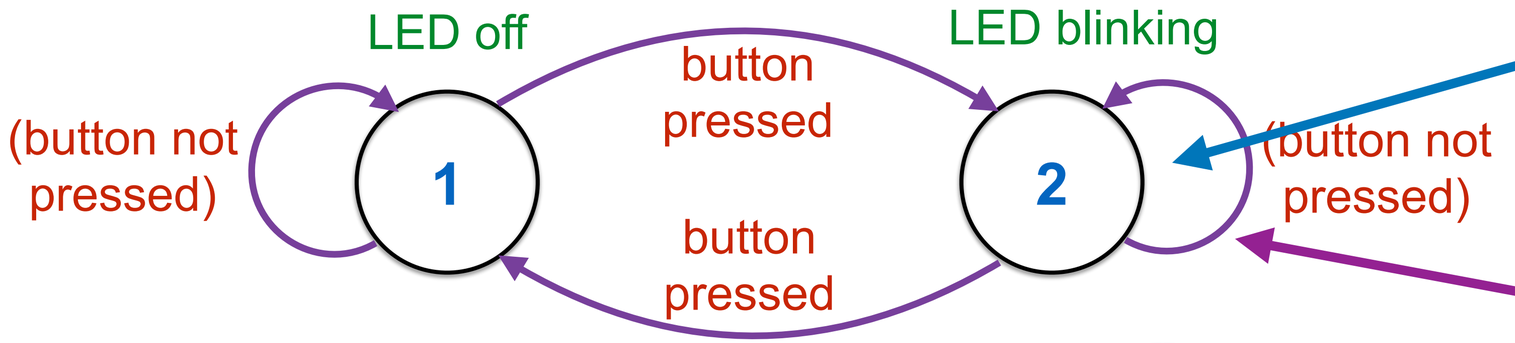
- A finite state machine (or FSM or state machine) is a simple mathematical model of computation
  - Lots of useful systems can be modelled this way!
- Four requirements:
  1. Set of **states** that the system can be in
  2. Set of **transitions** between those states
  3. Set of **inputs** which determine the transitions
  4. Set of **outputs** generated by the machine
- Only a finite number of states, and behaviour is deterministic
  - Transitions can be from one state to another, or self transitions



Simple state machine example

- Consider a simple LED blinker
- Push button to start blinking, push button again to stop:

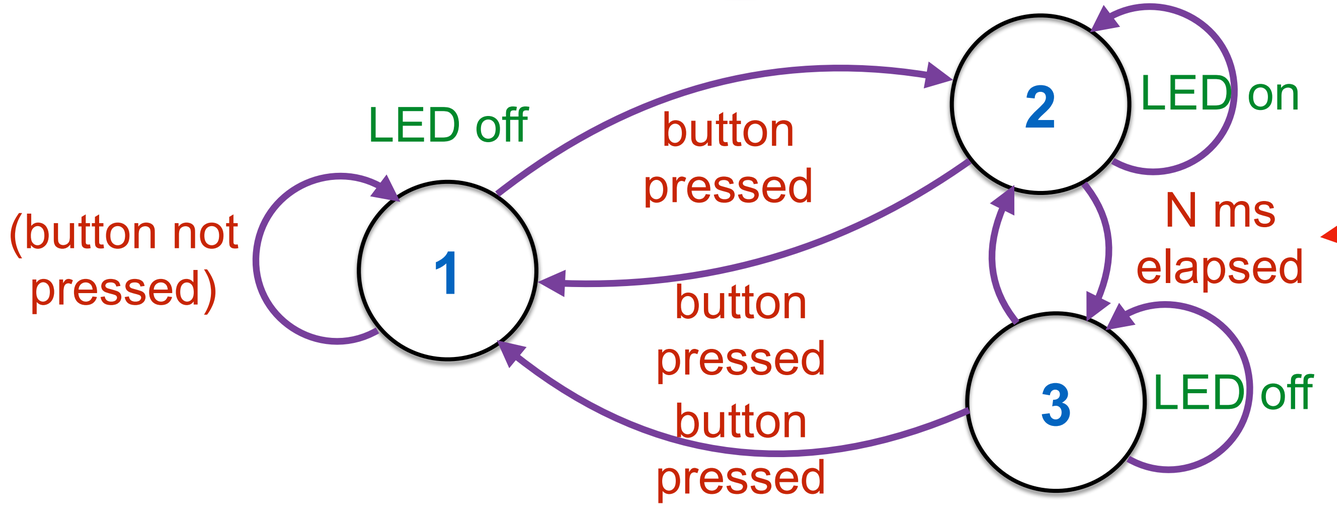
Version 1:



At any given time, the system is in either state 1 or state 2 (but not both)

Sometimes these self transitions will be omitted for clarity (they are still implied)

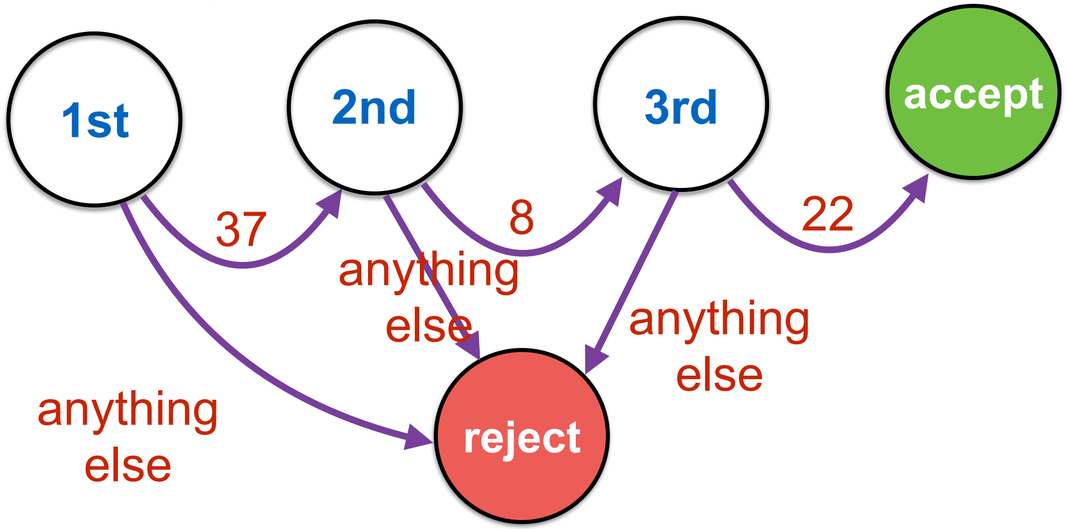
Version 2:
(equivalent)



Notice: time can be an input that causes a state transition

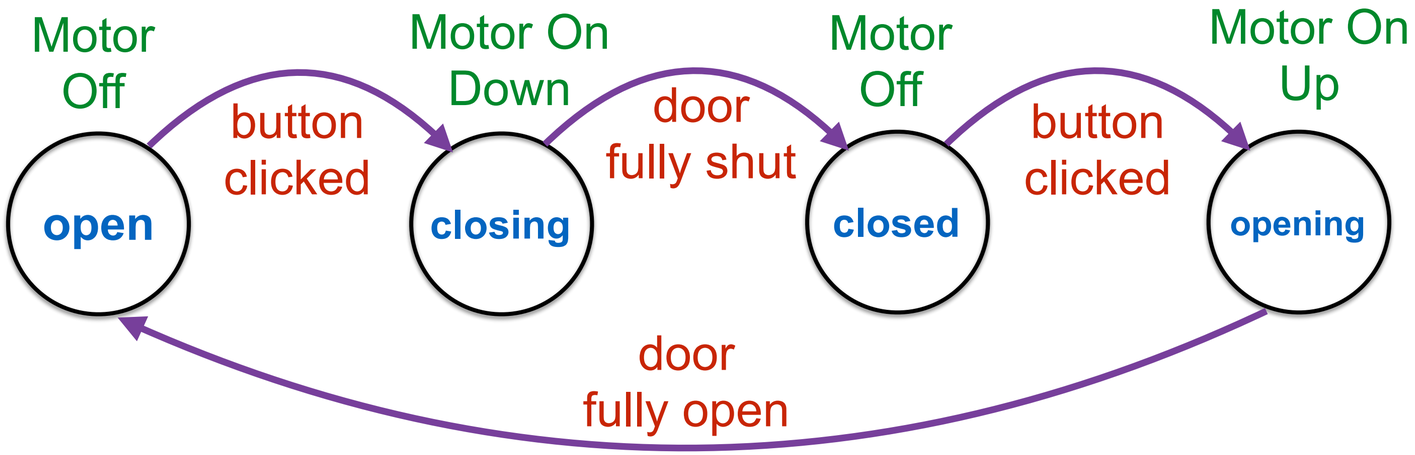
Types of state machine

- Finite state acceptors or classifiers
  - This subclass of state machine takes input only
  - Recognises sequences of inputs by reaching a particular state when a valid sequence is received
- Example: combination lock
  - States: whether we're awaiting the first, second or third number to be entered
  - Inputs: which numbers you turn to on the dial



Types of state machine

- Finite state transducers
  - Have both input and output
  - Most practical cases we work with will be these
- Example: garage door opener
  - States: door open, closing, closed, opening
  - Transitions: only certain possibilities
  - Inputs: button click, door sensor
  - Outputs: motor control

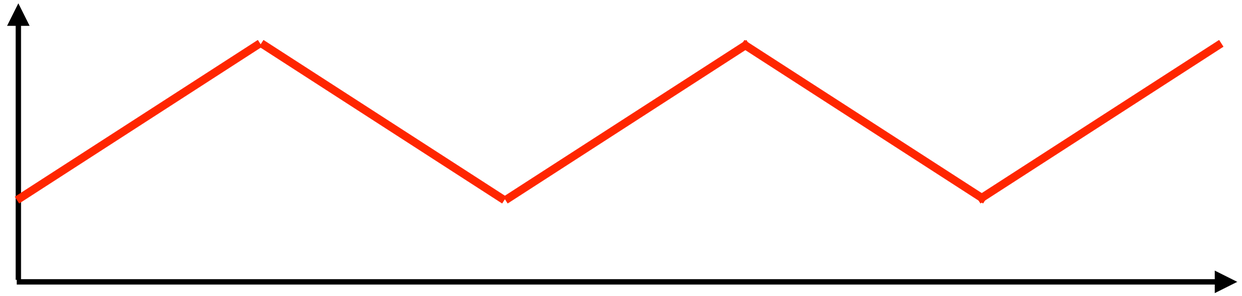


Generating outputs

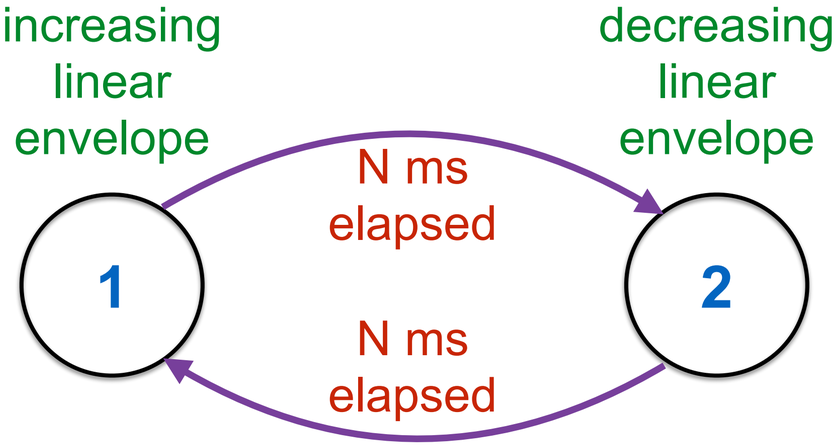
- When are the outputs of a state machine generated?
  - Whenever we enter a particular state (entry actions)
  - As long as we remain in a particular state (could think of this as a self-transition)
  - Whenever we leave a particular state (exit actions)
- Different models of state machines
  - Moore model: outputs depend only on the state
  - Mealy model: outputs depend on the state and its inputs
- We will treat this topic very informally!
  - Practical advice: choose whatever implementation is the clearest, with the least duplication of code
- Important: state machines are deterministic
  - Each set of input conditions should allow only one transition from any given state
  - Clearly specify the transition criteria (guards) in terms of all of the relevant inputs

State machine envelope example

- Back to our increasing and decreasing line segments:



- How many states?
  - 2: increasing and decreasing
- What determines the transitions?
  - Elapsed time (or reaching the desired level)
- Any other inputs?
  - Not in this example
- What are the outputs?
  - Linear envelopes going upwards and downwards



State machine implementation

Practically speaking, coding a state machine needs:

1. One or more variables to keep track of the state
   - If using a state machine in `render()` or across different functions, you will need global variables to remember the state
   - Could use a single variable to hold all possible states
     - e.g. assign a unique number to each state
     - the variable holds the number of whichever state we're in
   - Or might be conceptually clearer to use multiple variables
     - e.g. a boolean for whether you're in a particular state (on/off for example), plus another variable to say which of several "on" states you might be in
2. A set of `if()` statements to check the state
   - Check which state the system is in, using the variables above
   - Take actions and look for transitions accordingly

```
int gState = 0;
```

```
if(gState == 0) {
    // Actions and transitions
    // for state 0
}
else if(gState == 1) {
    // Actions and transitions
    // for state 1
}
// etc.
```

State machine implementation

- For clarity, it can be useful to name each state
  - As opposed to just giving each one a number
  - Define constants at the top of the code file to associate each name with a number
- C/C++ `enum` keyword is useful here
  - enumerate: define lots of (integer) constants at once
  - Unless otherwise specified, the constants are assigned numbers in increasing order
  - After you define the names, never use the numbers directly in your code
  - Here, the "k" prefix means constant: a coding style, not a requirement

```
enum {
    kStateOpen = 0,
    kStateClosing,  // = 1
    kStateClosed,   // = 2
    kStateOpening   // = 3
};

int gState = kStateOpen;

void myFunction() {
    if(gState == kStateOpen) {
        // ...
    }
    else if(gState == kStateClosing) {
        // ...
    }
    // etc.
}
```

State machine implementation

Practically speaking, coding a state machine needs:

3. Other `if()` statements using inputs to decide on transitions between states
   - Look at the inputs, decide which state to go to next
   - Self-transitions (no state change) are possible, and may even be the most frequent event
   - Remember, time can be one of your inputs
     - Can measured elapsed time by counting samples
     - Remember to reset the counter when needed (e.g. when changing state)

Changing state is easy!
Just need to assign a new value into the state variable, and next time something different will happen

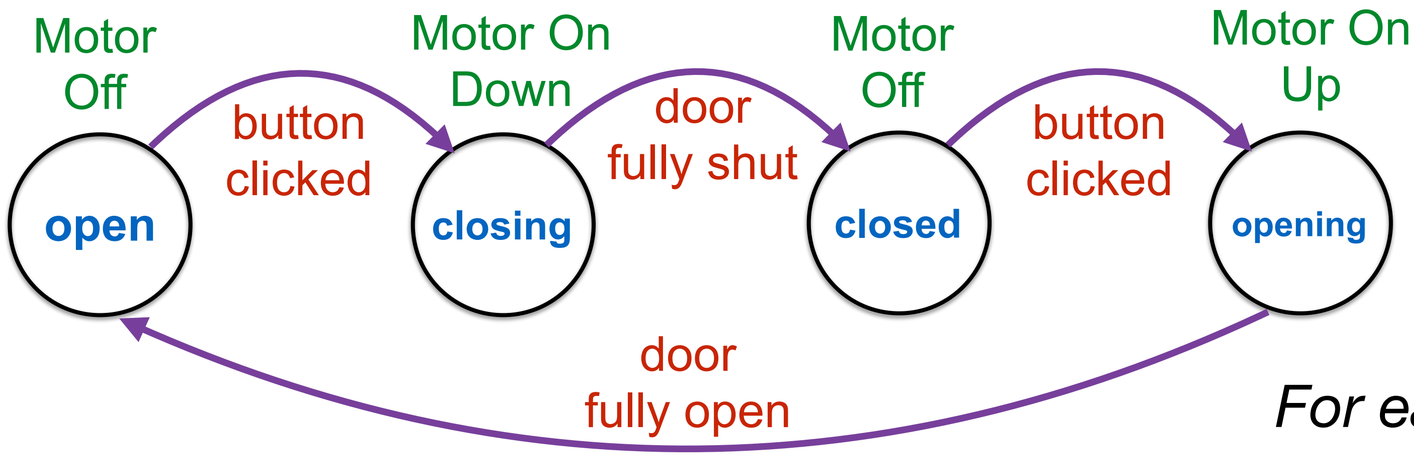
```
if(gState == kStateOpen) {
    motorOff(); // Action for this state
    if(buttonWasPushed) {
        gState = kStateClosing; // Transition
    }
}
else if(gState == kStateClosing) {
    motorDown(); // Action for this state
    if(doorHasClosed) {
        gState = kStateClosed;
    }
}
// etc.
```

State machine implementation

Practically speaking, coding a state machine needs:

4. Clear planning on when to check for transitions
   - In digital logic, state machine is often driven by a clock
   - Edges of the clock determine when machine checks its state and when it can transition
   - If using real-time audio, audio frame clock will work
     - Check for actions and transitions on each iteration of the `for()` loop in `render()`
     - Each frame, perform actions for a particular state, then decide what state to go to for the next frame
   - Also consider which actions should be performed once on entry to a state (or on transition, or exit), and which should happen every cycle we're in a state

State machine example



At the top of the file:

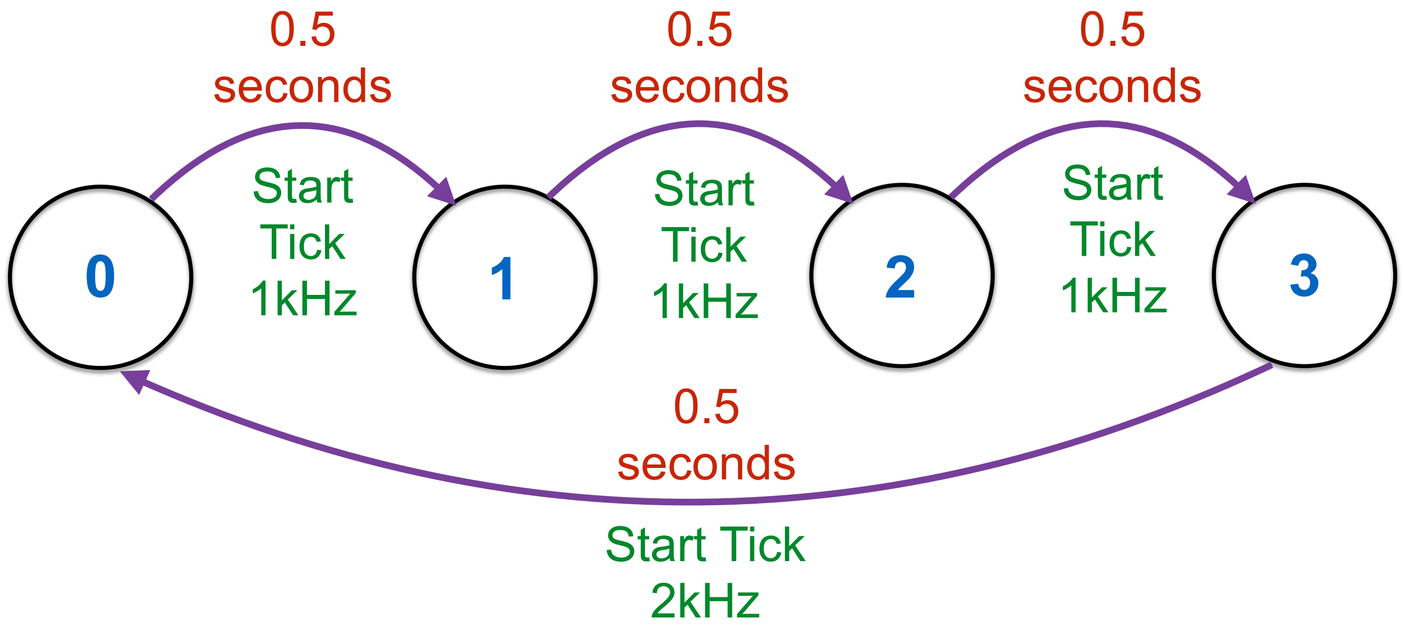
```
// Defining four possible states:
enum {
    kStateOpen = 0,
    kStateClosing,  // = 1
    kStateClosed,   // = 2
    kStateOpening   // = 3
};

// This tells us which state we're in:
int gState = kStateOpen;
```

For each iteration in real time:

```
if(gState == kStateOpen) {
    motorOff();       // Action for this state
    if(buttonWasPushed) {       // Check input
        gState = kStateClosing; // Transition
    }
}
else if(gState == kStateClosing) {
    motorDown();     // Action for this state
    if(doorHasClosed) {        // Check input
        gState = kStateClosed; // Transition
    }
}
// etc.
```

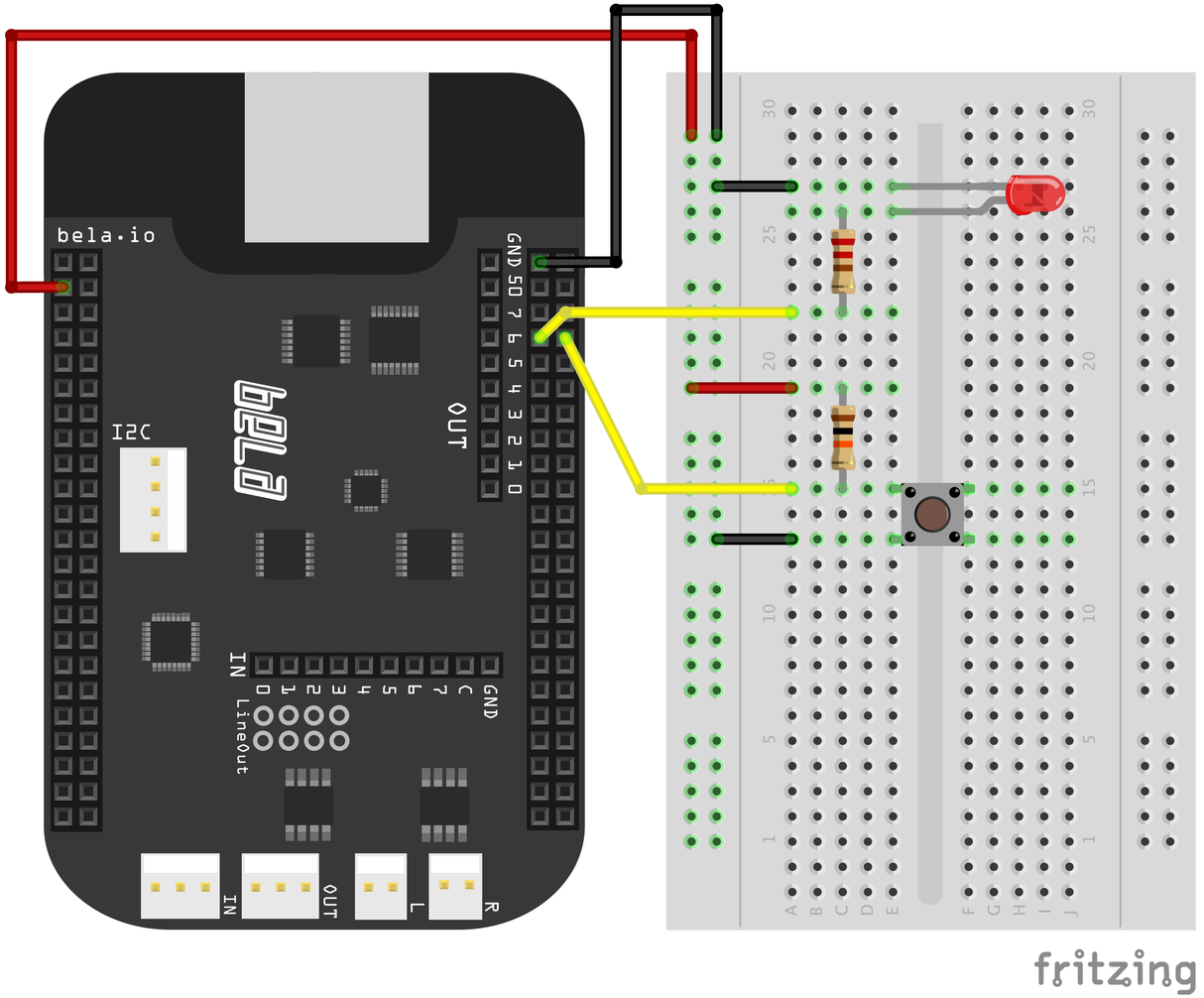
State machine task

- Task: using the metronome-envelope example
  - Make every fourth tick have twice the frequency
  - `gFrequency` = 2000 for tick 0; `gFrequency` = 1000 for ticks 1-3
  - Create a state variable to keep track of which of 4 states we're in (i.e. which tick in the cycle)
  - Reset the envelope and change frequency on entering the new state (i.e. on the transition)

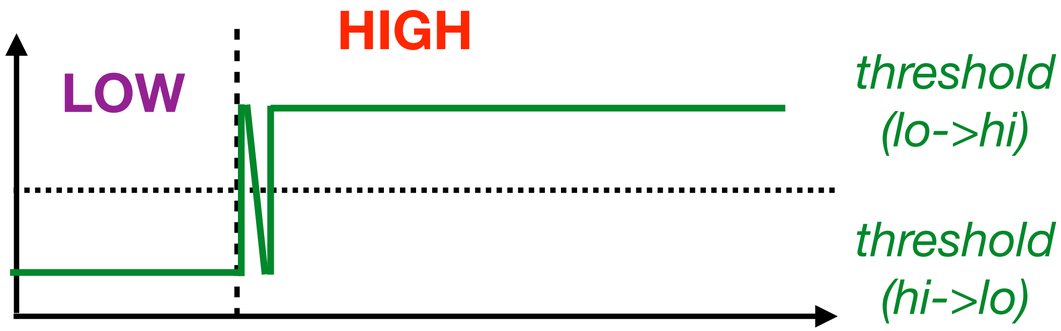


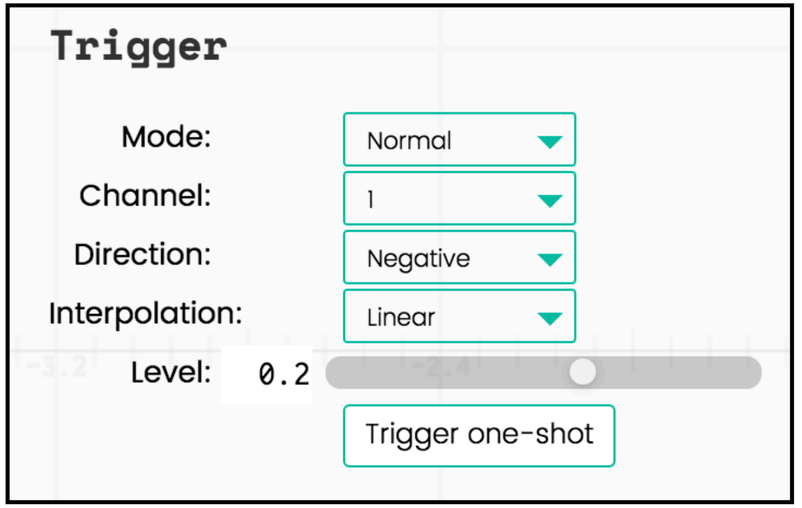
State machine task 2

- Task 2: using the metronome-envelope example
  - Add a button to start and stop the metronome
  - Add a 5th state to represent “stopped”
  - When the metronome is stopped, a click should always start at tick 0 (2kHz)
  - When the metronome is running, a click should go to the stopped state
  - Don’t have to immediately silence the sound, just don’t start another tick



Debouncing

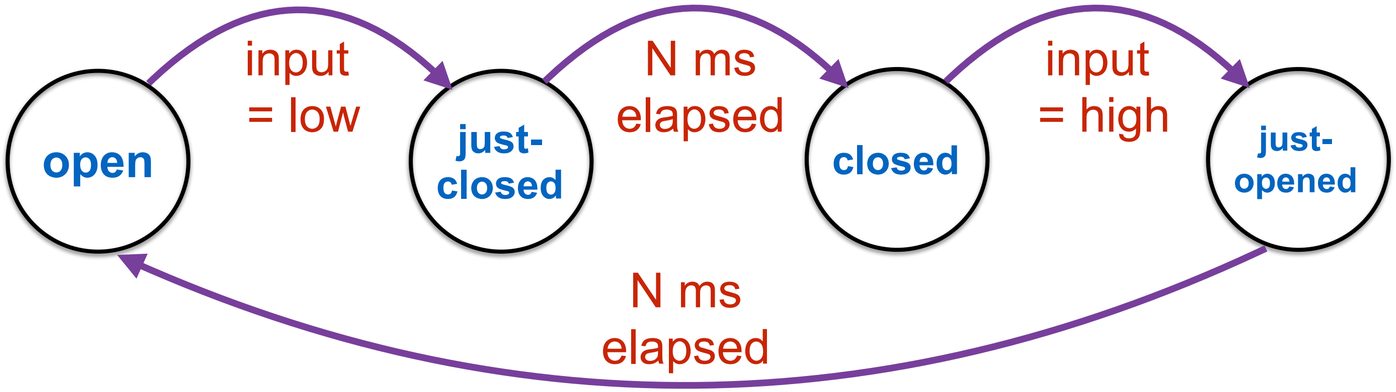




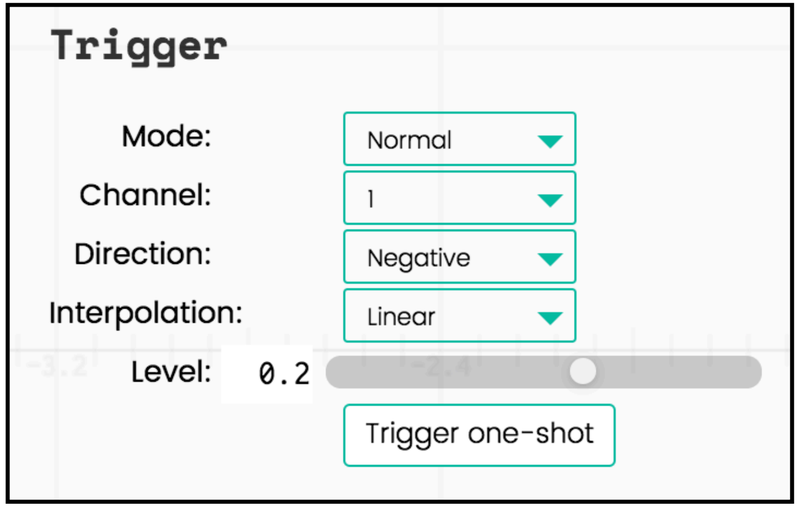
- A button is a spring-loaded set of plates which can physically bounce when pressed and released
  - This can cause errors in the signal
  - A process called debouncing compensates for false triggers
- Several approaches to debouncing
  - Simplest is a timer that ignores input from the switch for a window after a state change
- Task: run the scope-button example, look at the button signal on the Bela scope
  - Set to the trigger mode to normal, negative, threshold > 0 to see if you can spot the bouncing
  - How long does the bouncing last?

Debouncing state machine

- We can consider debouncing as a simple state machine:

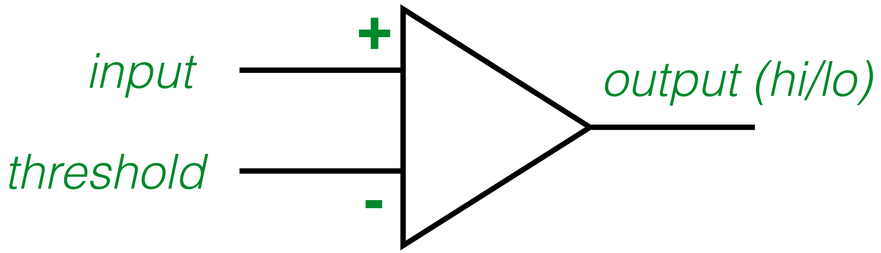


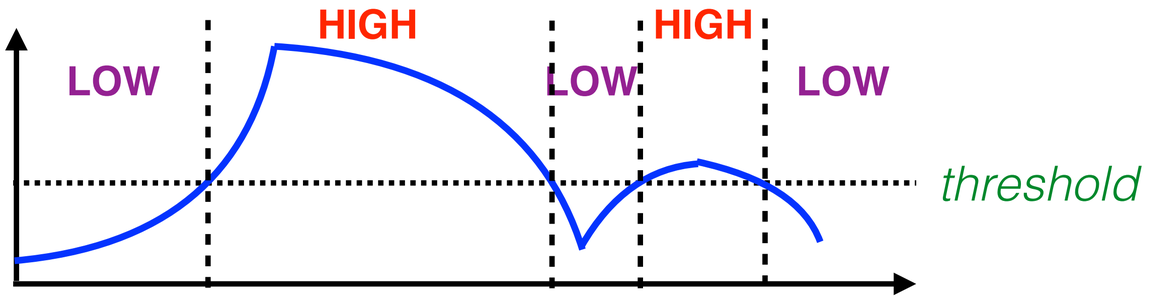
  - Four states: switch open; switch closed; plus two transient states
  - The transient states wait a short time before allowing the button to register another change
    - How long should the wait time be?
    - How do we handle the timer for the wait?
    - Remember what time we entered the state (or reset a counter)



- Task: using debounce example, implement a debouncing state machine
  - When entering the just-closed state, toggle an LED on or off
  - Toggling the LED will also need a second variable to keep track of whether it was on or off

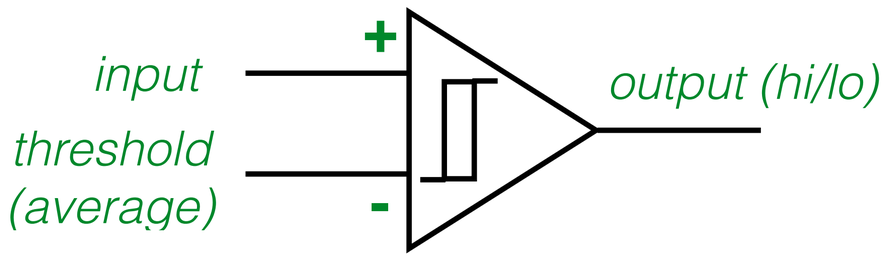
Comparator

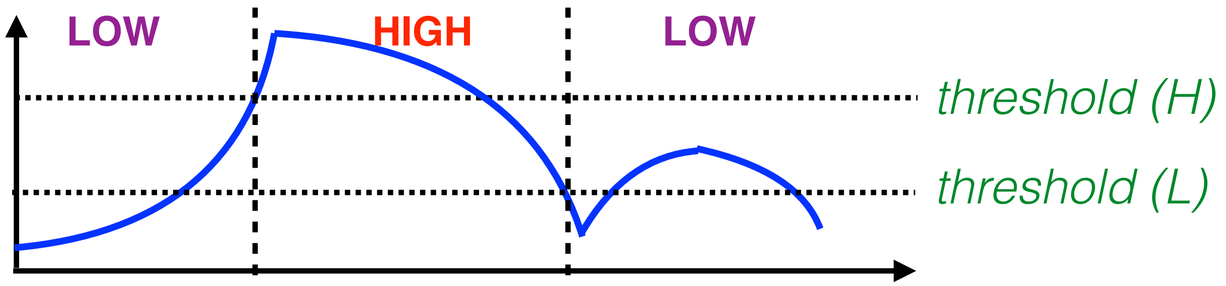




- A comparator is a simple analog component
  - Takes two input signals, outputs high or low depending on which one is bigger
  - In practice, we often compare an input signal to a fixed threshold
  - Note: continuous input, discrete output (only 2 states)
- In code, what kind of statement is this?
  - `if()`
  -
```
if(value > threshold)
  output = 1; // or run some action
else
  output = 0; // or run some other action
```

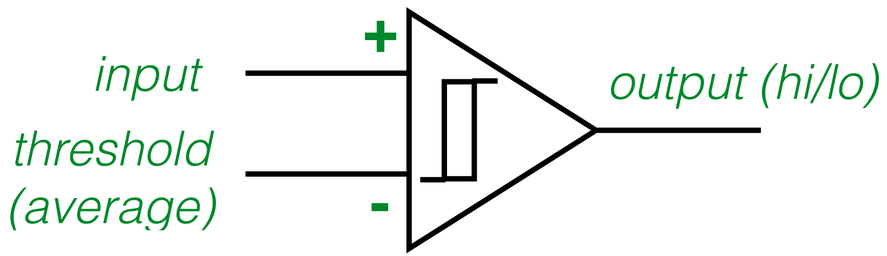
Comparator with hysteresis

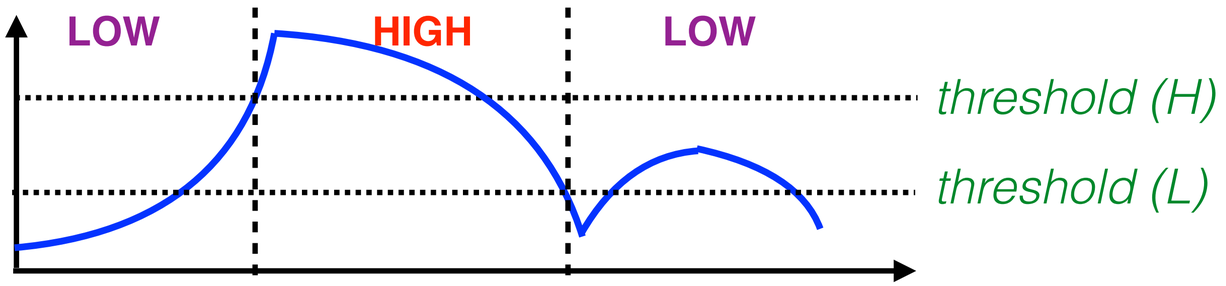




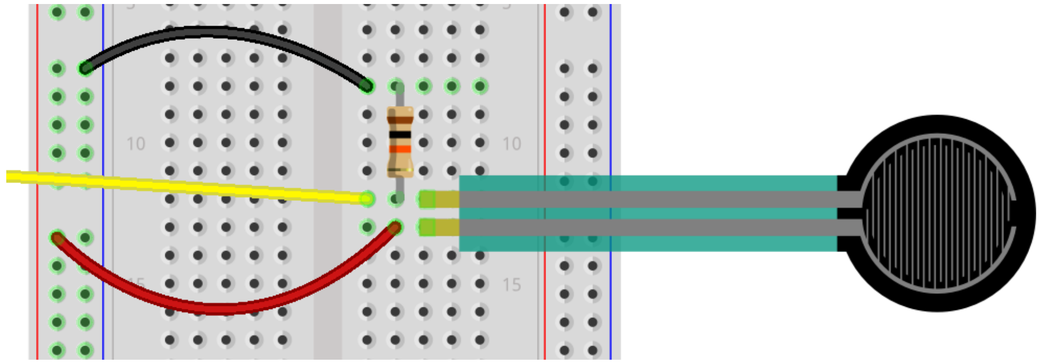
- Comparator with hysteresis (or Schmitt trigger)
  - Output depends on the input and the past state
  - Threshold changes depending on whether last output was high or low
    - Higher threshold for L→H transition, lower threshold for H→L
  - Hysteresis is useful for noise immunity
    - Small changes will not cause output to rapidly flip back and forth
- Digital implementation is a form of state machine
  - Two states: high and low
  - Transition conditions are different for each state

Hysteresis task





- Task: using project hysteresis-comparator
  - Implement a hysteresis comparator on analog input 0
  - Connect an FSR to the analog input
  - Make the thresholds 0.75 (L→H) and 0.25 (H→L)
  - Use an LED to indicate the output state
  - Optionally, print a message to the console when state changes
    - e.g. `rt_printf("LOW ---> HIGH");`



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