ESP32 & Core Electronics Lab Blueprint — Vol. 1 (v2)

Foundational Hardware Kit, Analog/Discrete Bench Circuits & Intermediate Embedded Systems

ECE Design Philosophy & Bench Setup: Solve local sensing, power regulation, and analog conditioning in silicon and copper first (op-amps, 555 timers, comparators, MOSFETs). Reserve the ESP32 for wireless telemetry, DSP, and rich user interfaces. Power rails cleanly using your **Samsung 5V chargers** (bypassed with 100 µF + 0.1 µF decoupling caps) and verify signal integrity, rise times, and ripple directly on your **oscilloscope**.

Part 1: Master Lab Hardware & Analog IC Shopping List

Category	Recommended Components	ECE Engineering Purpose
Microcontrollers & Prototyping	1× ESP32-S3 DevKitC-1 N16R8 (16MB Flash / 8MB PSRAM) 1× Classic ESP32 DevKit V1 (30-pin) 2× 830-pt Breadboards + 120 Jumper Wires + MB102 Module	Dual-core FreeRTOS, PSRAM web/LVGL hosting, ESP-NOW multi-node testing; dual breadboards span the wide S3 footprint.
Passives & Power Semiconductors	1/4W Resistor Kit (10Ω–1MΩ), Ceramic & Electrolytic Capacitor Kit (10pF–1000µF), 2N2222/BC547 NPN, BD139/BD140 Complimentary Pair, IRLZ44N N-MOSFET, AO3401/IRF9540 P-MOSFET, 1N4007 & 1N5819 Schottky Diodes	Pull-ups, RC filters, rail decoupling, high-side/low-side MOSFET switching, flyback protection, and discrete push-pull output stages.
Essential Analog & Power ICs	NE555 Timers, LM358 Dual Op-Amp, LM393 Dual Comparator, LM317 Adjustable Regulator, LM3914 Dot/Bar Driver, 4-Ch Bidirectional Level Shifter (3.3V↔5V)	Pure hardware oscillators, active filters, threshold comparators, linear regulators, analog LED bar-graphs, and 5V↔3.3V bus interfacing.
Sensors (I2C / SPI / Analog)	BME280 (Temp/Humidity/Pressure), MPU6050 (6-Axis IMU), INA219 (High-Side Current/Power), VL53L0X / HC-SR04 Distance, PIR HC-SR501, Capacitive Soil Sensor	Hardware bus protocols, DMA interrupt handling, sensor fusion, and real-time mA/mW power profiling.
Displays, Audio & Storage	0.96" SSD1306 OLED (I2C), 2.8" ILI9341 SPI Touch TFT, INMP441 I2S Mic, MAX98357A I2S Amp + 3W Speaker, MicroSD SPI Module + 16GB Card, WS2812B Strip	LVGL touch GUIs, digital I2S PCM audio capture/playback, hardware FFT visualization, and FAT32 offline logging.
Actuators & Bench Tools	2-Ch 5V Optocoupler Relay, SG90 Servo, TB6612FNG Motor Driver, 60W Temp-Controlled Soldering Iron, Solder/Flux/Wick, Digital Multimeter	Opto-isolated load switching, PWM motor control, and reliable PCB/header soldering alongside your oscilloscope.

Part 2: Pure Electrical & Analog Bench Projects (Zero Firmware)

ANALOG & POWER BENCH 01 • LINEAR REGULATION

1. Variable Bench Power Supply (1.25V–12V) with Load Regulation Testing

- **Circuit Architecture:** Build an adjustable linear regulator around an **LM317** (or discrete pass-transistor booster using a **BD139/2N3055** on a heatsink) fed from your 12V adapter, using a 240Ω reference resistor and 2kΩ potentiometer.
- **ECE Skills:** Dropout voltage analysis, thermal dissipation math (`P = (Vin - Vout) × Iload`), and input/output ripple capacitor sizing.
- **Oscilloscope Check:** Set scope to **AC Coupling (20mV/div)** across the output under step-load switching to measure peak-to-peak ripple and transient recovery.

ANALOG & SIGNAL BENCH 02 • WAVEFORM GENERATION

2. Op-Amp Function Generator (Square, Triangle & Sine Waves)

- **Circuit Architecture:** Cascade an **LM358 Schmitt Trigger** (square wave) into an **Op-Amp Integrator** (linear triangle wave), followed by a diode-resistor piecewise-linear shaping network to approximate a sine wave.
- **ECE Skills:** Hysteresis threshold calculation, RC integrator time constants, slew-rate limitations, and harmonic shaping.
- **Oscilloscope Check:** Display input square wave on CH1 and integrated triangle/sine output on CH2 in X-Y or dual-trace mode to inspect symmetry and clipping.

ANALOG & AUDIO BENCH 03 • DISCRETE AMPLIFICATION

3. Class-AB Complementary Push-Pull Audio Amplifier

- **Circuit Architecture:** Drive a matched **BD139 (NPN) + BD140 (PNP)** emitter-follower output stage from an LM358 preamp, biased with two series **1N4148 diodes** (`V_BE` multiplier) to eliminate the 0.7V dead-zone.
- **ECE Skills:** Quiescent bias current adjustment, thermal runaway prevention, and output impedance matching into a 4Ω/8Ω speaker.
- **Oscilloscope Check:** Feed a 1 kHz sine wave and observe the zero-crossing region on CH2—watch crossover distortion vanish as bias diodes are engaged.

Part 3: Five Intermediate Embedded & Mixed-Signal Projects

EMBEDDED PROJECT 01 • INSTRUMENTATION & WEBSOCKETS

1. Real-Time High-Side Power Profiler & Web Oscilloscope

- **Hardware:** ESP32-S3 N16R8, INA219 I2C current/voltage sensor, analog RC test circuit, decoupling capacitors.
- **System Design:** Pin a deterministic FreeRTOS sampling task on Core 0 (using hardware timers and PSRAM ring buffers) and stream binary frames via WebSockets on Core 1 to a lightweight web dashboard hosted in 16MB Flash.
- **Oscilloscope Check:** Toggle a debug GPIO inside the ISR to verify jitter-free sampling intervals on your scope.

EMBEDDED PROJECT 02 • LOW-POWER RF & LVGL

2. Multi-Node ESP-NOW Sensor Mesh with Local Touchscreen Hub

- **Hardware:** Classic ESP32 (battery sender with BME280 + soil sensor) + ESP32-S3 (gateway with 2.8" ILI9341 Touch TFT).
- **System Design:** Classic ESP32 wakes from Deep Sleep (<20 µA), bursts a connectionless ESP-NOW packet in <5 ms, and sleeps; S3 renders an LVGL touchscreen UI and bridges telemetry over MQTT.
- **Oscilloscope Check:** Measure voltage drop across a 1Ω series shunt resistor on the sender node to profile sleep vs. TX current spikes.

EMBEDDED PROJECT 03 • DIGITAL AUDIO & DSP

3. Offline I2S Voice-Controlled Relay & Real-Time FFT Analyzer

- **Hardware:** ESP32-S3 N16R8, INMP441 I2S MEMS Mic, MAX98357A I2S Amp + Speaker, 2-Ch Opto-Relay, WS2812B LEDs.
- **System Design:** Capture 16 kHz PCM audio via I2S DMA into PSRAM, compute real-time FFT magnitude bins for LED spectrum visualization, and run local ESP-SR wake-word detection without cloud latency.
- **Oscilloscope Check:** Inspect I2S `BCLK`, `WS` (LRCLK), and `SD` data framing on your oscilloscope.

EMBEDDED PROJECT 04 • CONTROL SYSTEMS

4. Closed-Loop PID Gimbal Stabilizer with Sensor Fusion

- **Hardware:** ESP32-S3, MPU6050 6-axis IMU, 2× SG90 Servos (powered from dedicated 5V rail), 4.7kΩ I2C pull-ups.
- **System Design:** Fuse accelerometer and gyroscope readings via a Complementary/Kalman filter, execute a 200 Hz PID control loop driving hardware LEDC PWM channels, and tune `Kp, Ki, Kd` live over Wi-Fi.
- **Oscilloscope Check:** Verify 50 Hz servo PWM pulse width (1.0–2.0 ms) and I2C clock rise-time sharpness.

EMBEDDED PROJECT 05 • RESILIENT EDGE STORAGE

5. Offline-First Environmental Logger with Store-and-Forward Sync

- **Hardware:** ESP32-S3, BME280, NEO-6M UART GPS, MicroSD SPI Module.
- **System Design:** Parse NMEA sentences over hardware UART, commit CRC-verified CSV records to FAT32 MicroSD over SPI, and batch-sync unsent rows with exponential backoff when Wi-Fi reconnects.
- **Oscilloscope Check:** Verify clean 3.3V logic transitions on SPI `SCLK/MOSI` during SD block writes.