THE ART AND SCIENCE OF PCB DESIGN

IAP 2026

Lecture 04 - Topologies

Common electrical topologies (2/2)

Outline

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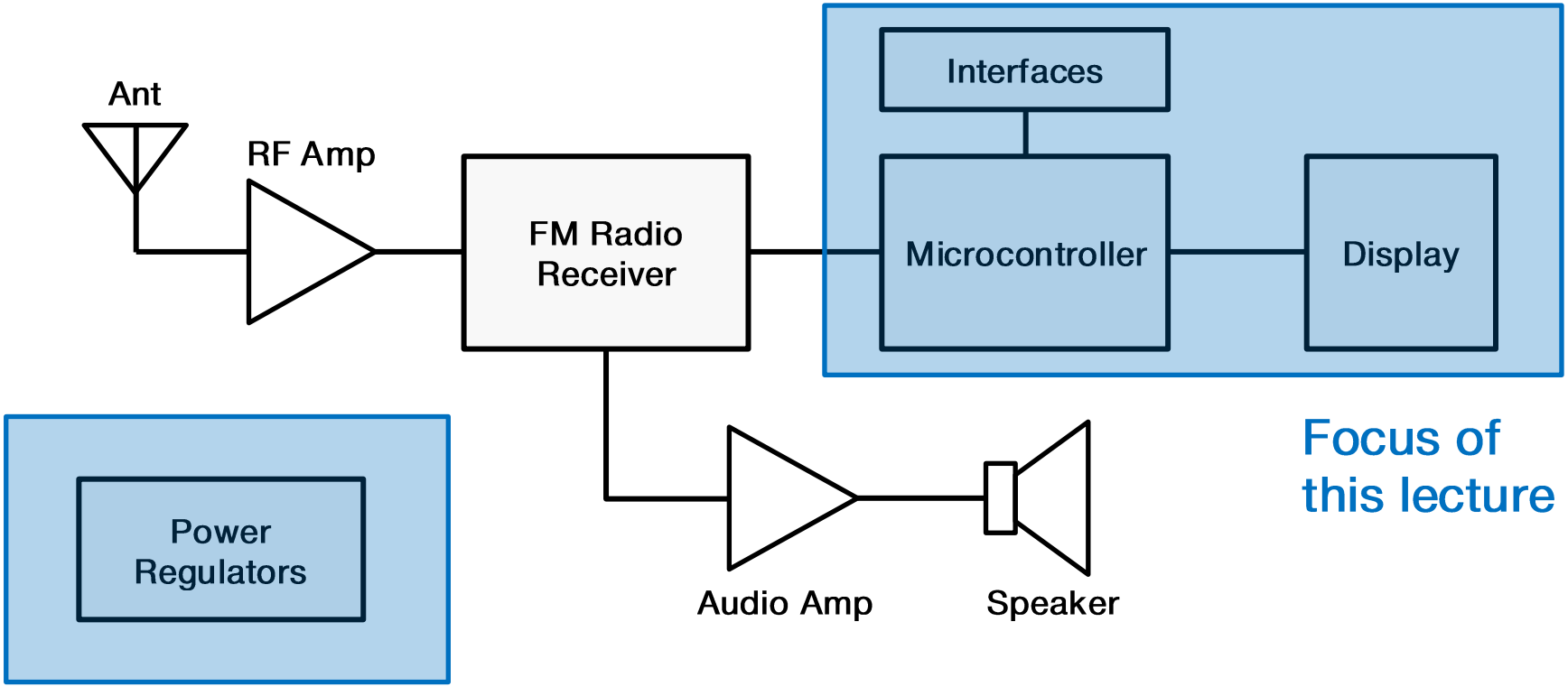
- Introduction
- LDO Regulators
- Buck and Boost Converters
- ESP Module
- Switches and Multiplexers
- Display and Shift Registers
- Summary

Introduction

Block Diagram



Low Dropout Regulators (LDOs)

Power Regulation

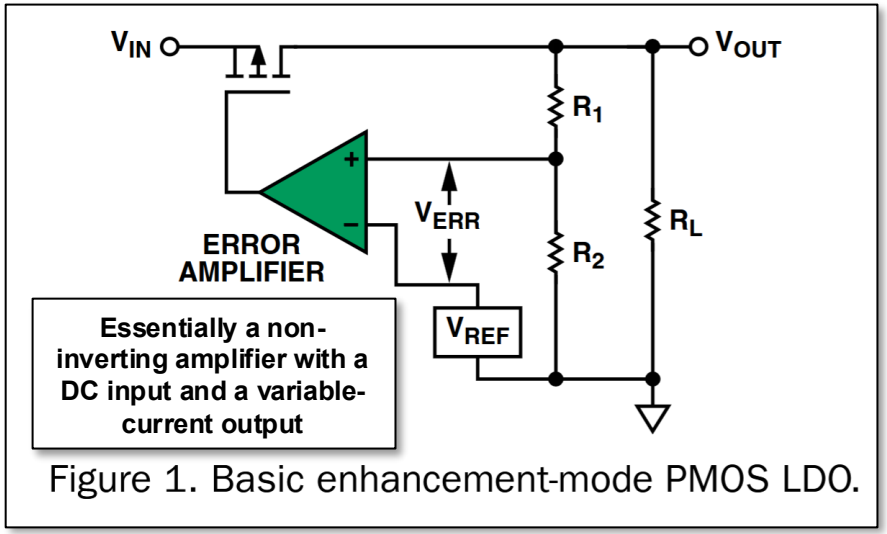


Figure 1. Basic enhancement-mode PMOS LDO.

LDOs are crucial for their low noise and simplicity

- No switching occurs
- Small size (no large inductors required)
- Cheaper

LDOs, however, cannot be used for all applications:

- Cannot boost voltages
- Lossy (requires heatsinking)
- In order to bias output transistor, a dropout voltage is required (0.1 V to 2 V depending on topology)

R_1 and R_2 form a voltage divider feedback network that amplifies V_{REF} to provide a variable voltage output

Typically, LDOs should be preferred for use in for low-noise and/or low current voltage step-down applications

Switching Converters

Schematics

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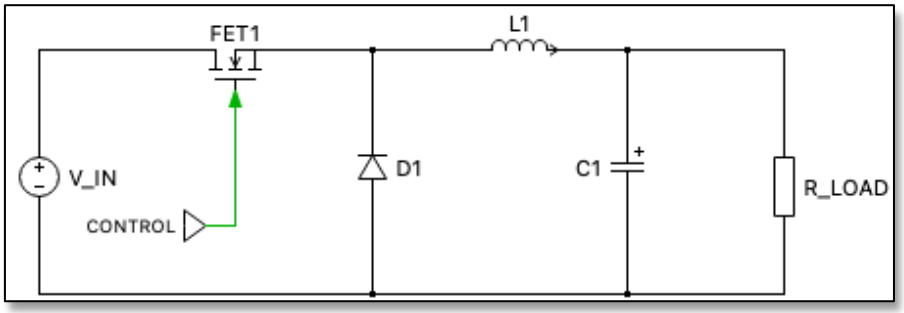
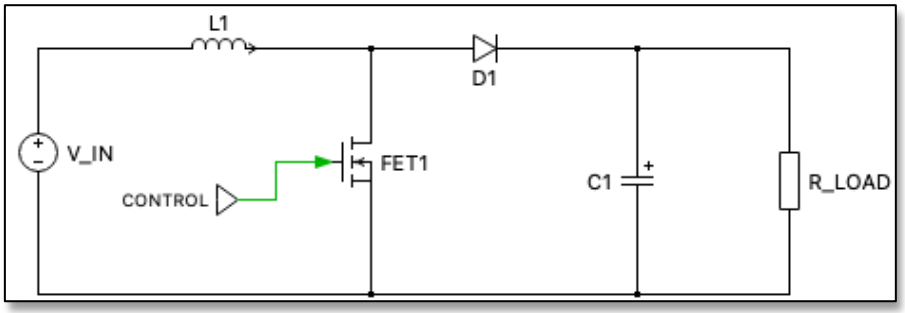
Buck Converter



Step-Down Converter
output voltage = duty cycle × input voltage

Boost Converter



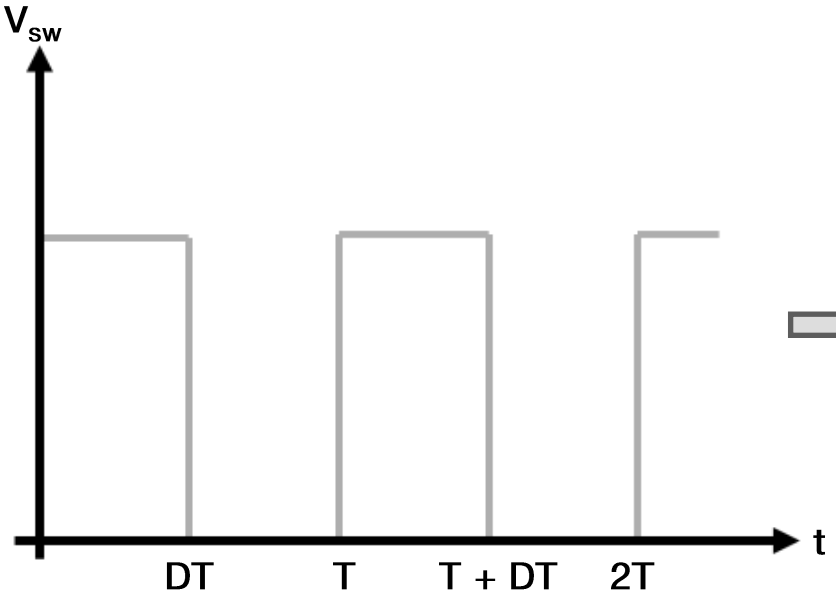
Step-Up Converter
output voltage = input voltage ÷ (1 – duty cycle)

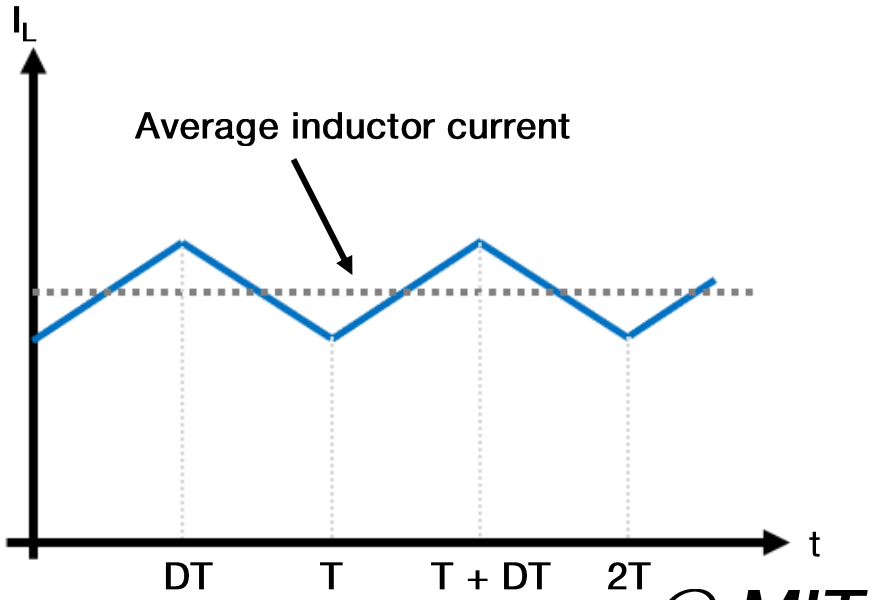
Switching Converters

Control

The FET of the converter is controlled via PWM, where the duty cycle determines the ratio between the input voltage and the output voltage.

This causes the current across the inductor to ramp up and ramp down, which in conjunction with the capacitor, provides a voltage to the load





Switching Converters

Buck Converter Operation

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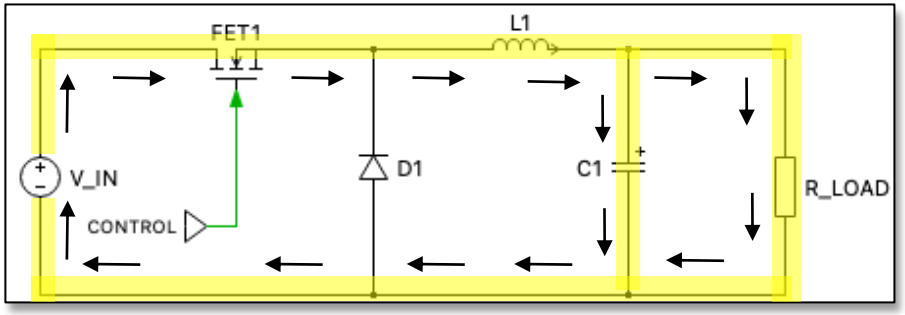
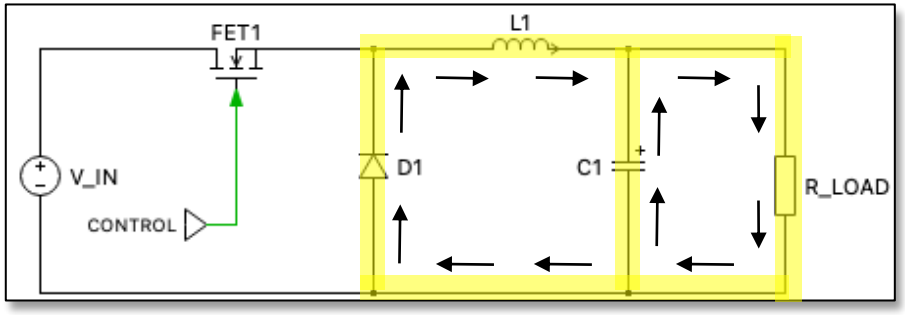
MODE 1: Switch On



When the switch is turned on, positive voltage is forced across the inductor, causing the current to increase. This inductor current flows through the capacitor and the load.

MODE 2: Switch Off



When the switch is turned off, the inductor current decreases, forcing a negative voltage across the inductor and turning on the diode. The capacitor discharges into the load as well.

Switching Converters

Boost Converter Operation

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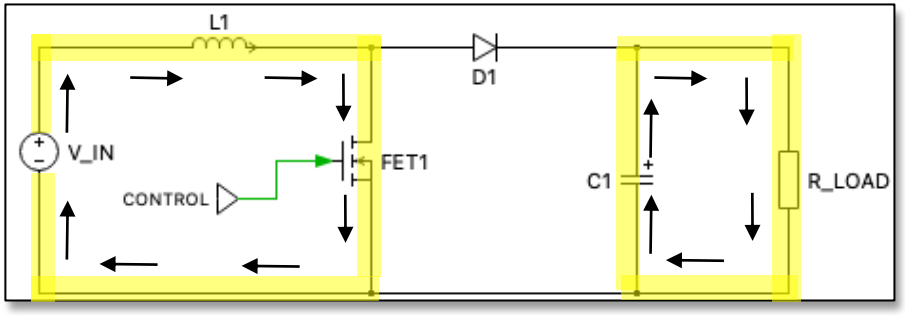
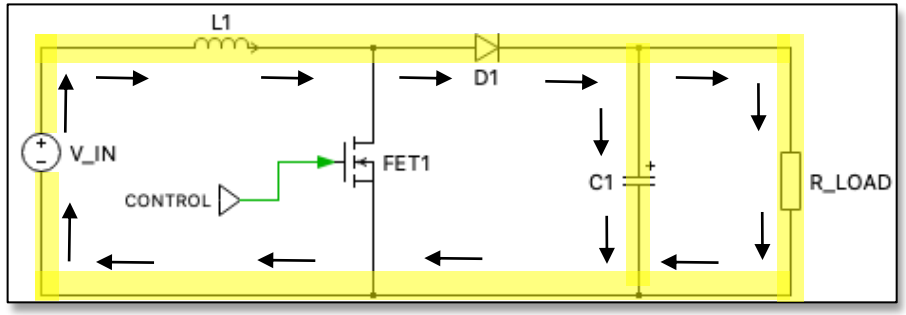
MODE 1: Switch On



When the switch is turned on, positive voltage is forced across the inductor, causing the current to increase. The capacitor supplies current to the load in isolation.

MODE 2: Switch Off



When the switch is turned off, the inductor current decreases, forcing a negative voltage drop across the inductor. This causes the capacitor voltage, and in turn the load voltage, to increase beyond the input voltage.

Switching Converters

Conversion Ratio Analysis

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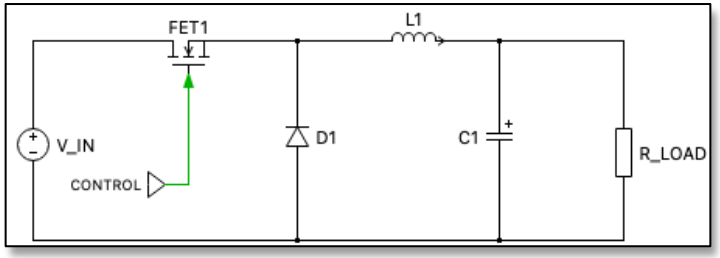
Average Value Analysis:

- The average values of voltages obey KVL
- The average values of currents obey KCL
- In Periodic Steady State (PSS) operation, $\langle v_L \rangle = 0$ and $\langle i_C \rangle = 0$

Buck Converter

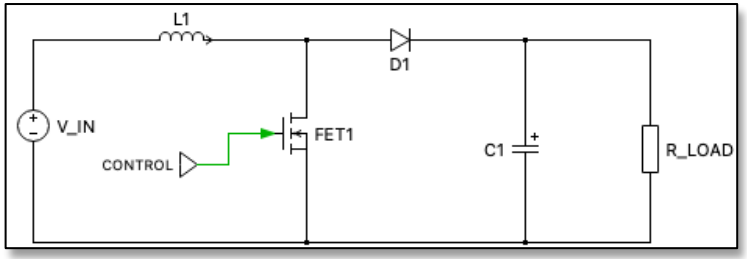


$$\langle V_{L1} \rangle = 0$$

$$D(V_{IN} - V_{OUT}) + (1-D)(-V_{OUT}) = 0$$

$$V_{OUT} = DV_{IN}$$

Boost Converter



$$\langle V_{L1} \rangle = 0$$

$$DV_{IN} + (1-D)(V_{IN} - V_{OUT}) = 0$$

$$V_{OUT} = V_{IN}/(1-D)$$

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Switching Converters

Buck-Boost IC

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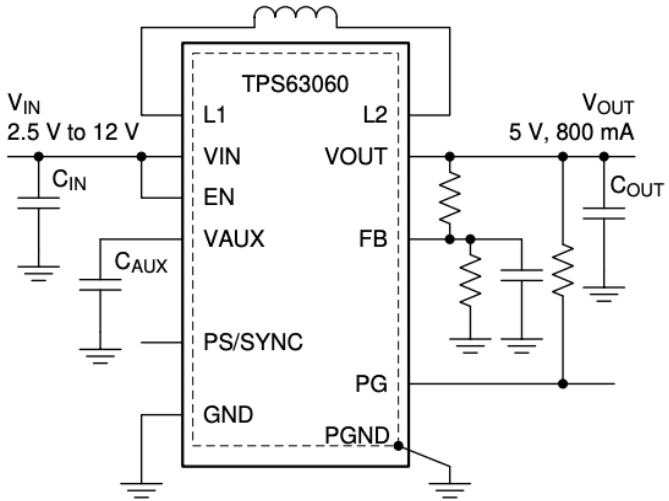
Application Circuit



Inductor is the energy storage element

Bypass capacitors

- C_{IN}, C_{AUX}, C_{OUT}

Feedback circuitry

- Resistor divider to set V_{OUT} based on V_{FB} = 0.5V
- V_{FB} is regulated through automatically adjusting the duty cycle of the internal PWM controller

ESP32 Module

The Brains of Our Circuit

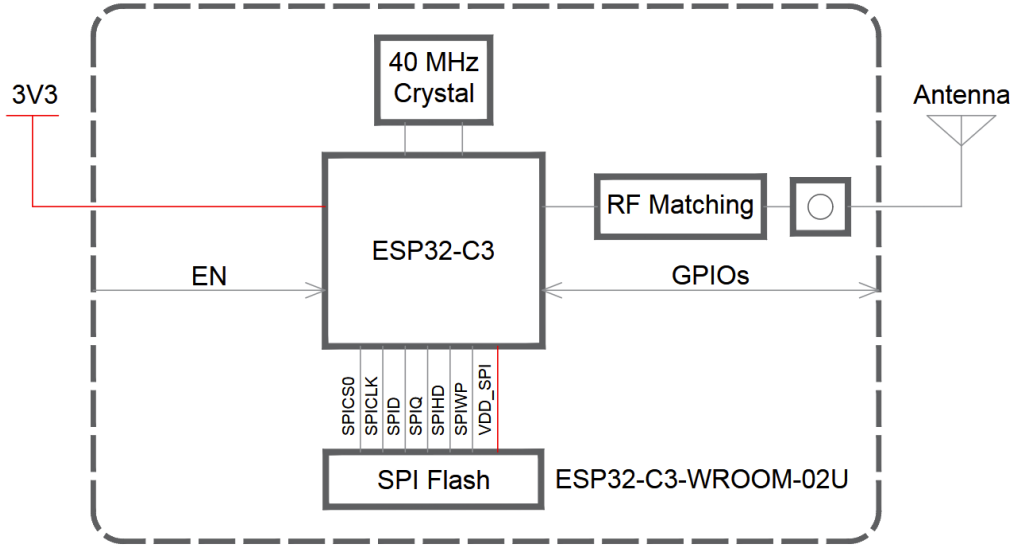


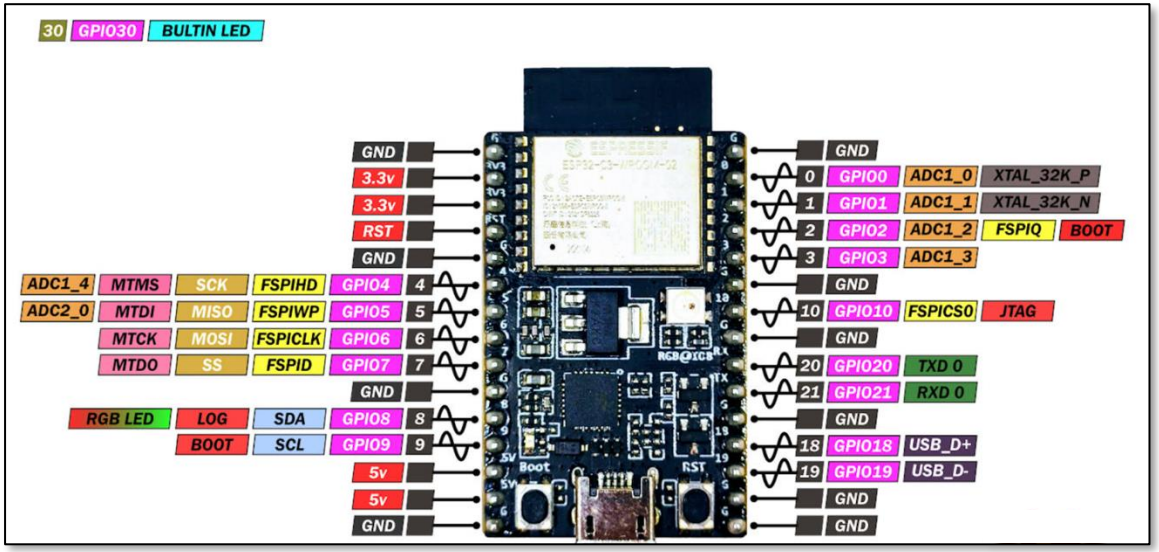
Figure 2: ESP32-C3-WROOM-02U Block Diagram

The ESP32-C3-WROOM-02U module conveniently houses the peripheral circuits needed the support the ESP32-C3 microcontroller, such as:

- Crystal oscillator – required to set the clock frequency and timing of the microprocessor
- SPI flash – to provide extra off-microcontroller storage for collected data or programs
- GPIO fanouts – makes routing to the GPIO pins much easier
- RF matching – for the WiFi/Bluetooth functionality
- Metal housing – for environmental and EMI shielding

ESP32 Module

Functionality



32 pins, several with multiple potential functions including:

- Power (3.3V and 5V power rails)
- GPIO
- USB data lines
- SPI functionality
- UART functionality
- I2C and I2S functionality
- ADC channels
- LED PWM Control

ESP32 Module

FM Radio Receiver Chip

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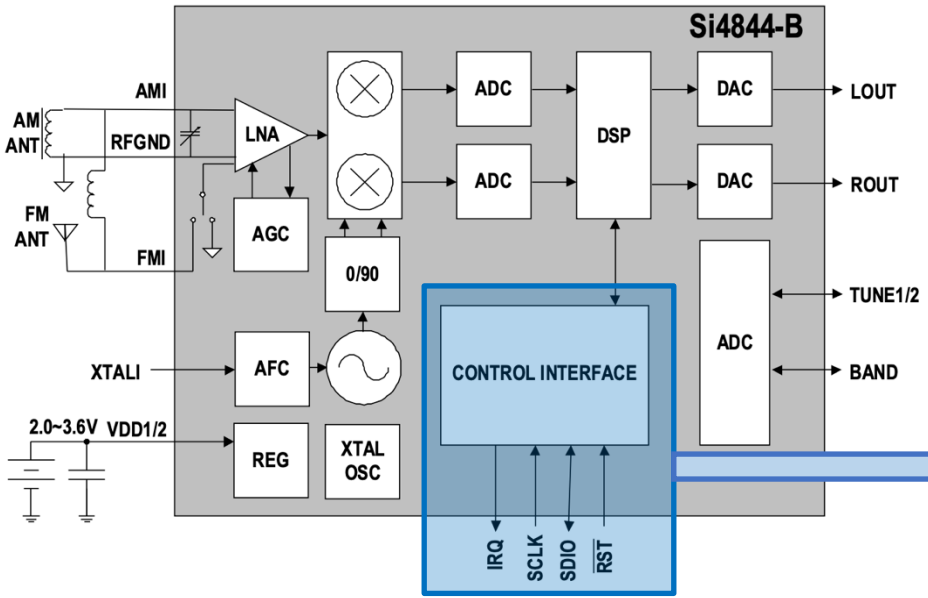
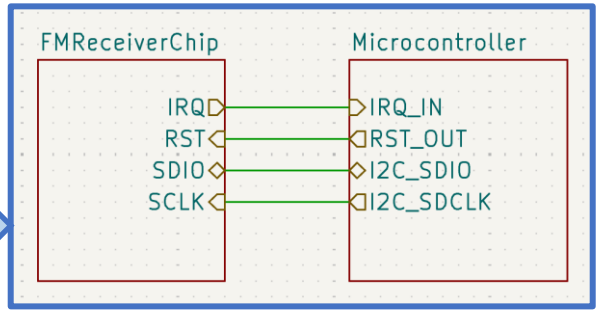
Functional Block Diagram



Communication signals:

- Chip sets interrupt
- Microcontroller sets clock
- Microcontroller and chip share data
- Microcontroller sets reset



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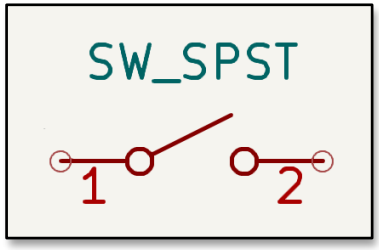
Switches

Types of Switches

SPST
Single-Pole, Single-Throw

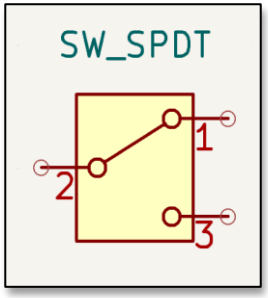
...aka one input, one output



Schematic Symbol

SPDT
Single-Pole, Double-Throw

...aka one input, two outputs



Schematic Symbol

Multiplexers

Fancy Switches

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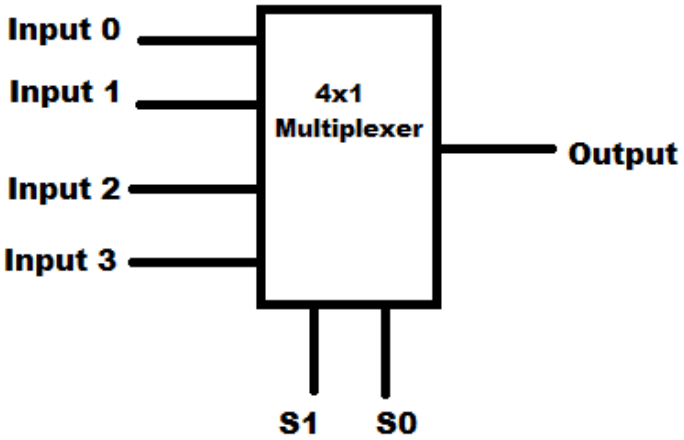
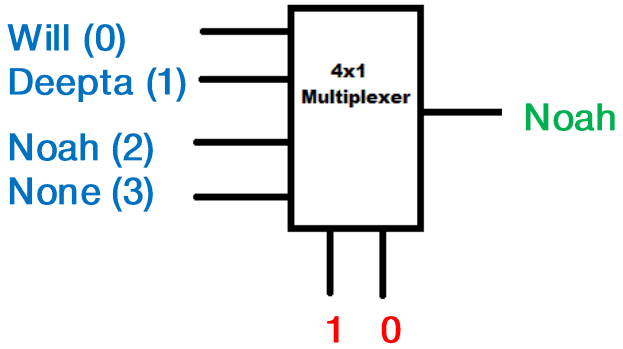
Multiple Inputs, Single Output



All possible inputs are separately fed into the multiplexer

The desired input is selected via a user-controlled signal

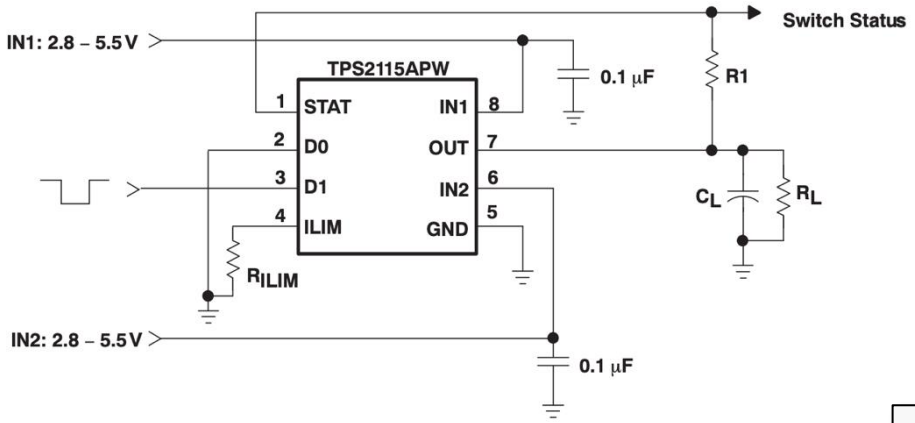
Ex:



Multiplexers

Autoswitching Power Mux

Typical Application Circuit



Inputs:

- 2 separate power sources

Modes:

- Autoswitching (source with higher voltage is used)
- Manual (D0 and D1 set source)

Reverse and cross-conduction blocking

If our USB gets disconnected, we can automatically switch to battery power.

Potentiometers

Variable Resistors

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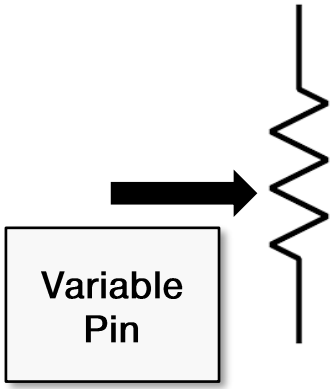
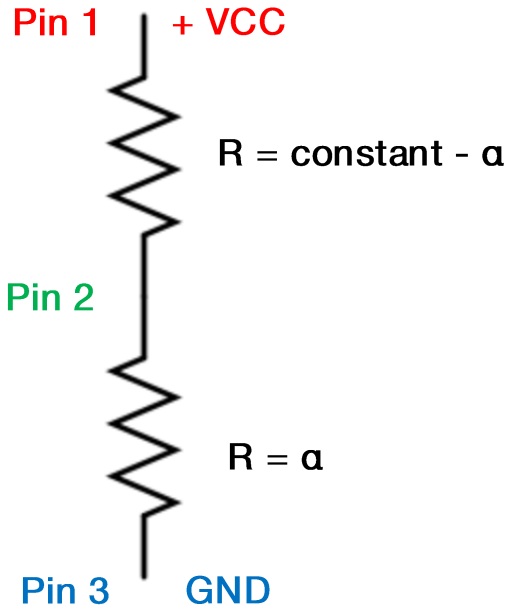
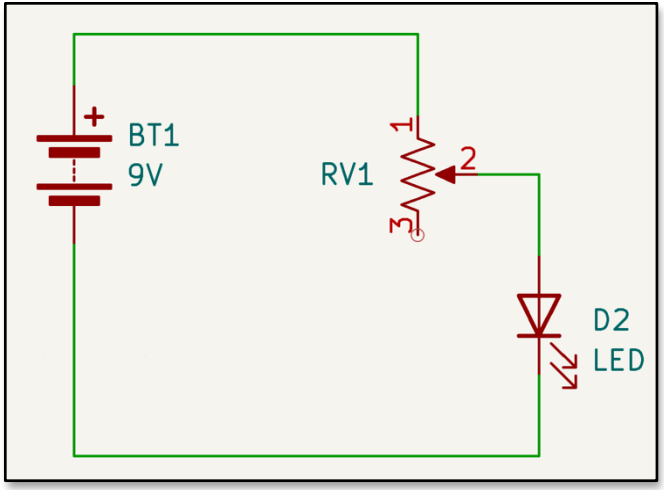
Symbol



Pinout



Example Circuit



Adjustable-brightness LED!

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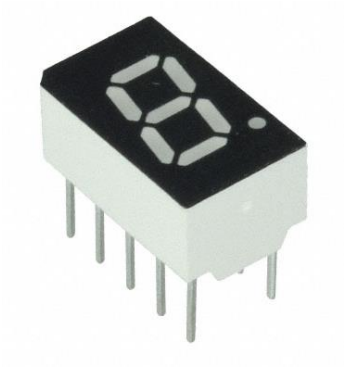
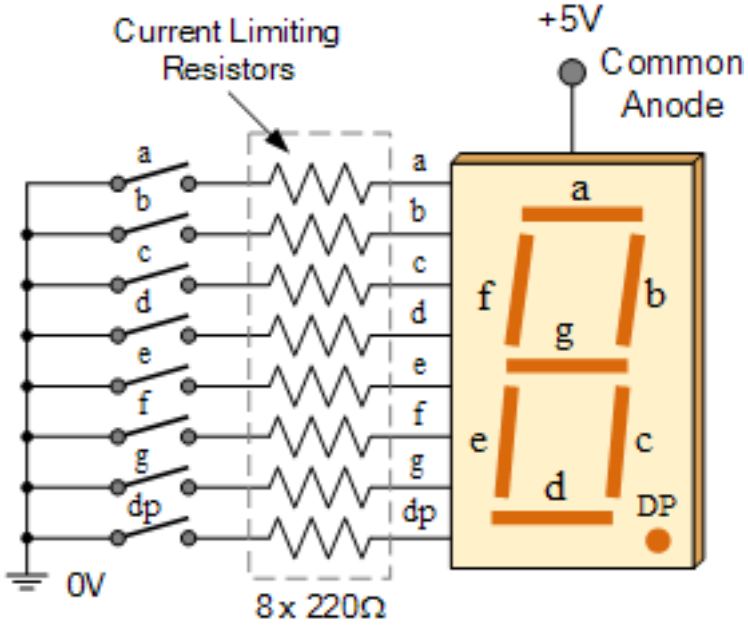
Display

7-Segment Display





7-Segment displays are commonly used for displaying numbers (and some letters).

- Consists of 7 individually addressable LEDs

If we decide to use four 7-segment displays for our FM radio to display tuned frequency (e.g., 101.5), that requires digital control of 4 x 7 = 28 pins!

But our ESP32 microcontroller only has 13 general-purpose input/output (GPIO) pins…
How do we control of the LEDs?

Shift Registers

Digital Control

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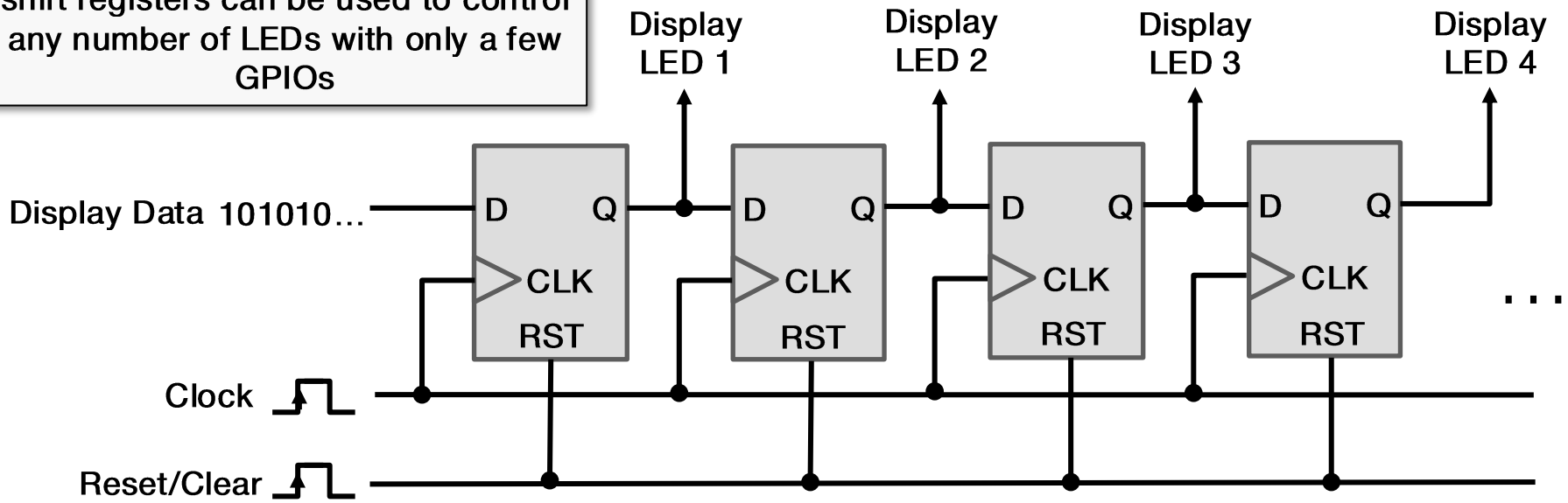
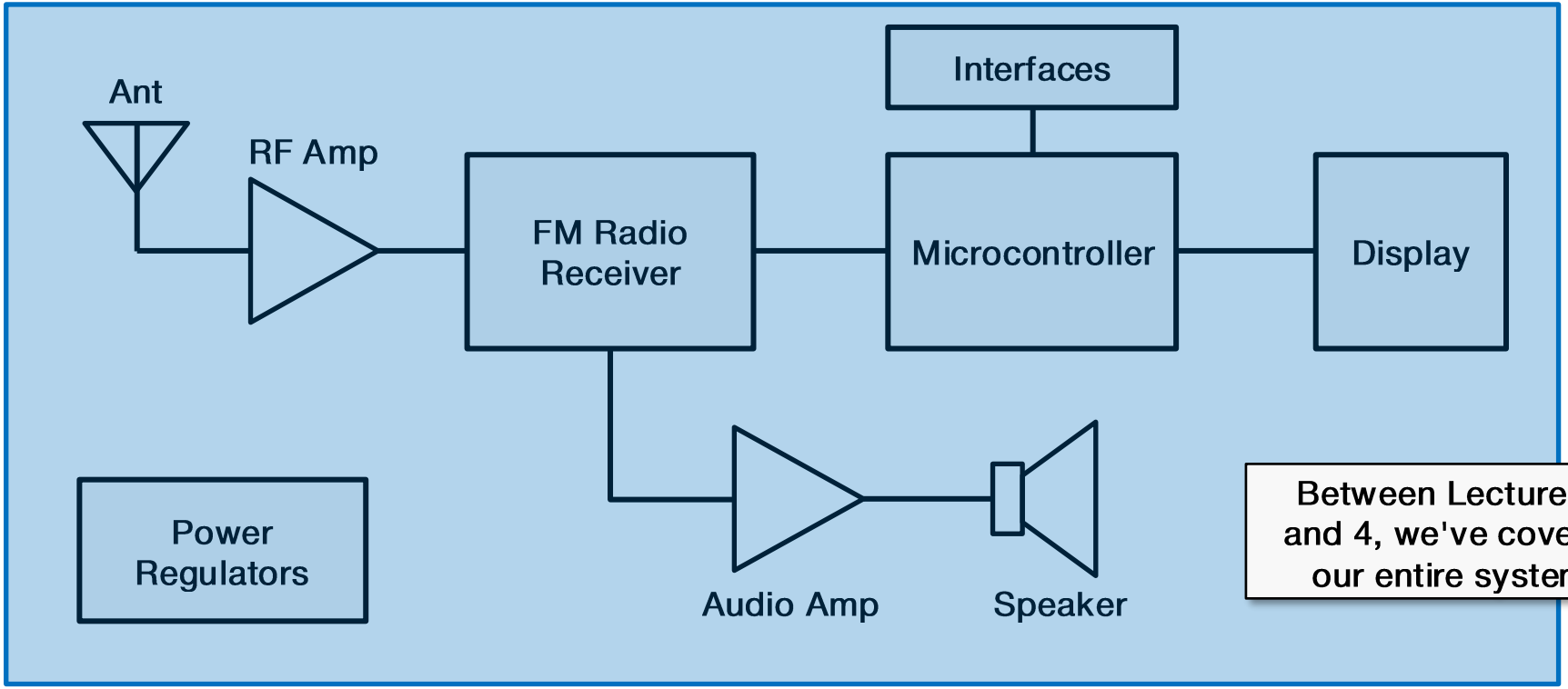
A chain of Serial-In, Parallel-Out shift registers can be used to control any number of LEDs with only a few GPIOs



Good solution for increasing number of digital outputs, given outputs that do not change often

Summary

Block Diagram, Revisited



Questions?