An undergraduate laboratory experiment
to build and characterize a thermionic
triode for use as an audio amplifier

Andrew James Murray¹,³,*, Peter Cunane² and
Matthew Harvey¹

¹ Photon Science Institute, Department of Physics & Astronomy, University of
Manchester, Manchester M13 9PL, United Kingdom
² Department of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom

E-mail: Andrew.Murray@Manchester.ac.uk

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Abstract
Although largely superseded by transistors for small signal amplification, the
thermionic valve (or tube) still finds use in high-fidelity audio amplifiers, in gui-
tar amplifiers and in high-power radio and television transmitters, where their
power to size scalability has advantages over solid state devices. In the under-
graduate experiments detailed here students construct a triode inside a vacuum
chamber, and investigate the effects of different designs on signal gain. The
characteristics of their triodes are measured to determine the optimal condition
for signal amplification. The triode is then used to amplify an audio signal to
determine the frequency response, and they can listen to the results via head-
phones using an input signal of their choice. This experiment hence introduces
students to vacuum technology, to electron beams and to analog electronics.

Keywords: triode, undergraduate experiment, thermionic emission, vacuum
experiment

(Some figures may appear in colour only in the online journal)
1. Introduction

One of the key transferable skills physics students need to learn in undergraduate laboratories is how to operate vacuum systems, since they play an integral role in many aspects of experimental science. Understanding the nature of electron beams in vacuum and how to manipulate them is also important in different areas, since collisions between electrons and a target (usually in the gas phase or as a solid) allow the target structure and nature to be determined. Electron beams are widely used as a source in particle physics, atomic and nuclear physics, plasma physics, laser physics and for studies of surfaces and molecules using electron microscopes and diffraction techniques. The energy of electron beams can be changed easily by adjusting the potential difference between the emitter (the cathode) and an accelerating plate (the anode), so that beams with energies from meV to GeV can be delivered. Since electrons are charged, the beams can be manipulated, focused and steered using electrostatic or magnetic field elements between cathode and anode, allowing them to be directed onto a target region where the interaction takes place.

In the experiments detailed here undergraduate students learn about vacuum systems and electron beams by building a triode amplifier inside the chamber. They then characterize their triode to determine its suitability as an audio amplifier. Students build their triode by spot-welding the internal components for the grid and cathode, and they assemble the triode using vacuum compatible materials and techniques. Once installed, they learn how to evacuate the chamber and measure the pressure. A viewport allows students to observe their triode when operating, and they adjust the parameters of different elements using external electronics. This allows them to ascertain how space charge affects the triode characteristics and its amplification. Since students build the triode themselves, they can investigate different designs and establish which delivers the maximum gain. They learn about transfer functions and load lines, and design their triode to amplify input from a signal generator to determine the frequency response. They can finally input a source of their choice (usually a mobile phone or electric guitar) and can listen to the result from their construction using headphones. This experiment normally takes students four full lab days to complete.

Over 1200 students are enrolled in the four-year honors degree program in Manchester and they are required to attend laboratory sessions in each semester throughout their degree. This requires nearly 300 individual experimental systems to be setup and maintained in the undergraduate laboratories. To reduce costs many are hence designed and constructed in the department, including the experiments detailed here. This has the advantage that they can be repaired quickly if damaged, and can be upgraded if required to suit the teaching program as it evolves.

Five triode experiments as described here now operate in the second year undergraduate laboratory in Manchester. A decision was made to use commercial vacuum components throughout, so that students are exposed to techniques used for production and measurement of high vacuum in industry and in scientific research. The cost of the vacuum components is \( \sim £3500 \) for each experiment, with the turbo-pump being the most expensive purchase. All other components were designed and built in-house, for a cost of around £800. These include the electronic control and data logging systems, and all vacuum compatible components inside the chambers. This paper details the design of these components so other institutions can build similar systems if they wish to. Results from experiments are also presented, showing the data that are obtained and how the gain of the triode can be determined.
These are the most popular experiments operating in the second year laboratory in Manchester, demonstrating their success with students. A significant factor in this popularity arises since students can input ideas into their design, and they then build and assemble their triodes from first principles. Students are almost always excited (and pleasantly surprised) that their construction from spot-welded wires can amplify music, and this positive affirmation strengthens and focuses their interest in the physics of the processes that are involved.

A number of other undergraduate experiments have been developed at different institutions to investigate thermionic emission in diodes and triodes, with examples being found in [1–5]. These all use a commercially obtained valve in the experiment, rather than asking students to build this from first principles as is carried out here. As such the experiments test and characterize the valve itself, but do not develop the skills in vacuum technology that are an essential facet of the experiments described here.

1.1. History and development of the thermionic triode

The evolution of the thermionic valve has a long history, with many milestones and discoveries in physics playing a central role. The first evidence of electrons was found by Crookes and Lenard in 1870, who built an apparatus that used a high voltage supply across two plates (the cathode and anode) inside an evacuated glass tube. They discovered that if a hole was introduced in the anode, a green glow appeared on the glass directly behind the hole. They called the rays creating this fluorescent glow ‘cathode rays’, since they were emanating from the cold cathode. Shortly after this discovery, Stoney proposed that the rays were individual particles of definite charge, later called electrons. In 1897 J J Thompson used a modified Crooke's tube immersed in a magnetic field to ascertain their charge to mass ratio, and further experiments by Millikan in 1908 determined their charge. The combined results of these studies established the mass of the electron to be \( \sim 1840 \) times smaller than hydrogen, demonstrating that the atom was not the smallest indivisible particle as had been thought. New discoveries soon followed, including the experimental work of Rutherford and co-workers who determined the structure of the atom in Manchester, and the subsequent theoretical work of Bohr, Schrödinger and Heisenberg that lead to the development of modern quantum theory.

The first person to investigate emission from a hot filament cathode was Edison in 1882. He could not explain his findings, since the electron had not yet been discovered. Edison did however note that he could allow or inhibit current flow by using a second plate (the anode) connected to either side of his filament, and so is credited as the inventor of the thermionic diode. Fleming used this effect to build a rectifier in 1896, and subsequently used a thermionic diode for detection of signals from radio waves while working for Marconi in 1904.

Fleming patented the thermionic diode in 1905 [6], and a year later Lee de Forest added a third electrode (the grid) between the heated cathode and anode, which he patented in 1908 for use in radio receivers [7]. It was subsequently discovered that his thermionic triode could act as an amplifier, since a small voltage applied to the grid would control the electrons flowing from cathode to anode. By passing the anode current though a load resistor, a larger output voltage was produced compared to that applied to the grid, and so the triode produced amplification. Langmuir developed triode technology further and could evacuate the tube far more efficiently [8]. He found that by operating the triode at high vacuum the effects of residual gas in the tube could be eliminated, leading to linear amplification and high-frequency operation. This was the birth of electronics, with the triode (and subsequent variations such as the tetrode and pentode) able to amplify very small signals so that they could be measured for the first time [8].
J J Thomson noted that electron emission from a surface was influenced by their charge, particularly if the emitted electrons remained close to the cathode. This space charge reduces the emission current due to electron–electron repulsion, so that electrons may not leave the surface or are sent back into the metal. Child [9] and Langmuir [10] independently calculated the emission from a filament under space-charge conditions using Laplace’s equation. For cylindrical symmetry (as adopted here) where the anode surrounds a thin filament, Langmuir calculated that the maximum (saturation) current emitted from a filament of surface area $A$ is given by

$$I \simeq \frac{2A}{9} \sqrt{\frac{2e V_{c-a}^{3/2}}{m_e r}}$$

(1)

where $e$ is the electron charge, $m_e$ is the electron mass, $V_{c-a}$ is the potential difference between cathode and anode, and $r$ is the radius of the anode cylinder. He further showed that the saturation current was proportional to $V_{c-a}^{3/2}$ for any shaped electrode that was used [10]. A more comprehensive description of the evolution of the thermionic valve can be found in [11].

In a triode the space charge around the filament is strongly influenced by the grid that is positioned between cathode and anode. The grid is usually constructed of a fine-wire transparent mesh that is held at a negative potential with respect to the cathode. Electrons emitted from the cathode are attracted to the anode by its positive potential, however they must first pass through the grid mesh before they can travel to the anode to produce a current. The transparency, wire size and radius of the grid hence all play a role in controlling the anode current. The electron space-charge density is highest near the cathode and the electrons have low velocity when emitted. Hence positioning the grid close to the cathode will produce the greatest change to the current that passes through it. By adopting a very fine mesh with high transparency, the field penetration of the anode potential into the cathode region is greatly reduced. Electrons emitted from the cathode hence will not appreciably accelerate until they have passed through the grid, further sensitizing the control of the grid potential on the anode current. This increased sensitivity leads to higher gain, since only a small change in grid voltage around a negative bias point will produce a large change in current. In a typical small signal triode (e.g. the 12AX7 [12]) the grid is spaced less than 1 mm from the cathode, and is constructed of a spiral of very fine tungsten wire with an inter-spiral spacing of less than 1 mm. The 12AX7 contains two triodes in a single package, each having a gain of $\sim\!100$, so that a single 12AX7 can produce gains of up to 10,000 when the triodes are connected in series.

In practical terms for an undergraduate experiment it is difficult to construct a grid from very fine wire placed close to the cathode without creating damaging short circuits, and so in these experiments the grid is constructed from 0.7 mm diameter constantan (advance) wire [13]. Students spot-weld the wires together to form the grid structure, which is held in position by legs secured into three electrical binding posts. Cylindrical formers with different diameters can be used to form the grid into a cylindrical shape, and students have the freedom to choose the structure of the grid (either hoops or a spiral) to study how this affects the gain. They are presented with an initial design (as shown in figure 1), and then must consider how they can improve on this by considering how the grid structure controls the anode current. Students also spot-weld the hairpin cathode filament wire to the support rods. The filament is constructed of 30 mm long 0.05 mm diameter tungsten wire [14] and the support rods are 1 mm diameter stainless steel welding wire spaced apart by 3 mm. The cathode is placed in the center of the triode as shown in figure 1. The anode is a 50 mm diameter 50 mm long stainless steel cylinder with a wall thickness of 1 mm. It is held in position using welding wire.
Figure 1. Diagram of the apparatus. The top left hand inset (a) shows how the triode is assembled, with the dimensions for the first grid shown to scale. This 60 mm long 30 mm diameter grid is built of five hoops spot-welded to six upstanding wires. The cathode is located centrally inside the grid and anode. The assembly is built onto a PEEK table-top that is secured to a feed-through. The lower right-hand diagram (b) shows the triode on the support table where it can be modified and assembled. The central figure (c) shows the vacuum system with the triode installed and the electrical connection made.

1.2. The experimental apparatus

Figure 1 shows a diagram of the vacuum system used here. A commercially available 4-way cross forms the main chamber [15]. This is constructed from 304-grade stainless steel and uses 4.5” conflat fittings. A viewport [16] is secured to the top of the chamber using a copper gasket seal, and a Leybold 801 s⁻¹ turbo-molecular pump is fixed to the side flange to evacuate the system [17]. The turbo-pump is backed by a 12 l s⁻¹ rotary backing-pump, connected to the turbo-pump using a flexible stainless steel hose. The turbo pump can be isolated from the backing pump using a valve, and an air-admittance valve is used when the chamber is to be opened. An Inficon BPG400 combined Pirani/ion gauge [18] is connected on the opposite side
to the pump. This gauge uses an in-built controller and LCD display, allowing students to monitor the vacuum pressure as it changes from atmosphere to high vacuum.

The triode is assembled outside the chamber as shown (b), and is built onto a PEEK tabletop that is secured to the lower 4.5″ (114 mm) flange. A 2.75″ (70 mm) electrical feed-through [19] allows voltages and currents to be sent to and from the triode. This flange is secured to the chamber using a Viton gasket so that the triode can easily be removed and reinstalled.

The vacuum system is held above the table so that the triode can be removed from the chamber. A support table is provided so that students can assemble their triode onto the PEEK table. Each experiment has a spot welder dedicated to it, so that they can build the triode close to the vacuum system. Once the triode is assembled and checked for short-circuits it is installed into the chamber and the pumping system is engaged. The backing pump takes around 5 min to evacuate the chamber to \( \sim 1.3 \text{ Pa} \left( 10^{-2} \text{ Torr} \right) \). The turbo pump is then switched on and typically reaches full speed in around 2 min. The vacuum chamber is small, and so reaches pressures of \( \sim 10^{-4} \text{ Pa} \) in around 10 min, at which time students can connect the electrical feedthrough and turn on their triode. The anode voltage is initially set to \( \sim 250 \text{ V}_{\text{DC}} \), the grid set to 0 VDC and the heating current increased slowly through the filament over a period of 5–10 min. If a new filament is used some outgassing from the tungsten wire might occur, and so the filament is heated slowly to a yellow hue while monitoring the pressure. The anode current is monitored as the filament is heated further, until a small emission current is observed. Further increasing the filament temperature to white hot leads to a rapid increase in the anode current. At this time students need to closely monitor the current and adjust the filament heater so that the emission current stabilizes, typically to around 0.5–2.5 mA. The anode current will slowly increase over a period of around an hour after emission before stabilizing, after which experiments can begin. The filament heater uses a constant current supply, so once the emission current is stable it is not changed for the duration of the experiment.

When opening the chamber all supplies must be switched off and the feed-through plug removed, the roughing pump must be isolated from the system and the turbo-pump switched off. Since the turbo-pump rotates at \( \sim 80000 \text{ revolutions per minute} \) at full speed, it is essential that it spins down before air is admitted into the system, or the pump may be destroyed. This typically takes 10–15 min after switch off, and is one of the important factors students need to learn about high vacuum systems and their operation. It is also important for the electrical connections to be switched off at high vacuum, or arcing may occur between triode elements as the pressure rises through \( \sim 0.1 \text{ Torr} \), which can damage the external power supplies. Students are taken through the correct operating procedures during the introduction to the experiment that is available on the department web pages, and these are re-emphasized by the demonstrator during the first few cycles of operation of the vacuum system.

Figure 2 shows a block diagram of the external control systems. The grid is supplied with voltage from a negative bias supply and an AC signal from an audio mixing stage can be added to this bias. The grid voltage is monitored using a 10:1 divider, so that \( -50 \text{ V} \) on the grid produces \( -5 \text{ V} \) at the monitor. The cathode is heated using a constant current supply, monitored so that a heater current of 1 A produces 1 VDC at this output. The heater current under normal conditions ranges from 500 mA to 600 mA, depending on the length of cathode that has been used. The anode supply voltage ranges from \( V_{\text{PS}}^A = 0 \text{ VDC} \) to 250 VDC. This supply can either be connected directly to the anode via switch \( S_{\text{GA}} \), or a load resistor can be connected in series with the anode. The anode current is monitored using an isolation amplifier that is at the anode potential, and has an output (referenced to ground) that produces 1 V for 1 mA of anode current. The anode voltage is monitored using a 50:1 divider. A power amplifier connects to the anode via a 100 nF bypass capacitor so that headphones can be used to listen to an audio signal. The AC output from the triode can also be monitored...
using an oscilloscope, and the voltages for the different supplies checked using standard digital voltmeters.

The divider and isolation monitoring networks are used so the grid voltage, anode voltage, anode current and filament current can be measured using digital voltmeters or via the digital control and monitoring system described below. The grid and anode potentials can also be adjusted using 12-bit digital to analog converters (DACs) and the currents and voltages measured using 10-bit analog to digital converters (ADCs). The digital interface systems are built on a dedicated board controlled by an Arduino microcontroller [20]. LabVIEW [21] is then used to control and monitor the systems via a USB connection from a PC to the Arduino. Details of the analog and digital control systems are given below.

1.3. The cathode supply

The cathode is comprised of a hairpin tungsten filament spot-welded to two co-linear stainless steel posts as shown in figure 1. The posts are closely spaced so their opposing current flow minimizes the effect of induced magnetic fields on the trajectory of electrons emitted from the cathode. A current of around 500–600 mA is required to heat the filament to ∼2200 °C where it emits electrons, and this has to remain constant throughout measurements.

Figure 3 is a schematic of the constant current supply. This uses an unregulated supply (b) sourced from a 20 VA transformer to provide ∼12 V to one side of the filament (‘+12 V cathode’). This is connected to 0 V (ground) for the triode circuitry, so that the ‘0 V cathode’ reference for this supply is around –12 V with respect to ground (see figure 2). The opposing side of the filament connects to the drain of a high current MOSFET (FQP9N90C) that is thermally connected to and electrically isolated from the chassis of the supply box that acts as a heatsink. A REF02 5 V precision reference is buffered by an OP277 operational amplifier A1, the output feeding a 68 kΩ resistor in series with a 10-turn 10 kΩ potentiometer so as to adjust the voltage on the non-inverting input of the second OP277 (A2) over a range from 0 mV to 640 mV. The heater current passing through the MOSFET from drain to source develops a voltage across the four 0.27 Ω resistors in series, and this is monitored by the negative input of A2. Amplifier A2 adjusts its output drive to the gate of the MOSFET, so that its negative input matches the voltage set by the potentiometer. The filament current is hence controlled

Figure 2. Block diagram of the experiment, showing the input voltage supplies to the grid, the filament supply, anode supply, anode current monitor and audio output stage. DC signal monitoring is via 6.35 mm jacks, whereas AC signals are monitored via BNC connectors on the front panel of the supply box.
Figure 3. The constant current power supply used to deliver heater current to the cathode. Note this supply is referenced to 0 V cathode, which is different to 0 V (ground). The current monitor hence needs to be measured using a floating digital voltmeter, and so a stereo jack is used here.

by the MOSFET and can vary from 0 mA to 593 mA. This current is independent of the filament resistance, which changes from $\sim 1 \Omega$ at room temperature to $\sim 6 \Omega$ at its operating temperature.

The inset schematic (a) ‘dual power supply’ uses an on-board 3.2 VA transformer, W08 bridge and filter capacitors to provide input to two voltage regulators (7815 and 7915). The 8.2 kΩ and 1.2 kΩ resistors at the output stabilize the regulators, and the 1 μF tantalum capacitors provide high frequency filtering. Several versions of this supply are used in different sections of the control electronics, and so are represented as a single block where appropriate.

1.4. The anode supply

The anode supply (figure 4) is required to operate from $V_{PS} = 0$ VDC to 250 VDC, and it follows a similar design to the cathode supply. A buffered REF02 provides an output at A1 that feeds a 10-turn 10 kΩ potentiometer VR1 located on the front panel of the supply box. A front panel switch selects either this output or that from an external DAC (see figure 7) for input to A2. An unregulated 380 VDC supply feeds the FQP9N90C MOSFET via three 12 kΩ resistors in series, and the drain connects to the anode circuit. This voltage is monitored by A2 through three 1MΩ resistors in series with a 56 kΩ resistor and 10 kΩ trim potentiometer VR2. The operational amplifier A2 drives the MOSFET into conduction so that the voltages at the inputs of A2 are equalized, and VR2 is adjusted so that 5 VDC at the input produces 250 VDC at the output (VR2 is set to $\sim 5.2$ kΩ). Since MOSFETs in this configuration are prone to high frequency oscillation, a 22 pF capacitor is placed across the feedback resistors to reduce gain at high frequencies. The voltage at the drain of the MOSFET is 180° out of phase with that from A2, and so feedback is to the positive input of A2. The output from the supply is monitored at the BNC and the trim potentiometer VR3 adjusted to deliver a reduction ratio of 50:1.

A dedicated dual power supply board (as in figure 3) supplies the regulated $\pm 15$ VDC for A1, A2 and the REF02. The −15 VDC supply connects to the MOSFET source via an 820 Ω
resistor, so that the output at the drain can be adjusted to 0 V\(_{\text{DC}}\). The A1, A2 and REF02 supply inputs are all bypassed by 1 \(\mu\)F tantalum capacitors directly at the component, as is the −15 V\(_{\text{DC}}\) supply for the MOSFET. The anode supply reference 0 V\(_{\text{DC}}\) is set at ground potential (see figure 2).

1.5. The grid supply

For the triode to operate correctly the grid potential must be set negative with respect to the cathode. In a triode operating in a commercial amplifier the grid bias potential is usually held near ground by a high impedance resistor from grid to 0 V. The grid is then negatively biased relative to the cathode by including an appropriate series resistor from cathode to ground, so that when current flows the cathode is set positive with respect to ground (and hence also to the grid). Since these experiments need to characterize the triode under different operating conditions a cathode resistor is not used here, and the grid bias is adjusted from 0 V\(_{\text{DC}}\) to −50 V\(_{\text{DC}}\) using an independent supply. For audio amplification the grid also needs to be driven by an AC signal either from a signal generator or from a source selected by students.

Figure 5 is a schematic of the grid drive circuit. A buffered REF02 is again used to supply a precise voltage set by VR1. A front panel switch either selects this reference voltage or that from an external DAC. An audio signal can be input via the stereo jack. A dual gang potentiometer VR2/1 and VR2/2 adjusts the stereo input signal to the grid. The potentiometers are buffered by A3/1 and A3/2, which are low-noise FET input operational amplifiers designed for audio. Their outputs are mixed together by the inverting amplifier A3/3 that has a gain of −10. This signal is fed via the 470 nF decoupling capacitor to the OPA445 amplifier A2, where it is mixed with the DC bias from A1.

The OPA445 (A2) is a high voltage amplifier that can operate with asymmetric supplies, and so a +5 V\(_{\text{DC}}\) regulated supply (a) and −53 V\(_{\text{DC}}\) unregulated supply (b) are used. The gain of this summing amplifier is −10 for both DC bias and AC inputs. The output feeding the grid hence varies from 0 V\(_{\text{DC}}\) to −50 V\(_{\text{DC}}\) when the DC input changes from 0 V\(_{\text{DC}}\) to +5 V\(_{\text{DC}}\), and the amplified AC signal is then impressed on this bias potential.

The 1N4148 and BZX79C diodes on the output protect the OPA445 should the anode short to the grid inside the chamber (usually due to the triode being poorly built). This is beneficial as the OPA445 amplifiers are quite expensive to replace. The 111 k\(\Omega\) and 1 M\(\Omega\) resistors on
the output reduce the monitor voltage range by a factor of 10, so that $-50 \text{ V}_{\text{DC}}$ at the grid is measured as $-5 \text{ V}_{\text{DC}}$.

The supplies to A1 and A3 and to the REF02 are sourced from the dual power supply (c). This is the same design as in figures 3 and 4.

1.6. The anode current monitor and audio output circuitry

Figure 6 shows the anode current monitor circuit and audio output stage that drives the headphones. The anode current is measured at the anode potential, and so an ISO124 isolation amplifier A1 is used to convert the anode current to a voltage that is then monitored at ground potential. A 1 kΩ resistor in series with the anode circuit produces a 1 V signal at the input to A1 for 1 mA of anode current. The ISO124 is a unity gain amplifier that passes signals across an isolation barrier by modulating a 500 kHz signal, and this high frequency carrier must be removed from the output using a low pass filter provided here by A2 and its network. The output monitor hence produces an output voltage of 1 VDC referenced to ground for 1 mA of anode current.

When the 100 kΩ anode resistor is switched in series with the anode (by opening the front panel switch $S_{GA}$), any variation in anode current due to an AC signal on the grid will vary the anode voltage. The AC signal at the anode is monitored by the TL081 amplifier A3, which is a low-noise audio amplifier with very high input impedance. The 100 nF 450 V capacitor decouples the AC signal from the DC potential at the anode. A3 drives an LM380 2.5 W audio power amplifier via the variable resistor VR1 to set the output at the headphones. The output from A3 can also be directly monitored at the BNC located on the front panel of the supply box.

Three ‘dual power supplies’ are required here. The ISO124 needs an isolated supply at the high voltage input side, and this is taken from a supply using a 1 VA transformer. The grounded referenced supply for the ISO124 and for A2 and A3 are fed by a dual supply board identical
to that in figure 3. The LM380 requires a higher power supply, and so a 6 VA transformer is fitted to the board for this amplifier, and the filter capacitors are increased to 10000 μF.

1.7 The digital control and monitoring system hardware

Adjustment of potentials to the triode and the monitoring of voltages and currents is normally carried out manually using the front panel potentiometers and using digital voltmeters, since this allows students to ascertain the characteristics of their triode in a methodical way. For a more detailed analysis of these characteristics a digital control and monitoring system can also be used. This is particularly useful when the gain profile of the triode is being measured for amplification of AC signals, since students can then determine the current/voltage characteristics in detail and draw an appropriate load-line.

Figure 7 is a schematic of the digital system developed here. An Arduino nano [20] is used as the on-board microprocessor, since these are inexpensive and have sufficient input and output connections to both measure the analog signals and drive the DACs. The analog input circuits are shown to the right of the Arduino in the schematic. Three inputs are used so that the grid voltage, anode voltage and anode current can be measured. The quad operational amplifiers A1 and A2 buffer the input signals and also act as unity gain inverting amplifiers. The circuit can be configured to either measure a positive input (up to +5 V), or can measure a negative input of up to −5 V (so as to measure the grid monitor output). Selection of the polarity is carried out using switches 1–4. A 1N914 diode prevents the output of each stage becoming less than −0.6 V DC if an incorrect polarity is used, thereby protecting the ADC inputs to the Arduino. The OP4277 quad amplifiers A3 are non-inverting amplifiers whose gain can be varied from unity (as shown) or they can deliver gain by setting the feedback resistors appropriately. This is not required in the present configuration, but can be useful for other applications where this interface board is used.
Figure 7. The digital control and monitoring system using an Arduino nano microcontroller [20]. This communicates with a PC running LabVIEW [21] via USB, so students can scan the supplies and monitor the triode voltages and currents.

The outputs from A3 feed four of the Arduino’s inbuilt 10-bit ADCs and so these monitors have an analog resolution of $5\,\text{V}/2^{10} \approx 5\,\text{mV}$. This equates to a resolution of $\Delta V_a = 0.25\,\text{V}$ when monitoring the anode voltage, $\Delta V_g = 50\,\text{mV}$ for the grid monitor and $\Delta I_a = 5\,\mu\text{A}$ for the anode current, all of which are adequate here.

The Arduino also sets the analog output from the DACs, which can drive the grid and anode supplies as in figures 4 and 5. These are MCP4822 12-bit dual output DACs [22] that are addressed using the SPI protocol built into the Arduino. The DACs require serial clock (SCK) and serial data (SDI) inputs and are addressed when the clock select inputs (CS5, CS6) are sent low. Each DAC has two outputs that can be set independently from 0 V to 4.095 V. The quad amplifier A7 buffers these outputs and applies a gain of 1.22, so that the final output from the board varies from 0 V to 5 V, as required for the drive circuits shown in figures 4 and 5. This board features four DAC outputs for flexibility, however for this experiment only one dual DAC is used to vary the grid and anode voltages.

A dedicated power supply is used for this interface unit that uses LM317 and LM337 variable voltage regulators to set outputs around $\pm 6\,\text{V}_\text{DC}$ for the OP4277 supplies. The supplies are adjusted so that the output from each amplifier cannot rise above $+5\,\text{V}$, which is the maximum allowed for the Arduino ADC inputs. The supply voltages are adjusted using the trim potentiometers VR1 and VR2 located on the power supply board.

1.8. The digital control and monitoring system firmware and software

The control and monitoring system shown in figure 7 uses an Arduino nano microcontroller (MCU) programmed within the Arduino development environment [23]. A LabVIEW program on a Microsoft Windows PC is used to interface with and log data from the Arduino via a USB serial connection. The firmware and software described below are available online under an open source license at [24].

The firmware running on the Arduino, written in C++, performs the following initialization steps:

- The universal asynchronous receiver/transmitter (UART) connected to the USB interface is initialized as a serial port to communicate with the PC running LabVIEW.
• Four of the MCU’s general purpose input and output (GPIO) pins are configured to act as ADCs for analog measurements.
• The SPI interface is initialized to communicate with the MCP4288 DACs.

The firmware then enters an infinite loop in which:

(1) The serial port is checked for commands from the PC. These include setting or requesting the default measurement time-step $dt$, and requesting the device identity to which the unit responds with the string ‘TR’ (triode) to differentiate it from other similar Arduino-based units connected to the PC. DAC voltages can be updated, and ADC readings requested.

(2) ADC readings are taken and added to running totals, and a ‘number of readings’ counter incremented. If the measurement time $dt$ has elapsed, average values are calculated, and a flag changed to highlight that a new reading is available. If a serial request for a new reading has been sent, the reading is transmitted to the PC and the flag reset. When DAC voltage changes are made in step 1, any current ADC readings that have been accumulated for averaging are discarded and a new measurement started. The measurement time-step is typically set to 20 ms, which at a rate of 2500 samples/s, allows on average of 50 ADC readings to be taken on each of the four channels.

(3) The loop then returns to step 1.

The Arduino’s USB connection is recognised as a simple serial peripheral device by the PC and so can be controlled by programs written in languages such as Python or LabVIEW. For this experiment, a control and monitoring program has been written in LabVIEW which features a graphical user interface (GUI), allowing for real-time plotting of ADC readings and setting of DAC values, as well as to save results as comma separated variable (‘.csv’) files.

At the start of the program, the Arduino’s serial port is located by sending an identification request to all serial peripherals so a connection can be established. A serial request is then sent to reset the DAC outputs to zero and to set a default measurement time-step. The main loop then commences, which responds to user inputs from the GUI, and which plots data from the Arduino. The program features four display tabs, of which only one can be displayed at a time. The functionality of the main program loop changes depending on which tab is being displayed as follows:

• Real-time tab: the program requests regular updates from the ADC channels and continuously plots results corresponding to the grid voltage, anode voltage and anode current. If the GUI’s DAC voltage control values are changed by the user, the program sends corresponding serial commands to the Arduino to update the grid and anode voltages.

• Anode scan tab: allows the anode current to be plotted as a function of anode voltage for a range of fixed grid voltages as in figure 8(a). Once a scan has been started, the main loop iterates through the voltages, updating the plot as the scan proceeds.

• Grid scan tab: allows the anode current to be plotted as a function of grid voltage for a range of fixed anode voltages as in figure 8(b). The loop functions in a similar way to the anode scan case.

• Calibration tab: here the calibration coefficients are set to appropriately scale DAC values and ADC readings to their corresponding physical readings. The values can be written to or read from a settings file.

Both the anode and grid scan tabs feature user controls in order to start, reset and stop scanning as well as set the voltage scan ranges and measurement time-step. Once a scan has been completed or stopped, the results can be saved to a time-stamped ‘.csv’ file.
program exits, serial commands are sent to the Arduino to request that all DAC outputs are reset to zero before the serial connection is released, and the user is returned to the operating system.

2. Results from experiments

In the initial stage of experimentation students build their first triode using a grid of diameter 30 mm which has five hoops equally spaced apart, and six vertical supports to which the hoops are welded (figure 1). The cathode is spot welded onto the support pillars and the triode is built and checked for continuity and for short circuits that may have arisen during assembly. The triode is then inserted into the chamber that is evacuated to $\sim 10^{-6}$ Torr. The cathode is heated and the process of outgassing and cathode stabilization carried out. Experiments can then begin.

To determine the triode amplification factor, two sets of measurements are conducted with the anode connected directly to the supply by closing switch SGA (figures 2 and 6). The first measurement sets the grid to a series of constant voltages $V_g$ and varies the anode voltage $V_a$ while measuring the anode current $I_a$. The second sets $V_a$ constant and varies $V_g$ while monitoring $I_a$. In each case a relatively linear region of the curves is selected and its gradient ascertained. For the first set of measurements the slope conductance $g_a$ is given by

$$g_a = \left( \frac{\partial I_a}{\partial V_a} \right)_{V_g \text{constant}}.$$

(2)

For the second set the mutual conductance $g_m$ is determined:

$$g_m = \left( \frac{\partial I_a}{\partial V_g} \right)_{V_a \text{constant}}.$$

(3)

The amplification factor $\mu$ is then given by their ratio so that

$$\mu = \left( \frac{\partial V_a}{\partial V_g} \right)_{I_a \text{constant}} = \frac{g_m}{g_a}.$$

(4)
This is the maximum gain possible from a triode. Typical values for the triodes constructed here range from \( \mu \sim 2 \) for their first triode, to \( \mu > 20 \) where the grid is positioned close to the cathode and is built using a large number of hoops or spirals.

Figure 8 shows an example of data for a triode with a grid diameter \( \sim 20 \text{ mm} \) using a similar design as in figure 1. The anode current varies in a non-linear way with voltage as can be seen, and so regions from each curve are chosen where the results are reasonably linear to estimate \( g_m \) and \( g_a \). An average is then taken to determine \( \langle \mu \rangle \).

In experiment (a) \( V_a \) was incremented by 5 V from 0 VDC to 250 VDC and the grid voltage stepped from 0 VDC to −40 VDC. In (b) the grid was changed from −45 VDC to 0 VDC in 5 V increments, and the anode adjusted from 0 VDC to 250 VDC in 50 V steps. No attempt was made to fit to the data for \( V_a = 0 \text{ VDC} \) and 50 VDC in (b) as there were insufficient data points obtained in this region.

\( \langle \mu \rangle \) is calculated when there is no anode resistor in circuit. To use the triode as an audio amplifier it is necessary to include a load resistor in series with the anode, as in figures 2 and 6. The voltage on the anode is then given by

\[ V_a = V_{\text{PS}}^A - I_A R_A \]  

(5)

where \( V_{\text{PS}}^A \) is the anode power supply potential which is held constant. When the grid voltage \( V_G \) changes (e.g. due to an audio signal on the grid), \( I_A \) will also change and so the anode voltage will then vary (equation (5)). Under these conditions it can be seen that

\[ \begin{align*}
    \left( \frac{dV_a}{dI_A} \right)_{V_{\text{PS}}^A = \text{const}} &= -R_A \\
    \left( \frac{dI_A}{dV_a} \right)_{V_{\text{PS}}^A = \text{const}} &= -\frac{1}{R_A}
\end{align*} \]

(6)

To calculate the effect of the anode resistor on the triode gain, a load line is hence drawn as in figure 9. Equation (6) shows this will be a straight line with a slope given by \( -\frac{1}{R_A} \). In figure 9 the triode characteristic curves were generated using the digital control system, allowing a more detailed data set to be produced. In this example the triode amplifier was operated with a maximum current of 2.5 mA and the anode supply was set to \( V_{\text{PS}}^A = 250 \text{ VDC} \). The load line is drawn by noting that if no current flows, the anode voltage is \( V_a \) (i.e. the right side of the load-line). If the triode is completely switched on there is (effectively) no voltage across the triode, and so the full \( V_{\text{PS}}^A = 250 \text{ VDC} \) will appear across \( R_A \). In the example where \( R_A = 100 \text{k}\Omega \) the current will then be 2.5 mA, represented by the left side of this load line. If the anode resistance is increased to \( R_A = 250 \text{k}\Omega \) the slope \( -\frac{1}{R_A} \) decreases, and so the load line terminates at 1 mA when \( V_a = 0 \text{ VDC} \) as shown.

To calculate the AC gain of the triode under these conditions a bias point is chosen where the curves are reasonably linear, and the variation of \( V_a \) as a function of \( V_g \) is determined. In this example a bias of \( V_a = -10 \text{ VDC} \) is selected. If the grid voltage then changes from −5 V to −15 V (by e.g. application of an audio signal with a peak to peak amplitude of ±5 V) then for \( R_A = 100 \text{k}\Omega \) the anode changes by ±16.7 V, and the triode has an AC gain of 3.34. For a load resistor with \( R_A = 250 \text{k}\Omega \) this increases to 4.4. Note the gain increase is not proportional to the increase in anode resistance due to variations in the characteristic curves for the different regions selected by these external components.

After students have set the operating conditions of their triode, they can use this to amplify an AC signal. By selecting an input from a signal generator the frequency response of the circuit can then be determined. Typical measurements show the frequency response is flat from \( \sim 50 \text{ Hz} \) to \( \sim 25 \text{ kHz} \) when the bias is set in the linear region (as in figure 8), and this is well
Figure 9. Triode characteristic curves generated and measured using the digital control and monitoring system. Two load lines are shown where the load (anode) resistance is 100 kΩ and 250 kΩ. The gain is calculated from the load line once a bias point has been selected.

suited for amplification of audio signals. Students can then explore the effect of biasing, and in particular can see how the output signal distorts when the grid bias is adjusted either towards $-50 \, \text{V}_\text{DC}$ (‘cold’ biasing, since the current is low), or towards $0 \, \text{V}_\text{DC}$ (‘hot’ biasing, where the anode current is high). Under both conditions a sinusoidal input on the grid produces an asymmetrically distorted sinusoidal signal on the output, which produces overtones with high even-harmonic content. This technique is exploited in some guitar amplifiers to deliberately create these overtones, and is one reason why valve amplifiers are popular with guitarists. Students can finally use their triode to listen to a signal from their own audio source connected to the output. They can then convince themselves that the triode they have built themselves from spot-welded wires and metal cylinders really does operate successfully as an audio amplifier.

3. Conclusion & summary

In this paper details of a new undergraduate experiment are presented where a triode is designed and built by students. The paper details the power supplies, control systems and vacuum design using commercial components. The experiments introduce students to vacuum techniques and pumps as used in research laboratories, so they can learn about these for the future. Students are required to physically build the triode before installation into the vacuum system, and this introduces them to spot-welding techniques and to the electronics used to control and monitor the electron beam. They determine the characteristics of their triode, optimise their design and establish the conditions required for use as an audio amplifier using load lines. They finally test their triode by inputting an audio signal into the experiment and listening to the results.

This has proven to be the most popular experiment in the second year undergraduate lab in Manchester, its popularity arising since it allows students to design and build their triode, as well as test it with a music signal. As such, it succeeds in teaching key physical principles while ensuring students engage fully with them.
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ORCID iDs

Andrew James Murray © https://orcid.org/0000-0001-9546-6644
Matthew Harvey © https://orcid.org/0000-0002-0381-5921

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