Saturday Science: Sensors

Neil A Downie
Diane Downie
Neil A Downie

- Studied Physics at Oxford
- Fundamental Particle Physics at Imperial
- One of TASSO/DESY team that discovered the gluon
- Career in industry, mainly in gases R&D – now Air Products, > 30 patents
- Need a factual base, theoretical understanding and a practical ‘feel’ to do problem solving
Diane Downie

- Studied A level Physics, Maths, Chemistry
- Medicine at Oxford, King’s College London
- Human engineering
- Physics / engineering can be good alternative for girls who can’t do medicine
- Need a factual base, theoretical understanding and a practical ‘feel’ to do problem solving
Why are we here?
Why Saturday Science?

- Most kids will...
- Need a knowledge base, theoretical understanding and a practical ‘feel’ to do problem solving for a successful career

BUT

- A lot of kids don’t get enough of this
- Especially the practical ‘feel for stuff’
  - Eg. see the Royal Academy of Engineering report ‘Thinking like an Engineer’
Saturday Science... in books / on the Internet ...and in kits

- Vacuum Bazookas
- Ink Sandwiches
- Exploding Disk Cannons
- Ultimate Saturday Science – the Latest and Greatest!

- YouTube + Facebook (Neil A Downie)

- Kits – simple quick route to get started
Why is this Engineering?

- Engineering uses theoretical understanding
- Engineering uses factual knowledge
- Engineering uses a practical ‘feel for stuff’
- Engineering is solving problems

Doing practical work feeds back to and widens your knowledge of physics – and so does engineering.

- Today’s projects are about all of these!
- The projects use inexpensive DIY sensors
- The projects mostly use the principle of feedback – see if you can see where and how
The Science and Engineering of Vacuum Bazookas

- Vacuum cleaner creates differential pressure
- $\Delta P$ acts over area of barrel to give force
- The Tee piece lets the projectile out
  - Doesn’t it get sucked down the side arm?
    - Nope – its Newton’s First Law
- Muzzle paper – doesn’t that get in the way?
The Science and Engineering of Vacuum Bazookas

- Measure speed
- Projectile shape, density, length
- Projectile spin
- Can you make a rapid fire version?
  - Royal Institution Rapid Fire Vacuum Bazooka
- Can you make it faster?
- Can you fire a shot further?
  - More $\Delta P$
  - angle of launch
  - longer tube
  - Seagull assist
Vacuum Bazookas – SUBTLE EFFECTS

- Friction
- Length of side tube
- Pause before launch
- Size of tube
- Compression of air in front
- Projectile fit
- Muzzle paper
The Vacuum Bazooka Equation

\[ V = k \sqrt{\frac{2L\Delta P}{z\rho}} \]

- \( k \) is constant, \( L \) length of barrel, \( \Delta P \) is differential pressure, \( z \) and \( \rho \) length and density of projectile.
SAND Flow

- Using electrons to measure quantities of particulates
- How much use could it be?
  - Warning system for risk/safety?
  - Measurement system for quantitative
- Lots to ‘fettle’, lots to find out about
- Simple but Subtle
Laser Pumpkins

- Feedback – an important principle – in science, in biology, in industry
- Cheap fun project
- Uses eye-safe laser
New sorts of Rotameter

- Flow measurement is an area of...
  - Enormous importance
  - Enormous ingenuity
- How does the standard rotameter actually work?
- How can you improve it?
- Uses gravity but is smaller than a LIGO
- The Digital Rotameter
- The Curved Tube Rotameter
Acoustic Molecule Meters

- Measure the speed of sound in a gas
- Speed of sound depends upon molecular mass of gas
- Used very rarely – one Cambridge company has an acoustic sensor
- Ultrasimple electronics
- But needs ‘tuning’ to get a Molecular Mass readout
- Try your mobile phone spectrum analyzer on it
- Would be suitable project for BBC Microbit or Crumble credit-card computers*

(*already tried on Raspberry Pi)
Quartz Molecule Meters

- A classic harmonic oscillator
- Uses quartz tuning fork – from your watch
- Measures density of gas and hence Molecular Mass
- Can be controlled / calibrated by credit-card computer
- BBC Microbit, Crumble, Raspberry Pi all work
- Make it yourself – simple electronics
- Patented, so you can read all about it
And Finally...

- HUNDREDS MORE PROJECTS in...
  - The Ultimate Book of Saturday Science
    - Has a chapter on molecular weight meters
  - Vacuum Bazookas, Electric Rainbow Jelly
  - Ink Sandwiches, Electric Worms
  - Exploding Disk Cannons, Slimemobiles

- Also on YouTube, and on
  - www.eruditiondigital.co.uk
  - www.saturday-science.com
  - downniena@airproducts.com

← you didn’t see these @ New Year: Oxygen Fireworks
RMM is what used to be called ‘molecular weight’
Basically, it’s the number of protons and neutrons in the atoms of a molecule
The chemists’ “mole” contains an Avogadro’s Number of molecules
Avogadro’s Number = $6.023 \times 10^{23}$
Molecular Mass used to be
  • Difficult to imagine
  • even more difficult to measure...

Not Any More!
Relative molecular masses

- H$_2$ 2
- He 4
- CH$_4$ 16
- H$_2$O 18
- C$_2$H$_2$ acetylene (hot flame) 26
- N$_2$ 28
- O$_2$ 32
- Ar (arc welding) 40
- Propylene C$_3$H$_6$ (hot flame) 42
Relative Molecular Masses – the heavies

- $\text{C}_3\text{H}_8$ propane (LPG) 44
- $\text{CO}_2$ 44
- Butane $\text{C}_4\text{H}_{10}$ (BBQs, lighter fuel) 58
- Sulfur dioxide $\text{SO}_2$ (steriliser) 64
- Isopentane $\text{C}_5\text{H}_{12}$ (shaving foam) 72
- Refrigerant 134a $\text{CF}_3\text{-CFH}_2$ 102
- SF6 (HV switchgear) 146
How fast does sound go?

- Sound travels in air at 340 meter per second.
- That’s 680 miles per hour.
- That’s what we mean by ‘sonic’.
- Last year we tried out a new way to see sound waves moving.
- You can ‘see’ a sound wave going along a row of microphones, if each has an LED connected to it.

Figure 1. Side viewpoint geometry.
See a Sound Wave going through the air

- It's now published in a scientific journal, *Physics Education*
- It's also on YouTube
- Thanks to Overton Scouts!
The speed of sound in a gas...

- It goes down with increase of Mw: \( c \propto \frac{1}{\sqrt{M_w}} \)
- It goes down as number of atoms in a molecule goes up:
  - Monatomic \( \sqrt{(C_p/C_v)} \) factor = 1.29
  - Diatomic \( \sqrt{(C_p/C_v)} \) factor = 1.18 (-8%)
  - Polyatomic \( \sqrt{(C_p/C_v)} \) factor = 1.15 (-11%)
- It goes up with the absolute temperature: \( c \propto \sqrt{T} \)

Or, putting it all together:

- \( c = \sqrt{(C_p/C_v) \cdot (R \cdot T / M_w)} \)

where R is the Gas Constant 8.31 J/K
Measuring the Speed of Sound in a small space...

- Ultrasonic pulses can be used
- Ultrasound $\rightarrow$ high frequency $\rightarrow$ small wavelength
- Small wavelength allows small apparatus
- We used 300kHz for measuring Xenon gas in medical air mixtures
- The technique is today being used in various places, including the ‘Toby Xenon’ neuroprotection trial
- I filed a patent, US7434580
- The patent explains how you have to absorb the CO2 first – otherwise it absorbs the ultrasound
Xe kit on test, Hammersmith Hosp
Music of the Molecules

- A pipe will oscillate at a frequency determined by the speed of sound of the gas inside the pipe.
- Frequency ~ speed of sound/length of pipe.
Oscillators from amplifiers

- Take a microphone
- Connect it up to a PA amplifier
- Connect that to a loudspeaker
- Put microphone next to loudspeaker

SQUAAAAAAAAAAAAWWWK!

- The slightest signal, the tiniest bit of noise, is amplified
- This comes out of the speaker
- This goes in the microphone
- It gets amplified again and comes out of the speaker
- It goes in the microphone again even bigger....
- And so on... It’s a recursive process
The Acoustic Molecule Meter

- 15cm pipe, 4.5cm diameter
- Microphone near speaker at one end
- Simple amplifier – 5 parts, none >£0.03
- Oscillates near to 1KHz in air

Results...

<table>
<thead>
<tr>
<th>Molecule</th>
<th>MWt</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>4</td>
<td>3330</td>
</tr>
<tr>
<td>Methane</td>
<td>18</td>
<td>1494</td>
</tr>
<tr>
<td>N2</td>
<td>28</td>
<td>1285</td>
</tr>
<tr>
<td>Air</td>
<td>29</td>
<td>1260</td>
</tr>
<tr>
<td>Ar</td>
<td>40</td>
<td>1160</td>
</tr>
<tr>
<td>CO2</td>
<td>44</td>
<td>1003</td>
</tr>
</tbody>
</table>
Acoustic Molecule Meter Circuit

- Electret-FET microphone, AC coupled to...
- Darlington Pair amplifier with 64 Ohm speaker as load
- DC bias via base to collector resistor – very simple

Problems/pitfalls
- Need to make sure that system stay on one harmonic, unlike the Vacuum Trumpet
- Check out the harmonics by using a spectrum analyzer. You can download one for your phone eg. FrequenSee.
MW meters – what more can you do?

- Hydrocarbons eg. small plumbing burners, lighter fuel
  - Methyl acetylene / propylene / propane / butane / isobutane
- Natural gas often ‘doped’ with 10% or so N2 to adjust Wobbe No. so burners run well – so it’s close to, but more than 16
- Aerosol propellant
  - Canned air blast cleaner & other ‘canned pressurized air’ products = just propellant
- Refrigerants
  - Eg. Freon 134a for air conditioning
- Gases prepared by chemistry (may need drier / condenser to take out H2O vapour)
  - CO2 from acid/carbonate
  - SO2 from sodium hydrogen sulfite
  - O2 from peroxide/catalyst
  - Corrosives might be OK if dry
MW meters – what more can you do?

- Compensate for pressure and temperature using Ideal Gas Law $PV = nRT$
  You get much more accurate molecular weights at higher pressures (but you need a good pressure sensor)
- Squeeze a quartz sensor inside tip of syringe, test “Boyles density law” $\rho = \text{const.} / \text{Volume}$
- And lots of other things – eg. see my patents for Air Products Plc on www.espacenet.org
The Acoustic Molecule Meter Challenge

1). Calibrate your meter

Measure the output of your AMM on air

The Mw will be about 29. What frequency are you seeing? Record it. Now pull out a gas sample tube, or block it. Check the output with your spectrum analyzer and see if you can figure out what is happening.

Measure the output of your AMM on CO2

The Mw will be about 44. What frequency are you seeing? Record it. Check the output with your spectrum analyzer.

Measure the output of your AMM on Ar

The Mw will be about 40. What frequency are you seeing? Record it. Check the output with your spectrum analyzer.

2). Work out the relations between the frequencies you see and the Molecular masses.

What do you think you will see with Helium? What frequency will you measure?

3). Now measure the output of your AMM on Helium.

What frequency did you get? Check the output with your spectrum analyzer and see if you can figure out what is happening.
The Molecule Meter –
I speak your molecular weight!

(A fuller explanation is contained in The Ultimate Book of Saturday Science by Neil A Downie from Princeton Press.)

‘Everything is composed of small particles of itself and they are flying around… never standing still or resting but spinning away and darting hither and thither and back again, all the time on the go. These diminutive gentlemen are called atoms. Do you follow me intelligently?’

‘Yes.’

‘They are as lively as twenty leprechauns doing a jig on the top of a tombstone.’

‘Now take a sheep,’ the Sergeant said. ‘What is a sheep only millions of little bits of sheepness whirling around and doing intricate convolutions inside the sheep? What else is it but that?’

‘That would be bound to make the beast dizzy,’ I observed, ‘especially if the whirling was going on inside the head as well.’

by “Flann O’ Brien” (Brian O’ Nolan), The Third Policeman (1967)

Here we measure molecular weight (or Relative Molecular Mass, to be strictly correct) with the aid of an item that you may well be wearing on your wrist as you read – a quartz crystal. The crystal is inside almost every wristwatch or clock today. It is a piece of pure quartz, a form of silicon dioxide, typically cut into the shape of a tiny tuning fork, just 4 or 5mm long, with tiny electrodes plated onto it.

The quartz is piezoelectric, so it can easily be made into an electric tuning fork. It makes a remarkably good tuning fork, in fact: when pinged, it will resonate for many thousands of oscillations. Put the quartz in an electronic feedback circuit and you have an oscillator, an almost perfect. Its accurate to better than a few parts per million – it is probably the most accurate thing you will ever have in your hands.

But how, you are wondering, can a tuning fork measure molecular weight? Well, it happens that the quartz, as it vibrates to and fro, will vibrate at a slightly different frequency when its sitting in a gas, versus its frequency in its normal vacuum environment.

As it vibrates in a gas, it takes some of the molecules of the gas in which it sits to and fro. And it turns out that the vibration frequency of the quartz will be changed by an amount almost precisely proportional to the density of the gas. So measure the change in frequency of the quartz, and you measure the density of the gas.

But how, you are wondering, can a density sensor, however convenient and accurate, measure molecular weight? Well, it happens because of the Kinetic Theory of gases, which says that the number of molecules in 22.4 liters of gas at standard temperature and pressure is always 6.023 x 10^{23}. If those molecules are heavy ones, then the mass of those 22.4 liters of
gas will be heavier than if they are light molecules. So in effect the density of a gas is proportional to its molecular weight. So measure the change in frequency of the quartz, and you measure the molecular weight of the gas.

**What you see in front of you**

1. A quartz crystal, connected to a very simple 3 transistor amplifier to make a feedback circuit. A quartz crystal with a tiny hole in it, connected to a very simple 3 transistor amplifier to make a feedback circuit. In most of the circuits, the holey crystal is inside a tee-piece so you can flow different gases past it easily.

Check out the frequencies of the quartz oscillators. They should be a little below 32,768 Hz, with the holey quartz in air around 7Hz to 10Hz lower than the vacuum crystal.

2. A XOR gate with an audio frequency filter circuit – a XOR gate is usually the most efficient way to get a difference or ‘beat’ frequency with the nicest waveform.

This takes the two oscillators and gives the difference frequency.

3. A frequency meter
   a. A multimeter set to ‘frequency’, should measure 7-10 Hz, if all is well.
   b. A commercial (designed by one of my students) circuit board with a small microprocessor which measures and multiplies by a factor so that it measures around 30 on air.
   c. A credit-card size computer – a BBC MicroBit or a Crumble, which can measure the frequency using the program printed out on the desk. You can re-program them if you want to by plugging in the micro USB lead and writing some new software using the simple ‘Scratch’ type block editor.

The quartz tuning fork is a Simple Harmonic Oscillator, whose frequency is given by the springiness k divided by the square root of the mass m, or \( f \propto \sqrt{\frac{k}{m}} \). But for a small shift in mass, the shift in frequency is proportional to the molecular mass, or \( \Delta f \propto \Delta m \), and in our case, that small shift in mass is proportional to density.

Now the answers you get will vary with temperature and pressure. You can correct the density you measure to standard temperature and pressure by using the Ideal Gas Equation:

\[ P \ V = n \ R \ T \]

where P is the pressure, V volume, n the number of moles, R the gas constant and T the absolute temperature. Density is mass /volume, and 1/V in the Gas Equation is given by nRT/P. Mass is given by nMWt, and you can figure it out now.
Testing temperature effects

So for example, if you normally measure at temperature Ta and in fact the temperature is Tb, then you must multiply the measured $\Delta f$ by Tb/Ta. If Ta is 273 K (freezing point of water) and Tb is 295K (room temperature), then the measured density will be too low by a factor of Tb/Ta (1.08), so you must multiply by 1.08 to fix it. You can check this out by putting the plastic heat pack (warm it up in very hot water at the end of the bench). This is equivalent to checking out Charles’ Law ($V/T = \text{constant}$).

Testing on pressure

Pressure works the other way: if the pressure Pb is higher in your measurement than your standard Pa, then you must multiply by Pa/Pb, reducing it, to correct it to standard. You can check this out by blocking the Tee piece on one side and plugging a syringe into the other side. As you pull a vacuum with the syringe the frequency will go down, as you pressurize the tee-piece with the syringe, you should see it go up. Check out if this tracks Boyle’s Law.

Testing on different gases

We have here today:

<table>
<thead>
<tr>
<th>Gas</th>
<th>MWt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>4</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>17 (it should be 16, but usually has a little N2)</td>
</tr>
<tr>
<td>Air</td>
<td>29 (that’s N2 @ 28 and O2 @ 32)</td>
</tr>
<tr>
<td>Argon</td>
<td>40</td>
</tr>
<tr>
<td>CO2</td>
<td>44</td>
</tr>
<tr>
<td>Tetrafluoroethane</td>
<td>MWt 102  (it’s the ‘Air Duster’ – its also used in refrigeration)</td>
</tr>
</tbody>
</table>

**Don’t breathe on it:** The quartz Molecule Meter will work on almost any dry gas but don’t blow into it! The huge (up to 10%) amount of moisture in your breath takes ages to come out and messes up things. And you won’t see much change in MWt, because air that you have breathed has less oxygen, but more CO2 and moisture, and so hardly changes at all in MWt.
The Q Molecular Mass Meter Challenge

The Mw meters we have here differ from the ones in the Ultimate Book of Saturday Science only by using two oscillators, one in vacuum, the other in gas, and using the difference frequency (obtained via a XOR gate) as the output. This means that you don’t need to measure the 32kHz crystal output with very high precision, using a fancy frequency meter. A very ordinary multimeter with frequency output can be used. Some of the meters just give the raw difference frequency (its about 6-10 Hz on air), whilst others have already been programmed with an approximate factor to scale that output up to about 30 (should be 29 for air).

The challenges:

1). Use the Molecular Mass (or Weight) meter to measure
   - Air (29)
   - CO2 (44)
   - Ar (40)
   - He (4)

Use your results to work out the slope (m) and zero (c) constants in the usual \( y = mx + c \) form. (graph paper does it just as well as Excel).

2). Now find out what effect changing pressure has on the measured MW, by connecting up a syringe and using the Ideal Gas Law:

\[
P V = n R T \quad \text{where } P \text{ is pressure, } V \text{ volume, } n \text{ no. of moles, } R \text{ gas constant, } T \text{ temp in K.}
\]

How can you correct the MW meter output for pressure?

3). Now explain the effects of temperature on the MW meter.

Using air, take a baseline reading, then put the MW meter in the Hot Pack and see what happens to the readout. Use the thermocouple to check the temperature.

Again, use the Ideal Gas Law to suggest how you might correct the Q MW meter for temperature.

You may find it useful to remember that \( \rho \) (density) = \( n \) MW / V where MW is the molecular weight. But \( V = nRT/P \), so \( \rho = P \) MW /RT.

4). There are brand new Crumble and BBC MicroBit credit card computers set up to read Mw. Have a play with them, see what you can do...
The Rotameter Principle: the variable orifice flow meter

A simple flow meter based on a clear vertical tube with a little indicator ball in it has been used for many years as a simple visual indicator of approximate gas and liquid flow rate. More flow, and the ball goes up, less flow, and it goes down. Why is it called a rotameter? Because in designs—especially those used in vital functions like anaesthesia, for example—the ball is replaced by a conical float equipped with small spiral-going grooves. The conical float can be seen to rotate slowly in the flow, assuring the user that the float hasn’t got stuck, and that there really is some gas flow.
There is another subtlety which may not be apparent to the casual user of a rotameter – and which is certainly not optional. The tube is just slightly conical. As Byron might have said, it is strange but true. This is the secret of the rotameter’s working. A simple tube would not work. With a low flow, the ball would sit immovably at the bottom of the tube. With a higher flow, the ball would lift, then accelerate, and slam into the top, where it would sit. The applied gas or liquid flow produces a net pressure (P on the bottom, less P on the top) $\Delta P$ on the ball which, when multiplied by the area $A$ of the ball, gives a force. When that force exceeds the weight $mg$, the ball moves off.

You can’t measure flow with a tube and a ball. However, with the conical tube, you can. As flow increases from a minimal level, the ball moves up, but once it has, it opens up an annular gap around it which increases as it moves up, until the gap that has opened up is so big that lots of gas or liquid can divert around the ball, which reduces the pressure on the underneath (and increases the pressure on the top) of the ball, until

\[
\Delta P \cdot A = mg
\]

where $\Delta P$ is $(P_n - P_o)$, pressure below and above the ball, $A$ area ($\pi R_o^2$), $m$ mass and $g$ gravity.

But, you might say, surely this means that a rotameter produces a big pressure drop when you measure flow with it? It does produce a $\Delta P$, its true, but it’s not much. For a typical rotameter with a 4mm glass ball of mass, say, 100mg, diameter 4mm, $\Delta P$ is only 1mbar.

With an orifice in a pressurized gas pipe, the volume flow $Q$ is given approximately by a very simple formula, if the pressure ratio $(P_n / P_o)$, upstream and downstream pressures, are $>\sim 2$:

\[
Q \sim k' c A_o
\]

where $k'$ is a constant, $c$ is the speed of sound, and $A_o$ is the area of the orifice. This applies roughly even if the orifice is an annulus. Its slightly more complicated at lower differential pressures:

\[
Q \sim k A_o \sqrt{(P_n \Delta P)}
\]

If a rotameter has a bore which is give by $R = R_o + b x$, follow through the algebra and you get

\[
Q \sim 2\pi k R_o b x \sqrt{(P_n \cdot mg / \pi R_o^3)}
\]

(with assumptions that $b x << R_o$ and $\Delta P >> P_o$.)

So $Q \propto b$ for many purposes.
Rotameters with constant diameter tubes

Although rotameters are good and useful, they are only available as a result of some fairly difficult fabrication: it isn’t that easy to make precisely slightly conical tubes of the type needed: certainly for a one-offs, and even in mass production. So mass-produced rotameters are surprisingly expensive, and special one-offs are pricey too and slow to make. But there are two ways of making a constant-diameter tube rotameter: the digital rotameter, and the curly or sector rotameter.

Digital rotameter theory

In the case of the digital rotameter, the ‘orifice’ is an annulus or width w around the ball, which is a constant, augmented by a set of parallel orifices – the additional holes. Approximately, we can consider that the orifice area Ao is given by:

\[ Ao = \pi \left( (R_o + w)^2 + N \pi R_h^2 \right) \]

where \( R_h \) is the hole radius and \( N \) is the number of holes underneath the indicator ball.

So

\[ Q \sim k \pi \left( (R_o + w)^2 + N \pi R_h^2 \right) \sqrt{P_o \sin \theta / \pi R_o^2} \]

Curly rotameter theory

In the case of the sector rotameter, again, the area of the tube cross section is \( \pi (R_o + w)^2 \), but the force varies.

The effective weight of the ball is given by:

\[ W_{eff} = mg \sin \theta \]

Where \( \theta \) is the angle to the horizontal. Now the ball is supported by pressure on its cross-section area:

\[ \Delta P \cdot \pi R_o^2 = mg \sin \theta \]

where \( R_o \) is the ball diameter.

Now once again, we can use \( Q \sim k A_o \sqrt{P_o \Delta P} \)

\[ Q \sim k \left( \pi (R_o + w)^2 - \pi R_o^2 \right) \sqrt{P_o \cdot mg \sin \theta / \pi R_o^2} \] or \( Q \sim k 2 \pi k R_o w \sqrt{P_o \cdot mg \sin \theta / \pi R_o^2} \)

\[ Q \sim 2k w \sqrt{P_o \cdot mg \sin \theta} \]

which clearly shows how the flow varies with the sine of the indicator ball angle.
Digital Rotameters

The digital rotameter works by deploying holes in a constant diameter tube. The pressure below the ball is higher than the pressure above, exactly according to the equation $\Delta P = m g$ we saw above. The drilled holes bleed off more and more gas as more of them are exposed to the higher pressure gas below the ball.

![Diagram of digital rotameter](image)

The sections of tube in between the holes are basically ‘no-go’ areas for the ball. The ball will tend to drift upwards or downwards unless the flow happens to be exactly correct, and will tend to then stick just either at the point at the top of the section where it is letting more gas out via the top hole, or just at the point at the bottom of the section where it is letting less gas out via the bottom hole.

Try ramping the flow very slowly up, and then very slowly down, seeing what happens to the ball. Is there ‘hysteresis’. I.e. does the ball always sit at a particular hole for a particular flow, or the flow where it sticks to a hole dependent upon whether you are ramping up or ramping down the flow?

It’s doesn’t much matter how the holes are placed along the tube, so long as they are not too close together. So you could space the holes out how you like. How could this be useful? And what about having two indicator balls? What would happen to them? If they were the same? If they were different mass / density / diameter?

And finally... more rotameter tricks

What about a sloping rotameter? As we explore below with the sector rotameter, you can dilute gravity by sloping the tube, relying on the weight of the ball being partly supported by the tube as it rolls up and down. What about having two indicator balls? And what happens if your rotameter is square in cross section instead of circular?
Curly rotameters

The curly or sector rotameter works with a constant diameter tube by applying, in effect, a force of gravity which varies along the length of the tube, instead of a tube diameter which varies.

The force of gravity is ‘diluted’ on the sloping sections of the tube, and the full weight of the ball, which is $mg$, is only deployed against gas flow in the final vertical section of the tube. The ball rolls up and down, its weight more (at the bottom) supported by the tube, and (at the top) more supported by the gas flow. The effective weight of the ball is given by $W_{\text{eff}} = mg \sin \theta$, provided it rolls smoothly and with zero friction, and the flow $Q$ indicated varies with $\sin \theta$.

You may have noticed that the ball is not perfectly round (although the black ball is pretty much perfect). What effects does this have?

And what about the effects of non-uniformity in the tube?
And finally... other curly rotameters

You don’t need to use an arc of a circle for the form of the tube.

What about a tube formed so that the length the ball is hovering at is proportional to the flow. What shape would the tube have to be to do that?

Or what about a tube where the height above the (horizontal) start is the measurement and is approximately linear?

Finally, it might actually be useful to have a rotameter with a greater-than-normal dynamic range, in which case, a nonlinear law like a square law response might be preferred, so that flow will vary as measurand\(^2\). What shape would that tube have to be?
The Laser Pumpkin

Don’t panic: there are a lot of instructions as we have broken them down into small steps rather than giant leaps.

You will also need a PP3 battery (doesn’t have to be rechargeable), a suitable pumpkin, and an eye safe laser – for example a laser pointer or a cat toy laser. Never, ever shine even an eye safe laser in an eye. A burn on the back of the eye results in permanent blindness.

You are going to wire together the parts using the connector block in series. This means the electrons flow through one component after another, like a train on a circular track. It is really important that the electrons flow in the right direction as the LEDs and the light dependent resistor only work when the electrons go the right way. To make this easier, Neil has put the wires on the parts so that a red wire must always be joined to a black wire.

If you look on Neil’s Facebook (Neil A Downie) page there are photos of the steps. You can also see the photos on Dropbox – email to profneiladownie@gmail.com for the link.

How to make your laser pumpkin.

1. Connect the battery snap to the connector block using the red wire. First slightly unscrew the screw then twist the bare wire at the end of the red wire and push it into the first hole on the block. You twist the wire so that is easier to thread into the hole but also so that the fine wires don’t get damaged by the screw and to improve the flow of electrons between the wires. Screw the screw down well so that a firm pull doesn’t pull the wire out. It is important that these wires have metal contact so electrons can flow, and firmly in place physically so they don’t fall out.

2. Take the black wire from the battery snap and the red wire from the switch and twist the bare wires together.

3. Push the twisted together wires into the next hole in the connector block, and screw in well.

4. There are three parts with LEDs. Look carefully and you will see that 2 are just LEDs. The third one is an LED with a small disc facing the lens of the LED. Put this one to one side.

5. Take one of the only LED parts and twist the red wire onto the black wire of the switch. Screw it into the next hole in the connector block.

6. Take the other one of the only LED parts and twist the red wire onto the black wire of the previous LED. Screw it into the next hole in the connector block.

7. Take the LED with the disc, and twist the red wire to the black wire of the LED you have just connected. Screw it into the next hole in the connector block.

The disc is the light dependent resistor. When light falls on it, it stops resisting the flow of the electrons, which allows the electrons to go around the circuit and light up the LEDs. When there is no light it stops the electrons.

8. You now need to complete the circuit. Push the twisted bare wires from the black wire on the LED/light dependent resistor into the connector block hole opposite the single red wire from the battery snap. Screw it in. There is a metal running through the block to complete the circuit. Well done! You now have an electric circuit.
9. Now you need to test it to make sure that all your connections are working. Just touch the terminals of your battery to the battery snap. The LEDs should come on. If they don’t check all your connections and try again.

10. Now check that your LED/ light dependent resistor is working. Connect the battery properly to the battery snap. All the lights should come on.

11. Hold down the switch for a moment – all the lights will go off. The switch breaks the circuit so the electrons can’t flow, but as soon as you let it go, this sort of switch allows the electrons to flow again.

12. Now hold the LED/ light dependent resistor in the palm of your hand and make a light tight fist around it. Not too hard – these are delicate electronics. The flow of electrons is too small to hurt you at all. All the LEDs will still be on.

13. With your other hand, press the switch, and release it. The LEDs go off. Very slowly start to open your fist one finger at a time. The other LEDs will come back on.

What has happened?

When you opened your fist eventually enough photons (particles of light) reached the light dependent resistor so it to allow current to flow again, so the other LEDs can come on.

14. Put the LED/ light dependent resistor in your closed fist again with all the lights on, and use the switch to switch the lights off. Open your fingers slowly again until the other LEDs come on. This time close your fist again. The other LEDs stay on.

Why do the LEDs stay on even though your fist is closed and no photons can get to them from the light in the room?

The LED in your fist is shining right onto the light dependent resistor, so it allows the electrons to flow. This is an example of positive feedback, a very important feature of electronic circuits.

It is important to understand this: to use your laser pumpkin you have to hide the LED/ light dependent resistor from photons in the room until you are ready to set it going using your laser gun.

To protect the LED/ light dependent resistor from stray photons you are going to put it in the end of the black tube, which then becomes the pumpkin’s nose.

15. Take the battery off the snap –this stops the circuit flowing and saves your battery.

16. Cut two 5cm lengths of the black tape and close off one end of the black tube by sticking them over the end of the tube, at right angles to each other. You are making a light proof cover for the end of the nose inside the head of the pumpkin.

17. Make a hole with the small screwdriver in the middle of the tape that is big enough for the LED/ light dependent resistor to be passed through without using force. You can enlarge the hole by making a slit with a pair of scissors.

18. Push the LED/ light dependent resistor in until most of the black tape on the wires is inside the tube. The LED/ light dependent resistor needs to sit deep inside the nose so that stray photons can’t set it off.

19. Keep the LED/ light dependent resistor in place by wrapping a sandwich bag tie around the wire and then wrap a 6 cm piece of black tape around the tails of the tie to hold them to the side of the nose tube.

20. Testing time! Connect the battery. Your other LEDs should stay off. If they come on, too much light (too many photons) are sneaking down the nose to the LED/ light dependent resistor. Fix it!

20. Shine your laser right down the nose. The other LEDs (which are going to be the eyes) should come on. You can switch them off with the switch and they should then stay off. See how far away you can get with your laser trigger.

You can now fit your electronics into your pumpkin. The switch needs to be on the outside, and the LED/ light dependent resistor deep inside the nose. The 2 other LEDs are for the eyes. The battery and connector block can be hidden in the head.
To set up your laser pumpkin, connect the battery and check it is working by shining the laser down the nose at very short range. Then use the switch to put the laser pumpkin into standby. Then you can switch it on by remote control using the laser. Remember not to shine the laser into anyone's eyes or face.

Have fun!
Laser Pumpkins and the science of Photoresistor Electronics

Fundamental electronics

Electronics uses the flow of electrons. The transistor in its various forms (bipolar, FET etc), which amplifies an input flow of electrons, is really the fundamental device. Transistors can then be used as the basis of a NOR or NAND gate, which itself can be considered to be the fundamental device of all computers. (NOR = [NOT.AND], and NAND = [NOT.OR]). NOR or NAND gates can be turned into memory ‘latches’ and into arithmetic processor units and ultimately into a computer.

But why electronics? The early pioneers like Charles Babbage and Ada Lovelace thought mechanical amplification and logic was the answer. And more recently, attempts have been made to make at photonic computers, with optical amplifiers and logic. But there are other ways...

Photonic-electronics

The combination of a photoresistor connected to an LED is a part electronic, part photonic device. With electrons for power, it can turn an input photon flow via an electron flow into an amplified output photon flow. When a laser shines on the photoresistor, the photoresistor conducts electrons, which light up the LED.

Feedback and creating a memory ‘latch’

Now if you take an amplifier and connect the output to the input, you have created a feedback loop. In the case of positive ‘DC’ feedback, you end up with a ‘latch’ or memory circuit. Now

1. when you shine a laser on the photoresistor (the light goes through the LED clear casing) and...
2. photoresistor electrons will flow and...
3. photons come out of the LED, and...
4. LED photon output redirected onto the photoresistor, and... go to 2

So the circuit stays switched on with electrons and photons flowing: it’s a memory. You can reset it simply by momentarily interrupting the flow of electrons.

Now the electron flow in the photoresistor-LED combination can also be allowed to flow through other devices – like more LEDs. We make use of this possibility in the Laser Pumpkin. Another two LEDs wired in series light up at the same time as the P-LED combo, and can be used as the eyes of the pumpkin lamp.

What else can you do with photoresistor electronics?

Why would photoresistor electronics be a good idea?

What could you use it for? How could you connect photoresistor electronic circuits together?

Could you make a memory circuit that can be switched on by a laser pulse and then switched off by another laser pulse? Draw the circuit diagram.

Could you make a NAND gate or a NOR gate? Draw the circuit diagram.

How could you make photoresistor electronics better: cheaper, faster, lower power?

Could you integrate photoresistor electronics onto slices of semiconductor like silicon electronics?

Could you make anything with photoresistor electronics?

Maybe. I’m not sure about this, but...
...Anything! You can amplify, make memory circuits as we have seen, but also logic circuits like NOR and NAND, arithmetic processing circuits, in fact anything including a complete computer.