1. Output filtering

- Remove higher harmonics from PWM demodulator’s pulse-amplitude-modulated output to recover “smooth” reconstruction of input
- Butterworth low-pass filter
  - Butterworth filter has maximally flat passband response (like a boring “graphic equalizer”)
    * Slow roll-off, but hard “knee” at −3 dB breakpoint corner frequency
    * Can get faster roll-off with higher order
    * In reality, component variations place ripples in passband
    * Other filters have ripples by design, but give steep roll-off at low order
  - Group delay/Phase delay
    * “Shape” of a wave is the result of summing a “group” of sinusoids
    * Can make a square wave look triangular by changing relative phase of harmonics
    * “Linear-phase” response leads to shape integrity
      * Every frequency sees same time delay
      * Result: “Group” appears to be delayed
      * Constant “group delay” of envelope = constant “phase delay” of harmonics
    * True linear phase possible with DSP (ECE 600)
  - “Nonlinear-phase” leads to “phase distortion” (i.e., group shape changes)
    * Crossover in speakers (e.g., tweeter and woofer off by 180°); church acoustics; etc.
    * Some acoustic phase distortion expected (position effects) or not noticeable to ear
      * Phase distortion demodulates to amplitude distortion for FM, PM, PWM, etc.
      * Butterworth have fairly constant group delay far below corner frequency
      * Frequencies near corner have frequency-dependent delay (compare with Bessel)
      * In lab, 10 kHz test signal has residual modulation harmonics that add out of phase
        * Not a concern in this for-human-ear application
- Implementation: Sallen-and-Key Filter (SKF) topology
  - How to get a hard Butterworth knee?
    * Begin with cascade of two RC voltage dividers
      * Second divider loads first divider; response is degraded
    * Add buffer between dividers so that first-order transfer functions multiply
      * High frequency response looks good, but knee is softer ($p^2 < p$ when $0 < p < 1$)
    * Use an RLC filter
      * Inductors suck
    * Use an active filter to get sharpness of RLC without an actual $L$
  - SKF bootstraps cascaded filter output
    (i) Start with two cascaded RC filters PLUS output buffer
    (ii) Reconnect first filter ground to buffer output
    (iii) Sharper response means Butterworth implementation is now possible
2. Speaker driver

- 0.25 W output means 2 V peak (procedure document explains why; also explains RMS)
  - At full-scale, we're already at 3 V peak (i.e., no amplification necessary)
  - Add voltage gain of 2
    * Will overdrive full-scale signals
    * Will ensure audible output for small signals
  - Use LSA circuit with gain of 2 and a pole for additional smoothing

- Need current amplifier to drive 8 Ω speaker load
  * Despite its looks, circuit is SIMPLE when broken into its parts

(i) Begin with Class-B push–pull amplifier

(ii) To remove crossover distortion, add biasing diodes for Class-AB operation

(iii) To reduce push–pull base current, implement transistors as Sziklai pairs
  - Sziklai pairs are like Darlington pairs
  - Darlington pair has two transistors of the same type with shared collectors
    * Use one transistor to “control” the base of another transistor
    * Acts like “big” transistor with \( \beta^2 \) current gain
    * Has twice the base–emitter drop
  - Sziklai pair uses two transistors of different types
    * Again, like “big” transistor (of “master” type) with \( \beta^2 \) gain
    * Normal base–emitter drop (i.e., not doubled)

(iv) Replace biasing diodes with “Rubber diode”/“Rubber Zener”
  - Shifts output offset
  - Allows tuning to ensure no class-B crossover distortion

(v) Add emitter–follower to drive biasing circuit
  - Stiff biasing circuit requires high current
  - Also reduces input-output offset

(vi) Add emitter resistors to reduce thermal runaway

(vii) Wrap amplifier in negative voltage feedback
  - Removes any output offset
  - Improves linearity
  - Can use separate feedback circuit or build current amplifier into voltage amplifier

(viii) Finally, capacitively couple speaker to output
  - Output has 5 V\(_{\text{DC}}\) offset that should not be placed across speaker
  - Dual rails would have allowed a direct connection
    * Output offset would have been 0 V\(_{\text{DC}}\)
    * Negative rail can be produced by DC-to-DC switcher
    * Input capacitor on both LSAs could be removed too
3. Parts in the lab

- NO CALCULATIONS are required. Component values are given (with explanations).
  - To help ensure component availability, different sets of components are given.
- Use low-leakage BiMOS (MOS input, BJT gain, CMOS push-pull output) CA3160 operational amplifier for BUFFER.
  - If CA3160 is not available, use CA3130 with 45–100 pF (e.g., 68 pF) from pin 1 to pin 8 (for feedback stability compensation).
- Use LM741 or LF351 operational amplifiers for filtering.
- DO NOT install speaker without SEEING ME FIRST.
  - A large electrolytic capacitor is required for AC coupling amplifier output (5 V average) to speaker (0 V average).

4. Laboratory experience

- Make use of **bypass capacitors** at **supply pins** to reduce output noise.
- When taking plots, save as CSV or BMP
  - Saving as BMP prevents extra work, but make sure scope plots show all required information
    * Intervals between horizontal and vertical divisions should be clear
    * In most cases, channel grounds should be shown
    * Channels should be labeled in report (e.g., “top waveform is input”)
  - If saving as CSV, be sure to . . .
    * Label axes and show units
    * Identify waveforms (e.g., “input” and “output”)
- See pin-out handout
- **Follow lab book procedures**
  - Handout gives detailed instructions.
    * Procedure pages have been marked in TOC with (*).
    * Additional pages given for explanation.
    * Bonus credit is available if time permits.
  - DO NOT use class-AB amplifier components from book!
    * Use design given in supplementary text.
  - If you finish, restore components TO THE CABINET!
    * Do **NOT** place them in the metal tin at your table!

5. Laboratory reports

- Answer all questions and provide all plots from lab procedures in lab text
- Include ALL PLOTS from procedure (even if they aren’t mentioned in book)
  - USE the plots in your discussion
- Consider answering some of the questions from the procedure
- As usual, **LAB REPORT** due a week after lab **COMPLETION**