Executive Summary

The purpose of this project was to prototype a hi-quality headphone amplifier, and to measure the amp’s performance using a dummy (pure resistive) or real headphone load. The idea was to either demonstrate how a headphone amp could quantifiably improve sound quality played out of a source, or to at least investigate typical usage scenarios and metrics for measuring sound quality.

Key metrics identified for characterising the amp’s performance were: input and output impedance, signal-to-noise + distortion (SINAD), and the gain response over audio frequencies.

The original discrete amplifier design chosen for the project was changed a more forgiving LM1875 op amp design during the prototyping stage due to deficiencies in parts ordered. The second amp was measured to have 21 Ω input and < 1 Ω output impedances, and a noise floor at -85 dB(V_{RMS}) relative to the audio signal. Qualitatively, the amplifier was able to drive audio transducers from computer Line Out with impedances from 8 Ω to 100 Ω without noticeable noise or degrading audio quality.

It was concluded that a medium-quality audio amplifier is not necessarily suitable for all applications. Recommendations include further testing and continued prototyping of the more ambitious (but trickier) hi-fi design.
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1.0 Introduction

1.1 Background and Motivation

In the era of the iPod and the earbud cheap portable audio set-ups have long since entered the mainstream. Unfortunately, the average consumer is unaware of audio source limitations and how much better their music would sound given proper amplification. Lack of industry standardisation regarding source/sink impedances has not helped, either [10].

Many measurements exist to characterise sound quality; the industry de-facto standard in many areas of audio testing is the Lindos sequence test system, which consists of over 25 different segments [16]. Two easy to understand and important concepts describing sound quality are: frequency response, and signal-to-noise ratio (SNR).

When performing objective measurements of audio signals a common unit used is decibels SPL, which describes Sound Pressure Levels. The $\text{dB}_{\text{SPL}}$ is a logarithmic unit which is calculated as$^1$:

$$dB_{\text{SPL}} = 10 \times \log_{10} \left( \frac{p_{\text{rms}}^2}{p_{\text{ref}}^2} \right) = 20 \times \log_{10} \left( \frac{p_{\text{rms}}}{p_{\text{ref}}} \right)$$

Thus, a sound that is 10 dB louder is of $10^{10/20} \approx 3.2 \times$ the actual pressure level in Pascals [19]. See Figure 1 below for a comparison of various sound pressure levels to commonly heard sounds. The logarithmic $\text{dB}_{\text{SPL}}$ makes sense as a unit for measuring sound as the human ear responds to sound pressure levels exponentially, not linearly, as this chart clearly illustrates.

---

$^1$ Note that the intensity of a sound pressure level is proportional to the square of the amplitude of the pressure.
The ear responds differently to sounds at different frequencies. For example, frequencies from 2-4 kHz are picked up readily by the ear and perceived as louder for a given intensity level than very low or very high frequencies. Standardised curves of equal-loudness exist that try to describe the frequency dependent response of human hearing. The most commonly used curve in North America is the A-weighting curve for sounds < 55 dB. [19] Headphones and earphones are designed to ‘match’ the frequency response of the human ear, as a transducer with a flat response would sound unbalanced to the ear. [9] The field of psychoacoustics is very broad however and the details of this ‘matching’ shall not be covered in further detail. In brief, the ideal audio source and any auxiliary equipment such as a headphone amplifier in the signal path should have a flat frequency response so that the head- or earphone’s transducer(s) may perform as originally designed.

<table>
<thead>
<tr>
<th>Source of sound</th>
<th>Sound pressure (pascal RMS)</th>
<th>Sound pressure level dB re 20 μPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shockwave (distorted sound waves &gt; 1 atm: waveform valleys are clipped at zero pressure)</td>
<td>&gt;101,325 Pa</td>
<td>&gt;194 dB</td>
</tr>
<tr>
<td>Theoretical limit for undistorted sound at 1 atmosphere environmental pressure</td>
<td>101,325 Pa</td>
<td>~154,094 dB</td>
</tr>
<tr>
<td>Grenades</td>
<td>6,000-20,000 Pa</td>
<td>170-180 dB</td>
</tr>
<tr>
<td>Rocket launch equipment acoustic tests</td>
<td>~4000 Pa</td>
<td>~165 dB</td>
</tr>
<tr>
<td>Simple open-ended thermoacoustic device[9]</td>
<td>12,619 Pa</td>
<td>176 dB</td>
</tr>
<tr>
<td>.30-06 rifle being fired 1 m to shooter’s side</td>
<td>7,265 Pa</td>
<td>171 dB (peak)</td>
</tr>
<tr>
<td>MG Garand rifle being fired 1 m</td>
<td>5,023 Pa</td>
<td>168 dB</td>
</tr>
<tr>
<td>Jet engine at 30 m</td>
<td>632 Pa</td>
<td>150 dB</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>63.2 Pa</td>
<td>130 dB</td>
</tr>
<tr>
<td>Vuvuzela horn at 1 m</td>
<td>20 Pa</td>
<td>120 dB (A)</td>
</tr>
<tr>
<td>Healing damage (possibly)</td>
<td>20 Pa</td>
<td>approx. 120 dB</td>
</tr>
<tr>
<td>Jet engine at 100 m</td>
<td>6.32 - 200 Pa</td>
<td>110 - 140 dB</td>
</tr>
<tr>
<td>Jack hammer at 1 m</td>
<td>2 Pa</td>
<td>approx. 100 dB</td>
</tr>
<tr>
<td>Traffic on a busy roadway at 10 m</td>
<td>2 x 10⁻¹ - 6.32 x 10⁻² Pa</td>
<td>80 - 90 dB</td>
</tr>
<tr>
<td>Hearing damage (ever long-term exposure, need not be continuous)</td>
<td>0.356 Pa</td>
<td>85 dB[10]</td>
</tr>
<tr>
<td>Passenger car at 10 m</td>
<td>2 x 10⁻² - 2 x 10⁻³ Pa</td>
<td>60 - 80 dB</td>
</tr>
<tr>
<td>EPA-identified maximum to protect against hearing loss and other disruptive effects from noise, such as sleep disturbance, stress, learning detriment, etc.</td>
<td>70 dB[10]</td>
<td></td>
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<tr>
<td>TV (set at home level) at 1 m</td>
<td>2 x 10⁻² Pa</td>
<td>approx. 60 dB</td>
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<tr>
<td>Handheld electric mixer</td>
<td>65 dB</td>
<td></td>
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<tr>
<td>Washing machine, dish washer</td>
<td>50-53 dB</td>
<td></td>
</tr>
<tr>
<td>Normal conversation at 1 m</td>
<td>2 x 10⁻³ - 2 x 10⁻² Pa</td>
<td>40 - 60 dB</td>
</tr>
<tr>
<td>Very calm room</td>
<td>2 x 10⁻⁴ - 6.32 x 10⁻⁵ Pa</td>
<td>20 - 30 dB</td>
</tr>
<tr>
<td>Light leaf rustling, calm breathing</td>
<td>6.32 x 10⁻⁵ Pa</td>
<td>10 dB</td>
</tr>
<tr>
<td>Auditory threshold at 1 kHz</td>
<td>2 x 10⁻⁵ Pa</td>
<td>0 dB[11]</td>
</tr>
</tbody>
</table>

Figure 1 - Chart illustrating loudness of various decibel sounds to the human ear. [20]
One important factor influencing the frequency response of an output source is its output impedance. Ideally, an audio source will have zero output impedance. This is due to several reasons listed below, summarized in brief from [10]:

1. Higher source impedance (Z) is proportional to less voltage being delivered across the load, according to Kirchhoff’s Voltage Law. With low Z loads, the voltage drop can be large enough to prevent driving the low impedance phones to loud enough levels.
2. The impedance response of headphones is frequency dependant, since headphones are not ideal resistive loads (esp. true for low-impedance phones like Grados [5]). Increase output impedance causes more frequency response deviations.
3. Higher output impedance is proportional to less electrical damping of the headphones. A common result is bass becoming “phat”, meaning “boomy”, “muddy”, or “uncontrolled”.

By adding a headphone amplifier stage between an audio source and sink, the output impedance seen by the sink can be controlled and the impact of these problems can be reduced. For an example of how much deviation in frequency response can result just by changing the output impedance, see Figure 3 and Figure 4 below. For 43 Ω $Z_{\text{out}}$, the 21 Ω Ultimate Ears SuperFi 5’s measure 12 dB frequency response deviation across the audio spectrum; for 10 Ω $Z_{\text{out}}$, the deviation is much less at 6 dB.
Figure 3 - Plot showing 12dB frequency response deviation for $Z_{\text{out}} = 43 \ \Omega$ with UE SuperFi 5’s. [10]

Figure 4 - Plot showing 12dB frequency response deviation for $Z_{\text{out}} = 10 \ \Omega$ with UE SuperFi 5’s. [10]
Consider the Thevenin equivalent representation of an audio source (for ex. an MP3 player or a headphone amp) hooked up to a purely resistive audio sink (for. an idealised pair of headphones) as shown below in Figure 5. A rule of thumb for the maximum output impedance of the source is:

\[ Z_{\text{out max}} = \frac{Z_{\text{headphone}}}{8} \]

For example, with a pair of 12 Ω AKG IP’s the max output impedance should be 1.5 Ω or less. At an output impedance of 1 Ω [11], the SanDisk Sansa Clip+ is an example of a portable audio player that would fulfill this maximum impedance requirement for optimal playback with these earphones. Unfortunately, the only industry standard on output impedance is IEC-G1938 which dates to 1996 and recommends that \( Z_{\text{out}} = 120 \Omega \)! In reality, the output impedances of modern MP3 players runs the gamut, and frequency response colourisation is commonplace. Of course, it is important to recognise that frequency response can be a matter of taste and some reference class monitor headphones (such as the Sennheiser HD650 for ex.) may in fact sound somewhat “dry”, “cold”, or “analytical” [7]. In fact, recording engineers mix music with colourisation of the frequency spectrum to make it sound more lively and interesting. [9, 15]

While frequency colouration is not always easily recognised lacking a reference source and is sometimes even desirable, signal noise can be readily identified if the signal to noise ratio is too low. Many types and sources of signal noise and interference and distortion exists, everything from thermal noise due to resistors (\( V_{\text{noise}} = \sqrt{4kTR_B} \), \( k = \text{Boltzmann constant}, B = \text{bandwidth} \) [23] to EMI and RFI picked up by earphone cords [8]. In fact, the initial motivation for this project was to look into ways of reducing background noise of a BlackBerry smartphone’s audio output. It is commonplace in smartphone design for space and power constraints to trump hi-fidelity audio design, and the multi-layer surface-mount IC heavy nature of smartphone electronics makes home DIY modding impractical in addition to aesthetic considerations. Therefore, I looked for a ‘black box’ style solution to eliminate a music player's noise and thereby improve the sound quality.
Hi-fi headphone amplifiers may decrease the noise fed to a pair of headphones from a music player. However, this reduction in noise is not done by filtering noise components out of the signal. While DC noise can and should be readily eliminated in a proper amp design, since over time DC may damage low-impedance headphones [5], an AC signal is what is used to drive a headphone's transducers to play music. AC noise cannot be readily filtered out of music, since by nature “one man’s noise is another man’s music” [18]. Likewise, noise may be purposefully introduced into a recording as part of the recording process or as part of digitally compressing the music to a lossy format. Headphone amps are designed to let an audio source drive its signal at lower power, which can reduce distortion and eliminate clipping of the source’s signal. If the amp is hi-fi, then it will be able to amplify this signal to levels appropriate for the headphones without introducing excess noise or distortion in the signal. [3]

1.2 Project Objectives

Headphone amps are part of somewhat of a niche market that caters to audio recording professionals and hi-fi enthusiasts. Still, many manufacturers exist (a quick Amazon search listed 51 [2]) and Do-It-Yourself (DIY) projects can easily be found as well [6].

In the field of audio equipment varying standards of documentation exist, however, and the primary novel component of this project will be to integrate information pertaining to all aspects of the project into one location. As such, the project objectives are listed below:

1. Prototype a headphone amplification unit.
2. Prototype a switchbox unit to aid in testing.
3. Quantitatively measure the amp’s performance using a dummy load.
4. Quantitatively measure amp’s performance using a real load.
5. Qualitatively measure amp’s performance.
6. Document circuit schematics, placement files, budget and parts, images of project components, trouble-shooting and debug walkthrough, and information on testing the completed design.
1.3 Scope and Limitations

Due to time limitations, the scope of the project completed before the writing of the final report ended up being scaled back severely. Objectives 2 (switchbox) and 4 (real headphone quantitative testing) were not pursued because of report deadlines.

The main factor for the project running behind schedule was the greatly extended time needed to debug the headphone amplifier power supply circuit and amp channels. Indeed, in the end the original circuit designs were abandoned in favour of less ambitious ones in order to be able to obtain measurable results. A compounding factor was the fact that most of the prototyping work was scheduled during late October / early November, which is the busiest part of the fall semester. (Refer to Original and Actual Project Schedule).

The completed deliverables include two CMoy-style [8] amplifier channels based on the LM1875 op-amp. The design was taken from a typical usage scenario from the device’s specifications sheet. [25] An adjustable +/- 15VDC power supply was found in the lab and used for the amp. A dummy 15 Ω 12W / 300 Ω 10W resistive load box was constructed to simulate a pair of headphones for use in testing.

The op-amp based amp design was characterised by measurements of gain, frequency response, noise and harmonic distortion, and input/output impedance.

1.4 Organization

The rest of the report will be divided into 4 sections: Discussion, Conclusion, Project Deliverables, and Recommendations.

The Discussion section will discuss sound quality metrics and the experimental methodology and equipment behind testing the headphone amplifier, in addition to a selection of results.

The Conclusions section outlines the most important conclusions that can be drawn from the results.

The Project Deliverables contains a list of the current state of the project deliverables in addition to a final budget for the project. The ongoing commitments to the project are also stated.

The Recommendations proposes future work to continue the project and sums up some recommendations regarding audio amplifiers for personal use.
2.0 Discussion

2.1 Theory

The proposed headphone amplifier design for this project was “A Pure Class A Dynamic Headphone Amplifier by Kevin Gilmore” [5]. It is a pure class-A amplifier, meaning that in all stages the amplifying elements (transistors, FET’s) continuously conduct over the entire cycle of the AC input signal at the expense of greatly reduced efficiency [17].

The design is unique in that it avoids placing any capacitors, transformers, op-amps, or servos in the audio signal path in order to reduce noise and non-linearities in the output signal. In order to keep DC offsets low to prevent damaging the headphones, an optional servo loop feeds the DC offset to the current sources of the stage 1 JFET differential amps which in turn reduces the amount the corresponding stage 2 output BJT’s are driven.
The schematic for a single-channel amplification circuit is as shown below. The circuit enclosed in the blue square is the whole amplifier channel; the sub-circuit with the green resistors immediately below is the channel’s op-amp. The OP27 op-amp is the servo which feeds DC bias from the amp’s headphone output back into the main op-amp via the DC Adjust nets.

The op-amp is composed of two halves, a “push” half and a “pull” half; each half is comprised of two stages.

The first stage is a differential amplifier composed of two dual JFET’s. In the prototyped circuit, two matched discrete JFET’s (2N5460 P-channel JFET and 2N5486 N-channel JFET) were used instead.
The DC Adjust net changes the amount of current provided by the BJT current sources to the differential amp first stage. This current controls the gain of the differential amps as:

\[ A_m = g_m R_c; \quad g_m = \frac{\alpha I}{2V_T} \]

The second stage is linked to the first by a common emitter BJT. This BJT drives the second stage common collector output BJT’s. When the servo changes DC Adjust and thereby adjusts the gain of the differential amp, the corresponding output stage will be driven more or less relative to the other polarity output stage and hence the DC output will decrease.

The schematic for the power supply circuit is shown below. It is designed to produce highly regulated precisely balanced +/- 16.4 VDC. It consists of a transformer to take 115VAC from wall down to 56VAC in centre-tapped configuration. Two bridge rectifiers rectify the AC to DC voltages. The rectified DC is fed into adjustable voltage regulators LM317/337 which produce regulated +/-24VDC rails. A 5VDC reference chip is fed into a non-inverting low-noise OPA548 op-amp. The gain of the op-amp as shown is:

\[ A_f = \left(1 + \frac{R_2}{R_1}\right), R_2 = 22.8 \text{k}\Omega \pm 0.05\%, R_1 = 10 \text{k}\Omega \pm 0.05\% \]

The resistors are picked to be as precise as possible in order to generate a voltage as close to +16.4VDC as possible. This positive voltage is fed into an inverting unity gain op-amp to produce -16.4VDC.

![Schematic for power supply circuit of headphone amp.](image)

Additional detail about the headphone amp design can be found in the HeadWize article publishing the circuits; refer to [5].
2.2 Methods / Testing Protocol

Amplifier and power supply designs were taken from “A Pure Class A Dynamic Headphone Amplifier by Kevin Gilmore” [5]. These ambitious designs were based on high-quality discrete components and aimed towards hi-fidelity audio response, at the expense of extra components cost and prototype time. Unfortunately, stability issues with the (adjustable) negative rail of the power supply forced abandoning the prototyped power supply circuit in favour of an adjustable 15 +/- 2 VDC supply. In addition, it was determined that large variations in $h_{FE}$ (a.k.a. $\beta$, or transistor current gain) between the PNP and NPN ordered transistors resulted in incorrect biasing conditions for the amplifier stages.

A late decision was made to abandon the Class A discrete amp design in favour of a more easily implemented op amp design. The op amp design chosen was a CMoy-style amp based on the LM1875 chip similar to that found in the technical specifications manual for the LM1875.

2.3 Alternative Designs

Alternative design would certainly have been possible in this project. Given enough time and an unlimited budget, many combinations of headphone amps and test set-ups could be construed.

The discrete component class A headphone amp design originally proposed for this project is designed with hi-fi amplification on low- to medium-impedance headphones in mind, given no space or power constraints, and to compete with much more expensive commercial headphone amplifiers. [5]

The classic basic op-amp headphone amp design later chosen in order to derive some results is called a CMoy-style amp. It was designed to provide necessary amplification for portable music listening with full-size headphones [21]. However, CMoy-style amps are simple projects designed more for preventing clipping and raising volume levels than for hi-fi amplification.

Another family of headphone amplifiers uses vacuum tubes, known for their characteristically “smooth” sound or high power (> 1W) output, instead of solid-state electronics for amplification. However, working with vacuum tubes can be dangerous as they operate at high voltages (some > 1000V) and for many headphones even 100mW is extremely loud depending on their impedance rating [14].
2.4 Experimental Equipment

Pictures illustrating the experimental set-up and the equipment used are provided below:

Figure 8 - Overall equipment set-up
Figure 9 - HP 35665A Spectrum analyser

Figure 10 - Tektronix TDS350 Oscilloscope. CH1 is input to amp; CH2 is output from amp
Figure 11 - Dummy resistive load box

Figure 12 - Headphone amp & 15+/−2 VDC PSU
Figure 13 - Gilmore prototyped PSU [5]

Figure 14 - Gilmore prototyped amp [5]
2.5 Flow Diagrams

These flow diagrams illustrate the process of measuring sound characteristics for the amplifier. Diagrams for making impedance and frequency response measurements have been provided.
The following notes explain how to use the HP 35665A Network Analyser to perform a frequency response measurement of the amp using a fixed sine wave:

**Figure 15 - Network analyser instructions 1**
Figure 16 - Network analyser instructions 2

(4) Trace Coord → X-axis → Log
(I) Marker (don’t hit anything yet)

- Turn amp on & verify output at 1000 Hz
- Press “→ Start” on analyser when no message displays

(J) - Press “→ Start” on analyser when no message displays
- Turn off any even “Average Complete”

(k) - Use: → Marker → Marker to Peak → Next Peak Right (Left to find harmonic peaks / spurious noise peaks

9 January 2012
(Cont.)
The following diagrams illustrate the process of measuring input and output impedances of the prototyped headphone amplifier:

**Figure 17 - Measuring $Z_{in}$ and $Z_{out}$**
2.6 Results

Gilmore Power Supply Circuit

The Gilmore power supply circuit [5] was constructed close to schematics and was verified to deliver at least 5W at +/-16.3 VDC into a power resistor plus 12V mini-bulb configuration shown in Figure 18.

![Figure 18 - PSU test circuit](image)

It was discovered that the LM1875 op amp creating the negative rail was stable for only a few seconds of continuous power at -16.3V before jumping close to GND. The stability time varied depending on the output capacitor between -16.3V and GND. Luckily, an adjustable and highly-regulated +/- 15VDC Power-One supply was found in the lab and was used instead.

Gilmore Discrete Amplifier Circuit

Two Gilmore amplifier circuits [5] were constructed according to the given circuit schematics on proto-PCB to avoid parasitic impedance from breadboard traces interfering with the audio signal path. Pairs of N-channel JFET’s were matched to 0.0 mV and 0.0 mV with respect to a reference JFET, and pairs of P-channel JFET’s to 0.9 mV and 0.8 mV w.r.t. reference. See Figure 19 for the experimental set-up.
BJT’s were characterised by their current gain $h_{FE}$ (a.k.a. $\beta$); due to being sourced from the same batch all of the NPN BJT’s were found to have $503 \leq \beta \leq 749$ and the PNP’s were found to have $305 \leq \beta \leq 353$. Usually pairs of transistors are aimed to be matched within $\Delta \beta < 20$ in applications where transistor matching is important [27]. Various combinations of BJT’s were tried for the circuit to try to minimize output DC offset of the amp, which can damage headphones. The DC offset was not stable and often 1 or 3 V, which would damage a low impedance pair of headphones. Ultimately, it was found that the DC biasing conditions of the P-channel and N-channel 1st stage differential amps were incorrect due to the severe mismatch in $\beta$’s and that either different transistors would have to be used or the amp redesigned in order to make it work. One example of the DC conditions recorded for a 1st stage channel can be found in the figure below.
Figure 20 - Faulty biasing conditions of 1st amp stage
LM1875 CMoy-style Op-Amp Amplifier Circuit

The two LM1875 CMoy-style [8, 25] channels were prototyped and qualitatively tested. When the amp’s gain was selected to be low (1 ~ 3) and the amp was connected to a Sansa Clip+’s Headphone Out or a computer Line Out no significant hissing and only a slight noise floor was present.

Figure 21 - Right amp channel driven by pure sine wave
The input impedance for the channels was found to be 20 - 21 kΩ over the audio frequency range 50 Hz to 22 kHz. For the output impedance, an upper bound was found to be 1 Ω with the amp unable to drive a dummy load with $Z < 0.15 \, \Omega$.

<table>
<thead>
<tr>
<th>f</th>
<th>v1</th>
<th>v2</th>
<th>$z_{in}$ = (7.5k * \frac{v2}{(v1-v2)})</th>
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<tr>
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<td>483</td>
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<td>20.60748</td>
</tr>
<tr>
<td>22000</td>
<td>256</td>
<td>186</td>
<td>19.92857</td>
</tr>
</tbody>
</table>

*Figure 22 - Calculating amp input impedance*
At 500 Hz a ratio of signal-to-max-spurious-noise of 75 dB(V\text{RMS}) and a noise floor of 85 dB(V\text{RMS}) down from carrier were measured. One significant source of noise obtained was from the 60 Hz AC power source, as high spurious noise levels were recorded at integer multiples of 60 Hz. The second and third harmonics are often the largest; in general harmonics are located at:

\[ |\pm K f_s \pm n f_a| \]

Where: \( f_s = \text{sample frequency} \), \( f_a = \text{audio signal frequency} \),
\( n = \text{harmonic order} \), \( K = 0,1,2,3 \ldots \) [29]

Figure 23 - FFT of 500 Hz from Headphone Out into amp driving 15 ohms showing harmonics
From the analyser FFT figures an FFT noise floor of 110 dB down is clearly observable. This corresponds to an ideal 12-bit ADC whose noise floor is:

\[
110 \, dB - 10 \log_{10} \left( \frac{M}{2} \right) = 110 - 33 \, dB = 77 \, dB; \text{if } M = \# \text{ pts. in FFT} = 4096 = 2^{12} \quad [28].
\]

Note as well that the frequency response of the fixed sine wave generated then immediately measured by the analyser is very similar to that fed through the audio amplifier then into the analyser for measurement. I.e., the audio analyser clearly produces “fixed sine waves” with measurable harmonic distortion and has a noise floor of its own.

![Figure 24 - Line out into amp showing 100dB floor](image)

![Figure 25 - Headphone out into amp showing 100dB floor](image)
Next, some test cases will be presented by showing spectrum analyser plots:

1. Average white noise into amp over 500 samples to find rough gain measurement; plot for gain with amp and without amp (just measuring source).
2. Average 10 samples of 500Hz fixed sine into amp and compare to signal straight from source.

1.

Figure 26 - Spectrum analyser source measurement showing -110dB floor

Figure 27 - Burst random waveform on scope
Figure 28 – “Simulated gain plot”: Burst random noise 500 sample average from amp

Figure 29 - “Simulated gain plot”: Burst random noise 500 sample average from amp; log freq scale
Figure 30 - 500Hz output from amp driving 15 ohm; 10 sample avg
Figure 31 - 500Hz source from analyser
3.0 Conclusions

Inspecting the similarity of the FFT’s produced off the analyser fixed sine wave source compared to the amplifier output, one may conclude that the amount of harmonic distortion or noise is really not distinguishable by the 12-bit HP 35665A.

The estimated LM1875 CMoy-style amplifier input and output impedances of 21 kΩ and <1 Ω, respectively, suggest that the amp will be able to drive audio transducers of most impedances that do not need voltage levels of more than 2-3VAC. The two amp channels drove a small pair of 8 Ω loudspeakers around 1VAC correctly (corresponding to ~ 100mW of power dissipation). It will not be able to drive electrostatic headphones that require hundreds of volts to operate.

The LM1875-based headphone amp channels were dummy-load tested to amplify pure sine waves from 50 Hz to 22,000 kHz at \( V_{pk-pk} \) on the order of 1 V stably. The amp channels were also qualitatively verified to work using 8, 16, 32, and 100 Ω audio transducers at reasonable listening levels, with the amp driven from computer Line Out, a portable Sansa Clip+ music player, an HP 35665A Dynamic signal analyser and a BK Precision 4012A function generator.

The Gilmore Discrete Class A Amp was abandoned due to mismatch between current gain between PNP and NPN transistors resulting in high DC offset and incorrect (saturation) biasing conditions. The Gilmore power supply design suffered from stability issues was abandoned in favour of a pre-existing +/-15 VDC adjustable lab power supply. This risk of ordering parts that might not necessarily work for the given circuit designs was both anticipated and accepted upon drafting the Project Charter; unfortunately in this case a lengthy debug process that impacted the quality of the project’s alternative results was required to prove that this was the case.
4.0 Deliverables and Financial Summary

Project Deliverables

The promised project deliverables are listed below along with an explanation of the current state of the deliverable. This section also includes a financial summary of project costs.

<table>
<thead>
<tr>
<th>Physical:</th>
</tr>
</thead>
</table>
| 1. **Headphone amp unit: power supply circuit + two 1-channel amplifier circuits**  
*Original amplifier channel design debugged, deemed too ambitious to complete given time constraints.*  
*Original PSU debugged; critical stability issue found with design → replaced with adjustable lab PSU.*  
*Alternative amp design constructed and working.* |
| 2. **Switchbox unit**  
*Not completed to save time for higher priority work. Could be constructed before presentation to demo amp unit more easily.* |
| 3. **Dummy resistive load box unit**  
*Completed and working.* |
| 4. **Any audio coupling platform or recording set-up derived from project budget**  
*No real headphone testing performed; no audio coupling platform constructed.* |

<table>
<thead>
<tr>
<th>Intellectual:</th>
</tr>
</thead>
</table>
| 1. **Project documentation including: circuit schematics, circuit placement files, budget and parts, images of project components, trouble-shooting and debug walkthrough, and information on testing the completed design**  
*Modified circuit schematics included in Appendix: A  LM1875 Op-Amp Amplifier Circuit Schematics.* |
Circuit placements files not created; manual prototyping on breadboard/proto-PCB done to save time.

Budget with parts ordered included in Financial Summary.

Parts lists for Discrete Class-A Amp and LM1875 Amp included in Appendix C List of Parts.

Project components images can be found in Section 2.4 Experimental Equipment.

Testing information is explained throughout Section 2.0 Discussion.

Refer to the included logbook for details on trouble-shooting and debug walkthrough, in addition to further details on testing the amplifiers.

2. Quantitative measurements of amplifier (and audio system) performance

Select results presented in 2.6 Results; others recorded in log book. Further measurements likely to be performed after formal completion of project and may be available to the Project Lab.

3. Engineering recommendation (Final) report

If required, this document may be followed up by an additional summary of further results. Regardless, the Project Completion report will be finished and handed in prior to project termination.

4. Project fair poster

Project fair slides will be posted to the Vista course page for printing.
## Financial Summary

Below is a summary of all requested for the project. This is not a list of what was actually ordered by the Project Lab or what was received. Refer to Appendix C List of Parts for the parts actually needed for each amplifier.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part #</th>
<th>Cost ea.</th>
<th># requested</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammond 166J50 115V to 50 C.T. Transformer</td>
<td>Newark 66F7394</td>
<td>37.99</td>
<td>1</td>
<td>37.99</td>
</tr>
<tr>
<td>5VDC REF02 precision voltage reference</td>
<td>Mouser 700-REF02CP</td>
<td>3.28</td>
<td>1</td>
<td>3.28</td>
</tr>
<tr>
<td>100V 2A single phase bridge rectifier</td>
<td>Newark 78K3297</td>
<td>0.361</td>
<td>4</td>
<td>1.444</td>
</tr>
<tr>
<td>LM3875 audio power amp</td>
<td>Newark 41K5106</td>
<td>8.06</td>
<td>2</td>
<td>16.12</td>
</tr>
<tr>
<td>4.7uF +/-10% 75uV/s poly film capacitor</td>
<td>Newark 29M0511</td>
<td>2.97</td>
<td>4</td>
<td>11.88</td>
</tr>
<tr>
<td>240Ohm 1% 250mW metal film resistor</td>
<td>Newark 58K3832</td>
<td>0.062</td>
<td>5</td>
<td>0.31</td>
</tr>
<tr>
<td>10kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 12P6367</td>
<td>0.222</td>
<td>4</td>
<td>0.888</td>
</tr>
<tr>
<td>22.6kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 78R5152</td>
<td>0.805</td>
<td>1</td>
<td>0.805</td>
</tr>
<tr>
<td>499 (500 replacement)Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 97K8700</td>
<td>0.749</td>
<td>2</td>
<td>1.498</td>
</tr>
<tr>
<td>510Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 12T2093</td>
<td>0.604</td>
<td>1</td>
<td>0.604</td>
</tr>
<tr>
<td>200Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 03P4750</td>
<td>0.639</td>
<td>4</td>
<td>2.556</td>
</tr>
<tr>
<td>5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 68P8706</td>
<td>0.278</td>
<td>4</td>
<td>1.112</td>
</tr>
<tr>
<td>1kOhm 0.1% 500mW metal film resistor</td>
<td>Newark 67P8682</td>
<td>0.356</td>
<td>2</td>
<td>0.712</td>
</tr>
<tr>
<td>7.5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 97K8736</td>
<td>0.659</td>
<td>2</td>
<td>1.318</td>
</tr>
<tr>
<td>3.32kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 78R5179</td>
<td>0.822</td>
<td>2</td>
<td>1.644</td>
</tr>
<tr>
<td>25Ohm 0.1% 250mW metal film resistor</td>
<td>RN65C25R0BB14</td>
<td>1.18</td>
<td>8</td>
<td>9.44</td>
</tr>
<tr>
<td>NTE460 P channel JFET (2SJ109 replacement)</td>
<td>Newark 31C4208</td>
<td>8.12</td>
<td>1</td>
<td>8.12</td>
</tr>
<tr>
<td>NTE458 N channel JFET (2SK389 replacement)</td>
<td>Newark 29C4607</td>
<td>7.64</td>
<td>1</td>
<td>7.64</td>
</tr>
<tr>
<td>BC549 NPN transistor 100mA (2SC1815 replacement)</td>
<td>Newark 58K8757</td>
<td>0.061</td>
<td>20</td>
<td>1.22</td>
</tr>
<tr>
<td>BC559 PNP transistor 100mA (2SA1015 replacement)</td>
<td>Newark 58K8762</td>
<td>0.142</td>
<td>20</td>
<td>2.84</td>
</tr>
<tr>
<td>LM833 (OP27 replacement)</td>
<td>Newark 26K3636</td>
<td>0.653</td>
<td>2</td>
<td>1.306</td>
</tr>
<tr>
<td>499 (500 replacement)Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 98K3835</td>
<td>0.402</td>
<td>4</td>
<td>1.608</td>
</tr>
<tr>
<td>200Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 03P4750</td>
<td>0.639</td>
<td>4</td>
<td>2.556</td>
</tr>
<tr>
<td>5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 68P8706</td>
<td>0.278</td>
<td>4</td>
<td>1.112</td>
</tr>
<tr>
<td>7.5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 97K8736</td>
<td>0.659</td>
<td>2</td>
<td>1.318</td>
</tr>
<tr>
<td>3.32kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 78R5179</td>
<td>0.822</td>
<td>2</td>
<td>1.644</td>
</tr>
<tr>
<td>25Ohm 0.1% 250mW metal film resistor</td>
<td>RN65C25R0BB14</td>
<td>1.18</td>
<td>8</td>
<td>9.44</td>
</tr>
<tr>
<td>N-Channel Dual JFET</td>
<td>Digikey 568-2084-1-ND</td>
<td>1.06</td>
<td>2</td>
<td>2.12</td>
</tr>
<tr>
<td>N-Channel Single JFET</td>
<td>Newark 58K9646</td>
<td>0.085</td>
<td>10</td>
<td>0.85</td>
</tr>
<tr>
<td>P-Channel Single JFET</td>
<td>Newark 58K2812</td>
<td>0.169</td>
<td>10</td>
<td>1.69</td>
</tr>
</tbody>
</table>

**TOTAL** 137.185
Below is a table of some additional audio connectors purchased:

<table>
<thead>
<tr>
<th>Additional parts purchased</th>
<th>Quantity</th>
<th>Price per item</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ft. Piggyback stereo RCA cable</td>
<td>-</td>
<td>3.99</td>
<td>19.95</td>
</tr>
<tr>
<td>3.5mm Stereo plug to 2 x RCA plug</td>
<td>-</td>
<td>2.99</td>
<td>2.99</td>
</tr>
<tr>
<td>6.35mm Stereo plug to 2 x RCA plug</td>
<td>-</td>
<td>2.99</td>
<td>2.99</td>
</tr>
</tbody>
</table>

| Total Tax                                      |          |                | 3.11   |

| TOTAL                                          |          |                | 29.04  |
5.0 Recommendations

Even though this project has not been completed on schedule, from the results at hand some recommendations may nonetheless be in order.

The LM1875-based amplifier was able to drive audio transducers from computer Line Out (but not Headphone Out) properly, but did not noticeably improve sound quality. It is therefore recommended to perform further repetitions of the quantitative amplifier tests to try to find if any sound quality difference exists. For future measurements of amplifier gain a network analyser with a built-in swept-sine gain response measurement should be used.

It would also be of interest to perform quantitative measurements on “typical usage scenarios”, in order to more easily convey the merits of proper audio set-ups and amplification to the average user.

Considering that only impedance, frequency response, and noise/harmonics were investigated, it is also logical to recommend performing different measurements of sound characteristics. Some other very important characteristics affecting an amp’s sound quality are discussed in [24]: output power, distortion, phase response, channel balance, crosstalk, and square wave response/slew rate.

Given that a medium-fidelity amp did not noticeably improve sound quality, it is also recommended to recalculate the biasing conditions for the transistors in the hi-fi discrete amplifier set-up and to continue with fixing the circuits. It is should not be necessary invest much more (if any) money into the amplifier to get it into a working state.

The prototyped power supply could be easily fixed and repurposed for another project if desired. Issues may remain with the audible noise produced by the transformer if it is used without proper mounting. The necessary modifications to fix the PSU’s stability issue are illustrated in Figure 32.
Figure 32 - Proposed modifications to attempt to solve PSU instability
Appendices

A  LM1875 Op-Amp Amplifier Circuit Schematics

Taken from LM1875 specifications sheet by National Semiconductor. [25] Note: modifications to components values as listed below in Figure 33.

<table>
<thead>
<tr>
<th>Part</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>6.8 µF polypropylene</td>
</tr>
<tr>
<td>C3</td>
<td>68 nF ceramic</td>
</tr>
<tr>
<td>C7</td>
<td>470 µF electrolytic</td>
</tr>
<tr>
<td>R5</td>
<td>1.1 Ω +/- 5% resistor</td>
</tr>
<tr>
<td>R3</td>
<td>1.7 kΩ +/- 5% resistor</td>
</tr>
<tr>
<td>R4</td>
<td>10 kΩ potentiometer</td>
</tr>
<tr>
<td>Load</td>
<td>15 Ω / 300 Ω dummy load</td>
</tr>
</tbody>
</table>

Figure 33 - Modified parts for LM1875 op-amp channel
B List of Equipment

- HP 35665A Dynamic Signal Analyzer
- Dummy resistive 15 Ω 12W / 300 Ω 10W load box
- 2x Prototyped headphone amplifier channels
- Power-One +/- 15VDC Adjustable power supply
- Tektronix TDS 350 2 Channel Oscilloscope
- Computer with Audacity [26] installed (for generating test tones)
- Fluke 177 True RMS Multimeter
C List of Parts

** NOTE: PARTS LISTS ARE PER AMPLIFIER CHANNEL. **
If stereo audio is desired, two separate amplifier channels must be constructed.

*Discrete Class-A Amplifier by Kevin Gilmore [5]*

* Parts marked with an asterisk must be matched, therefore extra quantity should be ordered.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part #</th>
<th>Price ea.</th>
<th>Min. Amt.</th>
<th>Sub-Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>499 (500 replacement) Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 98K3835</td>
<td>0.402</td>
<td>2</td>
<td>0.804</td>
</tr>
<tr>
<td>511 (510 replacement) Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 97K8700</td>
<td>0.749</td>
<td>1</td>
<td>0.749</td>
</tr>
<tr>
<td>200Ohm 0.1% 250mW metal film resistor</td>
<td>Newark 03P4750</td>
<td>0.639</td>
<td>4</td>
<td>2.556</td>
</tr>
<tr>
<td>5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 68P8706</td>
<td>0.278</td>
<td>4</td>
<td>1.112</td>
</tr>
<tr>
<td>7.5kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 97K8736</td>
<td>0.659</td>
<td>2</td>
<td>1.318</td>
</tr>
<tr>
<td>3.32kOhm 0.1% 250mW metal film resistor</td>
<td>Newark 78R5179</td>
<td>0.822</td>
<td>2</td>
<td>1.644</td>
</tr>
<tr>
<td>25Ohm 0.1% 250mW metal film resistor</td>
<td>RN65C25R0BB14</td>
<td>1.18</td>
<td>8</td>
<td>9.44</td>
</tr>
<tr>
<td>1kOhm 0.1% 500mW metal film resistor</td>
<td>Newark 67P8682</td>
<td>0.356</td>
<td>2</td>
<td>0.712</td>
</tr>
<tr>
<td><strong>Transistors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC549 N-Channel Single JFET (2SK389 replacement) *</td>
<td>Newark 58K9646</td>
<td>0.085</td>
<td>2</td>
<td>0.17</td>
</tr>
<tr>
<td>BC559 P-Channel Single JFET (2SJ109 replacement) *</td>
<td>Newark 58K2812</td>
<td>0.169</td>
<td>2</td>
<td>0.338</td>
</tr>
<tr>
<td>BC549 NPN transistor 100mA (2SC1815 replacement) *</td>
<td>Newark 58K8757</td>
<td>0.061</td>
<td>6</td>
<td>0.366</td>
</tr>
<tr>
<td>BC559 PNP transistor 100mA (2SA1015 replacement) *</td>
<td>Newark 58K8762</td>
<td>0.142</td>
<td>6</td>
<td>0.852</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.6V LED Red *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PER CHANNEL TOTAL AMOUNT 20.061
### Op-Amp LM1875 Amplifier by National Semiconductor [25]

<table>
<thead>
<tr>
<th>Part</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacitors</strong></td>
<td></td>
</tr>
<tr>
<td>6.8 µF polypropylene</td>
<td>1</td>
</tr>
<tr>
<td>68 nF ceramic</td>
<td>2</td>
</tr>
<tr>
<td>470 µF electrolytic</td>
<td>2</td>
</tr>
<tr>
<td>0.22 µF ceramic</td>
<td>1</td>
</tr>
<tr>
<td><strong>Resistors</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Ω</td>
<td>1</td>
</tr>
<tr>
<td>1.7 kΩ</td>
<td>1</td>
</tr>
<tr>
<td>10 kΩ potentiometer</td>
<td>1</td>
</tr>
<tr>
<td>1 MΩ</td>
<td>1</td>
</tr>
<tr>
<td>22 kΩ</td>
<td>1</td>
</tr>
<tr>
<td><strong>Active</strong></td>
<td></td>
</tr>
<tr>
<td>LM1875 op-amp</td>
<td>1</td>
</tr>
</tbody>
</table>
C  Original and Actual Project Schedule

Figure 34 - Planned and actual (red) project schedule
Figure 35 - Planned and actual (red) project schedule
References


http://www.amazon.com/gp/search/other/ref=sr in - 2 A?rh=i%3Aelectronics-accessories%2Cn%3A172282%2Cn%3A1493964%2Cn%3A281407%2Cn%3A172532%2Cn%3A11039351%2Cn%3A13880161&bbn=13880161&pickerToList=brandtextbin&ie=UTF8&qid=1316990685


http://gilmore2.chem.northwestern.edu/projects/showfile.php?file=gilmore3 prj.htm


http://gilmore2.chem.northwestern.edu/articles/judging art.htm

    http://nwavguy.blogspot.com/2011/02/sansa-clip-measured.html


    Safety TSE.htm


    Class_A_amplifier#Class_A


