5.4

Recognising a scientific report

Briefing sheet

Title of the article you are studying

____

1 You have a copy of a scientific article. In the table are questions likely to be answered in the article. Fill in the table by referring to different parts of the article.

Questions the reader may raise	Where the answers can be found
A What is the main subject? Who are the researchers?	
B Why is the study interesting and important? What questions does it address?	
C What is already known about the subject?	
D What methods and materials were used in the study?	
E What were the results?	
F What can be learnt from the results? Do the results answer the questions posed? Do the results confirm the researchers' assumptions or hypotheses?	
G What, if anything, unexpected happened? How can the results be explained? How has the study contributed to understanding the subject? Is there potential for future research in this area?	
H What were the sources of information on which the researchers relied?	

2 Discuss the table with the rest of the class.
What are the advantages of having a 'standard' format for a scientific article?
What are the different ways that scientists can publish reports of their studies?

5.4 Recognising a scientific report

Resource 1

The “shell effect”: Music from environmental noise

P. Diodati

Dipartimento di Fisica, Università di Perugia.

Istituto Nazionale per la Fisica della Materia Sezione di Perugia

Via Pascoli, 06123 Perugia Italy

Date October 1, 2004

Abbreviated title: Music by means of the Shell Effect

Abstract

The “shell effect” can be used to play music having a pleasant and characteristic timbre.
If you place a sensitive microphone at the rim of pipes of suitable length and diameter to obtain resonance frequencies, ambient noise will produce musical notes.
The corresponding optical effect, extracting visible light from ambient radiation considered dark by the human eyes), is also discussed.

I INTRODUCTION

With all probability, some of our ancestors noticed that it was possible to listen to the sound of the cane-brakes, only on particularly windy days. Then one of them, listening to a higher sound emitted from a particular cane, discovered that the cane had a hole or was broken, forming a cylinder with one end open. He decided to try and imitate Nature. He took a piece of cane, he blew inside and succeeded in hearing one of the first sounds produced by man using a flux of air.

From: *Phys. Educ.* 40 (2005) 147-150 - Copyright IOP Publishing Ltd
http://www.iop.org/EJ/toc/0031-9120/40/2

5.4 Recognising a scientific report

Resource 1

Flutes, clarinets, trumpets, horns, organs and all other wind instruments, can be considered as offspring of that first observation.

Sound generation, in these instruments, is due to air column vibrations, generating longitudinal stationary waves.

If that musical investigator, on a quiet and totally windless day, had placed a piece of cane or a shell, or simply a cupped hand to his ear, he would have heard either "the voice of the cane field" or "the voice of the sea". This is interesting: in an environment where we do not hear any sound or noise, near the open ends of the tube, we can hear a sound.

Since the best-known method for obtaining a sound from environmental noise, used especially by children on the beach, is to put a shell near an ear to listen to “the voice of the sea”, we call this effect the “shell effect”.

The shell effect is not used to construct musical instruments.. The extreme weakness of the shell effect and the presence of other frequencies in addition to the fundamental one make it unsuitable.

In this paper we present a pipe-organ in which audible sounds, musical notes, are generated without flux of air into the pipe.

Explaining the shell effect

The movements of the air molecules, in an open and quiet ambient, have random directions. In a cylindrical container the air molecules, bouncing elastically on the inner walls, are forced to assume, statistically, an oscillation direction parallel to the cylindrical surface. The cooperative action among molecules generates an "air tube”

5.4 Recognising a scientific report

Resource 1

vibrating at a frequency f, due to the characteristics of the container; in this case, the length and diameter of the cylinder.

Of the many waves propagating in the environment, the air column inside the tube responds to waves whose frequency f can generate resonant oscillations.

There is an increase in sound level, near the end of the tube.The increase is not due to an interaction between the tube and our auditory apparatus. Outdoors, when the ambient noise level was about 15 dB, we found an average increase of 5 dB, near the open ends of tubes. The electronic version of this journal offers a demonstration of the sound so obtained.

In addition, by eliminating some higher frequencies from the original, it is possible to obtain “pure” notes,that sound more agreeable. The electronic version also offers a piece of music entitled ‘Stromboli’. We dedicate this piece of music, together with the words, to that wonderful Italian volcano, since it generates whistles due to air fluxes along its ducts.

II EXPERIMENTAL

The length and internal diameter of a cylinder are the principal parameters that determine the characteristics of the emitted sound. The fundamental frequency of resonance f_0 for an open pipe is calculated by the formula:

$$f_0 = \frac{c}{2l} \tag{1}$$

5.4 Recognising a scientific report

Resource 1

where l is the length of the tube and c is the sound velocity in the medium inside the pipe (331.45 m/s in dry air).

Empirically it was found that an ‘end correction’ must be introduced to make the formula (1) more closely fit the frequency really emitted by the tube.

(2) $$f_0 = \frac{c}{l + 2(0.61\mathrm{R})}$$

where R is the internal radius of the tube.[2,3]

Initially we used this formula.

We started from the C above middle C, at 523.2 Hz, down to the C at 130.8 Hz, below middle C. Frequencies of the lower notes were determined considering the semitone interval given by the rule

$$\Delta f = f\left(1 - \frac{1}{2^{\frac{1}{12}}}\right)$$

So, for example, we have

$$f(B_b) = \frac{f(A)}{2^{\frac{1}{12}}}$$

and so on.

Looking at the keyboard of a piano, between each key and its successive octave, we find 12 keys. If f_0 is the frequency of the

sound emitted by middle C, and $f_1, f_2, ..., f_{12}$, are the respective

frequencies of the notes between middle C and the C an octave above it, the frequencies of the

, the ratios of these notes are related as follows

5.4 Recognising a scientific report

Resource 1

$$\frac{f_1}{f_0} = \frac{f_2}{f_1} = \ldots\ldots\ldots = \frac{f_{12}}{f_{11}} = k \text{ (constant)}$$

Considering the logarithm of each ratio, we can write

$$\log f_{i+1} - \log f_i = \log k$$

with i from 0 to 12.

So, adding up the right-hand and left-hand sides of the 12ratios, we have

$$\log f_{12} - \log f_0 = 12 \log k$$

As $f_{12} = 2 f_0$ (relation between f_0, the frequency of a note, and the frequency of f_{12},an octave above it), we obtain

$$\log 2 = \log (k^{12})$$

and then

$$2 = k^{12}$$

that is

$$k = 2^{1/12} \sim 1{,}059463.$$

This means that the number of vibrations of a given sound, multiplied or divided by 1,059463, furnishes the frequency of its superior or inferior semitone, respectively.

But we also used another simpler method, since it is possible to determine the right length of each pipe, without a mathematical calculation. We made “a trumpet extracting music from silence”, that is a tube of variable length, resounding with the environmental noise.

wo open pipes, made of Plexiglas, of appropriate length and diameter, one inserted into the other, altered the total length of the “trumpet” and enabled us to tune the “extracted” sound from the non-audible environmental noise. The small variation, of approximately 2 mm, between the two internal diameters (3,1 cm and 2,9 cm) of the tubes, produces negligible effects on the characteristics of the sounds.

5.4 Recognising a scientific report

Resource 1

By ear it is very easy to recognize a given note, but we also used a spectra analyser to establish the exact length needed to optimise the musical result.

We placed a microphone near the rim of each pipe. Each signal was amplified and sent to the corresponding key of a keyboard. Twenty-five switches were placed under the corresponding keys. Headphones were used to avoid feedback thatwould lead to saturation, but also so as not to introduce the amplified sound of the other tubes into the environment.

As the sound from a shell recalls the wind and sea, the musical sounds generated using this method suggests a mysterious, astral atmosphere, especially with the lower notes.

The higher the noise level, the worse the “purity” of the sound obtained, because of the appearance of higher harmonics.

A decrease in ambient noise level causes the amplitude of the higher harmonics to decrease and gradually disappear. With an external noise of about 20 dB, only the fundamental frequency and the first three harmonics were excited in the longest pipe.

Some tests were performed with different artificial background noise, but no meaningful differences were revealed. We used sources of white, pink and brown noise. The spectrum of white noise is flat with respect to a linear frequency axis, while for pink or brown noise the horizontal axis is $1/f$ or $1/f^2$ respectively.

III CONCLUSIONS

We have described a rather simple but clever musical instrument, based on the shell effect. Many other questions arise regarding the possibility to obtain new and pleasant sounds by this method. Tests must be done to verify if the emitted sound

5.4 Recognising a scientific report

Resource 1

intensity changes with pipe direction and to examine how environmental temperature, material and shape of the pipe can change the intensity and timbres.

This electro-mechanic extraction of music from noise gives us the opportunity to emphasise one of the most important similarities between different fields in physics: the phenomenological correspondence between acoustical and electromagnetic properties. It is well known that what we call the shell effectis routinely used in making antennas that detect particular frequencies from ambient electromagnetic noise.

In writing this paper we started with a very elementary and well-known observation: the shell effect. Many similar equations and mathematical expressions in these two fields demonstrate the existence of equivalent phenomena (reflection, refraction, diffraction, interference, Doppler effect). So, proceeding from the simple to the complex, we ask: does a device that "extracts" visible light from ambient electromagnetic noise that is completely dark to a human eye exist? If it does, what is it? If it does not exist, how can it be produced?

The dynamical Casimir effect[6] could be an “almost equivalent optical Shell Effect”.

Almost, because the two, parallel, oscillating metallic surfaces, generating eventually visible electromagnetic waves, constitute not a passive system, like our pipe [7,8]. They require energy to oscillate.

We think that the new nanotechnology will enable us to construct an equivalent optical effect. Nano-antennas structures, only a few nm long, with all probability made of carbon, will be able to resound at optical frequency, so “extracting” light from the environmental electromagnetic noise. These nano-antennas will allow light transmission and reception without optical fibers. We are aware of light being propagated, through its reflection fromobjects. Nano-antennas will resound at optical frequencies,

5.4 Recognising a scientific report

Resource 1

conceptually identical to acoustic resounding systems and electromagnetic antennas used at present, for radio-TV transmission-reception.

Yet, it should be possible to demonstrate that, since the human eye can see even only one photon of the visible frequency, it is impossible to have a passive mechanism that "extracts" visible photons, from an ambient where visible photons do not exist.

In conclusion, in order to answer one of the questions deriving from that first observation of canes in the wind, we must study and wait.

REFERENCES

J. Backus, *The Acoustical Foundations of Music*, (W.W. Norton \& Company Inc., New York, 1969), 65.

[3]Leo L. Beranek, *Acoustics*, (Mc Graw-Hill, London, 1954) 133.

[4]Diodati, P. et al. *Earth Planet Sc Lett* 184 (3,4): 719-724 JAN 30 2001.

[5]Diodati, P., Piazza, S., J*AJ ACOUST SOC AM* 116 (1): 45-48 JUL 2004.

[6]Casimir, HBG, *Phys Rev* 73 360, 1948.

[7]Schwinger, J P NATL ACAD SCI USA 90 958 1993.

[8]Sassaroli, E., Srivastava, Yn, Widom, A. Physical Review A 50 (2): 1027-1034 Part A Aug 1994.

5.4 Recognising a scientific report

Resource 2

Teaching Medical Physics

A P Gibson, E Cook, A Newing+

Department of Medical Physics and Bioengineering, University College London, UK

Cranfield Post Graduate Medical School, Gloucestershire Royal Hospital,
Gloucester GL1 3NN

Abstract: Medical Physics provides immediate and accessible examples which can assist in the teaching of a range of science subjects. To help teachers, we have produced a teaching pack which will be sent to all UK secondary schools in June 2006 and which will be available from *www.teachingmedicalphysics.org.uk*. Here we discuss the advantages of teaching using applications drawn from Medical Physics, careers in Medical Physics, and some sources of other Medical Physics related teaching resources.

1. Introduction

The number of students electing to study physics at University level is falling. This problem occurs worldwide and has been identified in the UK by the Government (HM Treasury 2002) and the Institute of Physics (2001). Even so, recruitment into Medical Physics is relatively healthy – the Institute of Physics and Engineering in Medicine's (IPEM) Basic Training Scheme is generally oversubscribed. Approximately 50% of undergraduates selecting Medical Physics options are women. We believe this suggests that promoting Medical Physics in school could encourage more pupils to study physics.

Anecdotally, there are two main reasons which students give when asked at UCAS interviews why they selected Medical Physics: they enjoy the way that the subject is closely linked to real-life applications; and they appreciate the way that Medical Physics can directly benefit people.

From: *Phys. Educ*. 41 (2006) 301-306 - Copyright IOP Publishing Ltd
http://www.iop.org/EJ/toc/0031-9120/41/4

5.4 Recognising a scientific report

Resource 2

Some physics courses already offer Medical Physics options. However, Science courses increasingly emphasise the applications of science, encouraging topics such as the electromagnetic spectrum and radioactivity to be taught in the context of medical applications. Such an approach can be used to teach many topical areas of science which are of interest to young people such as the safety of mobile telephones, decommissioning nuclear power plants and medical imaging.

In this article, we highlight some areas of Medical Physics which are relevant to teaching at secondary level; we outline potential career paths in Medical Physics; and we introduce a teaching pack which we will circulate to all UK secondary schools by June 2006. We also mention some resources which might be of use for teachers or pupils wishing to learn about Medical Physics.

2. Medical Physics

Medical Physics is traditionally seen as the application of radiation physics to medicine. This is the area in which most jobs are available and indeed, Medical Physicists are required by law in radiotherapy departments in the UK. Moreover, we suspect that both teachers and pupils will appreciate examples of beneficial uses of radiation. These include:

- x-radiography, which most pupils will have experienced at the hospital or the dentist's surgery;
- x-ray computed tomography (CT), a more complex application of x-rays in which views taken from different angles around the body are combined into a cross-sectional image;
- nuclear medicine, in which a radioisotope is injected into the body which then collects in an organ of interest, emitting gamma rays which can be imaged using a gamma camera. Positron Emission Tomography (or PET) is a particular example of nuclear medicine which relies on positron-emitting isotopes and which appears in some of the proposed GCSE curricula;
- radiotherapy, which uses high doses of x-rays or radioisotopes to destroy tumours.

Medical ultrasound provides examples both of imaging and of the Doppler Effect. Ultrasound systems can work in either of these two modes, or in a combined mode known as "colour Doppler". Most students and staff will have seen examples of ultrasound images of babies in the womb. Moving objects in the field of view change the frequency of the reflected signal by the Doppler Effect, allowing measurements of blood flow to be made non-invasively.

Optical methods are widely used to diagnose and treat illnesses. Endoscopy allows remote diagnosis in the gastro-intestinal tract. It can also be used through a surgical incision, in which case it is called keyhole surgery or "laparoscopy". By passing instruments along the endoscope, a biopsy can be taken for laboratory analysis, or simple surgery can be carried out. Other optical methods

5.4 Recognising a scientific report

Resource 2

include laser surgery which is often the method of choice for treating eye conditions, or for the removal of hair, birth marks or tattoos.

Bioengineering is closely related to Medical Physics, and in some centres the two areas overlap. Bioengineering includes the design of all types of medical devices including prostheses and pacemakers, cochlear implants which can stimulate hearing in people with some kinds of severe deafness, and assistive technologies which can help the elderly and the disabled to live normal lives.

3. Careers in Medical Physics

Medical physicists work in three main institutions: in hospitals, academia, and in industry. All three generally require a relevant first degree. However, one of the advantages of a career in Medical Physics is its interdisciplinary nature and a typical Department will include physicists, engineers, computer scientists, life scientists and mathematicians, all of whom might call themselves Medical Physicists or Bioengineers. One of the most useful skills you can have is computer literacy.

As a hospital Medical Physicist, you may be involved in applying diagnostic and therapeutic techniques directly to patients, or you may work more behind the scenes, either maintaining equipment or developing new techniques which are directly applied to healthcare. You will probably work closely with medical staff and other healthcare professionals. The Institute of Physics and Engineering in Medicine (IPEM*; www.ipem.ac.uk*) runs a two-year training scheme which acts as the first step in a career in Medical Physics. In academia, you are typically further removed from the patients and you are more likely to research new and emerging methods, perhaps by studying for a PhD. Employment in industry often involves designing or marketing new equipment in a large, established company or developing new products in a smaller, newer organisation.

For more information about careers in hospital Medical Physics, see *www.nhscareers.nhs.uk/nhs-knowledge_base/data/4847.html* and *www.connexions-direct.com/jobs4u/jobfamily/healthcare/medicalphysicist.cfm?fd=1252*.

4. Medical Physics Teaching Materials

Both teachers and students enjoy the immediacy of Medical Physics and its direct, beneficial applications to the real world. However, few teachers have specialist knowledge of Medical Physics and it is not easy to gain access to the latest images. Students have commented that despite studying Medical Physics options, they have often never seen medical images or even pictures of scanners. Physics is often taught by teachers trained in other scientific disciplines such as biology; we believe

5.4 Recognising a scientific report

Resource 2

that biologists in particular may find Medical Physics easier to teach than other areas of physics, given appropriate support.

In order to support the teaching of Medical Physics at 14-16, we have produced a pack of teaching materials which will be circulated to all UK secondary schools in June 2006. The pack is funded by the Engineering and Physical Sciences Research Council, the Institute of Physics and the Institute of Physics and Engineering in Medicine. It will include the following:

- three lessons as Powerpoint presentations covering the electromagnetic spectrum, radioactivity and ultrasound
- posters highlighting aspects of the lessons for publicity in schools
- a teachers' workbook, explaining the science behind each slide and containing worksheets for students
- a textbook which will provide more in-depth information about Medical Physics in general
- more images and other resources which are free from copyright

The electromagnetic spectrum and radioactivity lessons in particular are designed to fit into exam boards' specifications. All three lessons include high quality images taken from clinical and research applications of Medical Physics, and specially commissioned animations and movies to highlight particular areas. The teaching packs will be supported by a website which will act as an archive of Medical Physics-related teaching material. See *www.teachingmedicalphysics.org.uk*.

5. Other Medical Physics teaching resources

As part of Einstein Year, the Institute of Physics created a website *www.insidestory.iop.org* which consists of four activities related to Medical Physics including endoscopy and PET.

Good quality medical images can be obtained by searching the websites of manufacturers of medical equipment such as *www.gehealthcare.com*, *www.medical.siemens.com* and *www.medical.philips.com/main/index.asp*.

Two previous special issues of Physics Education (March 1996 and November 2001) provide accessible and stimulating articles. The small number of textbooks aimed at teaching Medical Physics at 14-16 or 16-18 include Pope (1999) *Medical Physics* (Heinemann) and Newing (1999) *Light, Visible and Invisible and its Medical Applications* (Imperial College Press). As always, wikipedia *en.wikipedia.org/wiki/Medical_physics* is comprehensive but should be used with care.

6. Potential sources of confusion

As Medical Physics appears in general textbooks and as options on the specifications of different exam boards, some potential sources of confusion have occurred. These are rare and are often due

5.4 Recognising a scientific report

Resource 2

to differences in terminology between Medical Physics and other areas of physics, or due to new advances in Medical Physics.

Potentially the most confusing of these is the statement that "gamma rays have higher energy than x-rays". Despite this being usually true, it can lead to confusion when teaching applications of Medical Physics, particularly in radiotherapy. A traditional x-ray tube can generate x-rays with energies of up to a few hundred keV. These low energies do not provide adequate penetration for radiotherapy of deep tumours. Treatment machines using the gamma rays emitted by cobalt-60 (energy = 1.17 MeV and 1.33 MeV) were therefore developed and were commonly used to treat cancer until the 1980s. However, since then, cobalt-60 machines have been mostly superseded by linear accelerators which produce x-rays with energies up to tens of MV, an order of magnitude higher than the gamma energy emitted by cobalt-60. This example of x-rays having a higher energy than gamma rays may confuse students who are taught that gamma rays always have the higher energy. In an (arguably unsuccessful) attempt to clarify this confusion, it is conventional to refer to x-ray energies in units of kV and MV, and gamma energies in units of keV and MeV to remind us that x-rays are created by a voltage across an x-ray tube while gamma rays are produced by radioactive decay.

Positron emission tomography (PET) is a rapidly expanding branch of Medical Physics. PET relies on radioisotopes which emit positrons. Students who have studied those syllabuses which describe only alpha, beta and gamma radiation can be confused when they learn about a fourth kind of radiation. This issue is likely to become more significant as PET begins to appear in more syllabuses.

A final source of confusion is in endoscopy. Endoscopes are often cited as an example of total internal reflection but in practice they have developed from simple light tubes into sophisticated pieces of medical equipment. A modern endoscope will include a miniature video camera at its tip instead of collecting the light using fibreoptics. It may, however, use fibreoptics to illuminate the field of view, although even this is sometimes done with a remote light source. A modern endoscope will also include devices for steering it remotely, a water channel to wash the field of view clear, and a channel through which instruments can be passed either for biopsy or for simple surgery using a blade or a laser.

7. Conclusion

Medical Physics is increasingly available as a specialist option at 14-18. Beyond this, Medical Physics can provide accessible applications which can assist in the teaching of courses in energy, mechanics, radioactivity and other areas of Science.

5.4 Recognising a scientific report

Resource 2

Some of the advantages of teaching by drawing examples from Medical Physics include:

- Students can bring their own experiences to the class
    - Most students will know someone who has had a medical image taken, they may have had a relative who has received radiotherapy, or they may have seen a younger sibling's prenatal ultrasound scan
- Backed up by news reports in the media
    - There are frequent reports in the press about new advances in medical imaging, which can be used in the classroom
- Equally attractive to boys and girls
    - Unusually in the physical sciences, recruitment into Medical Physics is typically 50% male, 50% female
- Very visual
    - Students enjoy looking at medical images, which can be used to teach both the physics of how they are acquired, and the biology of the part of the body being imaged.
- Can discuss Science in Society and ethics
    - Topics such as ethics, safety, and risk-benefit analysis can be readily drawn from Medical Physics.

8. Acknowledgements

We would like to thank the people who have contributed to the production of the teaching packs: Dr David Sang, Nicola Hannam, Jeff Jones and John Lewis, and the sponsors of the packs: the Engineering and Physical Sciences Research Council, the Institute of Physics (Education Department and Medical Physics Group), and the Institute of Physics and Engineering in Medicine.

9. References

HM Treasury (2002), "Investing in innovation: a strategy for science, engineering and technology"
http://www.ost.gov.uk/policy/science_strategy.pdf
Institute of Physics (2001), "Inquiry into undergraduate physics"
http://policy.iop.org/UPI/index.html

5.4 Recognising a scientific report

Resource 2

Institute *of* **Physics**

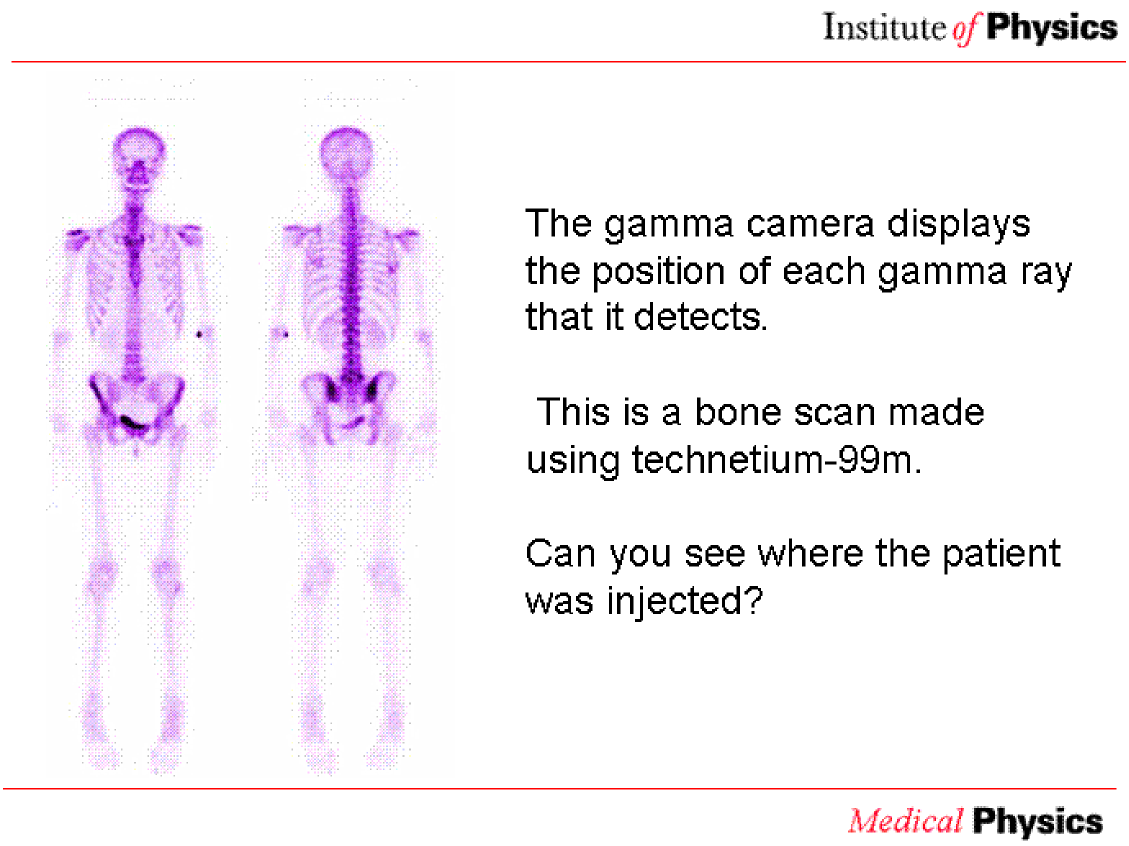
Radio Waves: **Mobile Phones**

Medical **Physics**

Figure 1: A copy of a slide in the lesson on the electromagnetic spectrum showing the results of a computer simulation which calculated the amount by which the head heats up due to the use of a mobile telephone. The maximum temperature rise is 0.2ºC. Is this safe? How does it compare with natural fluctuations in temperature due to warm blood entering the brain at each pulse, or sunlight, or wearing a hat? If we can’t prove whether mobile phones are safe or not, what advice should be given about their use?

5.4 Recognising a scientific report

Resource 2



Institute *of* **Physics**

The gamma camera displays the position of each gamma ray that it detects.

This is a bone scan made using technetium-99m.

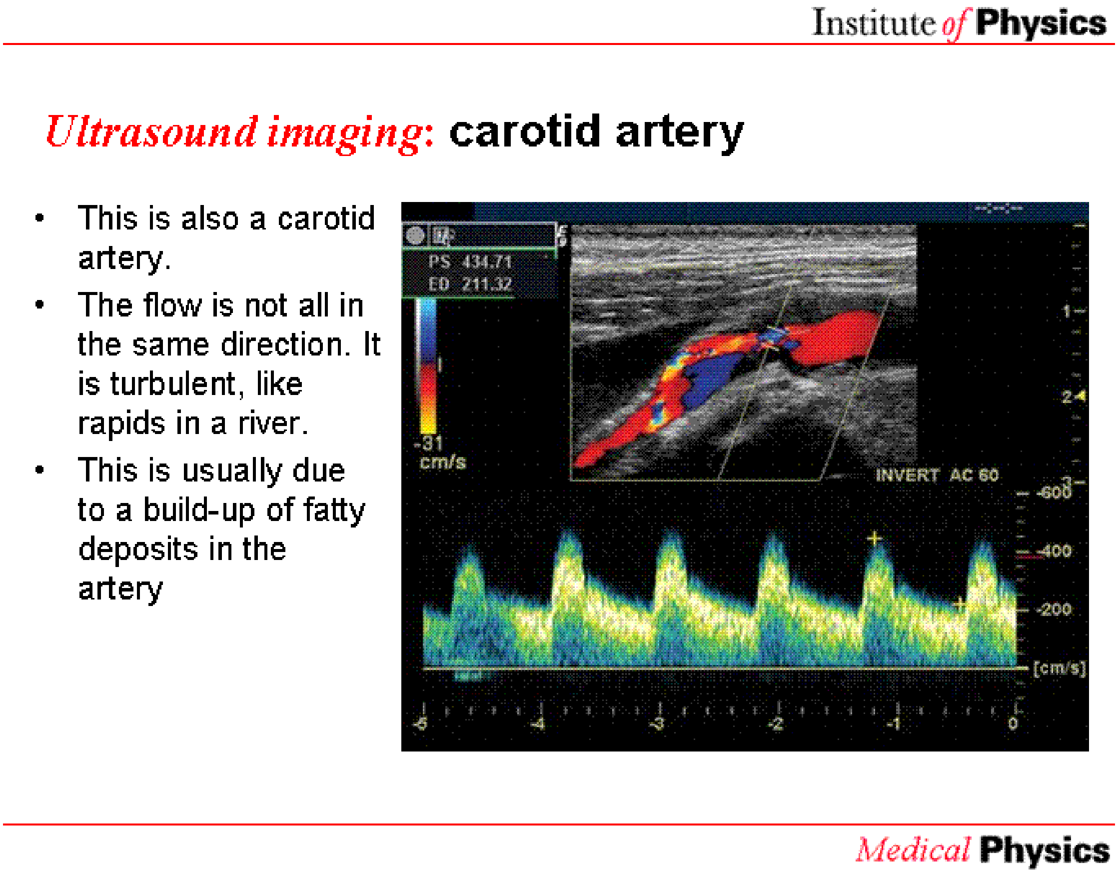
Can you see where the patient was injected?

Medical **Physics**

Figure 2: Slide from presentation on radioactivity showing a bone scan of a healthy patient. The view on the right is from the front and not shown here. That in the centre is from the back. You can see the tiny pool of radioactivity in the patient's left arm which remains from the injection.

5.4 Recognising a scientific report

Resource 2



Institute *of* **Physics**

Ultrasound imaging: carotid artery

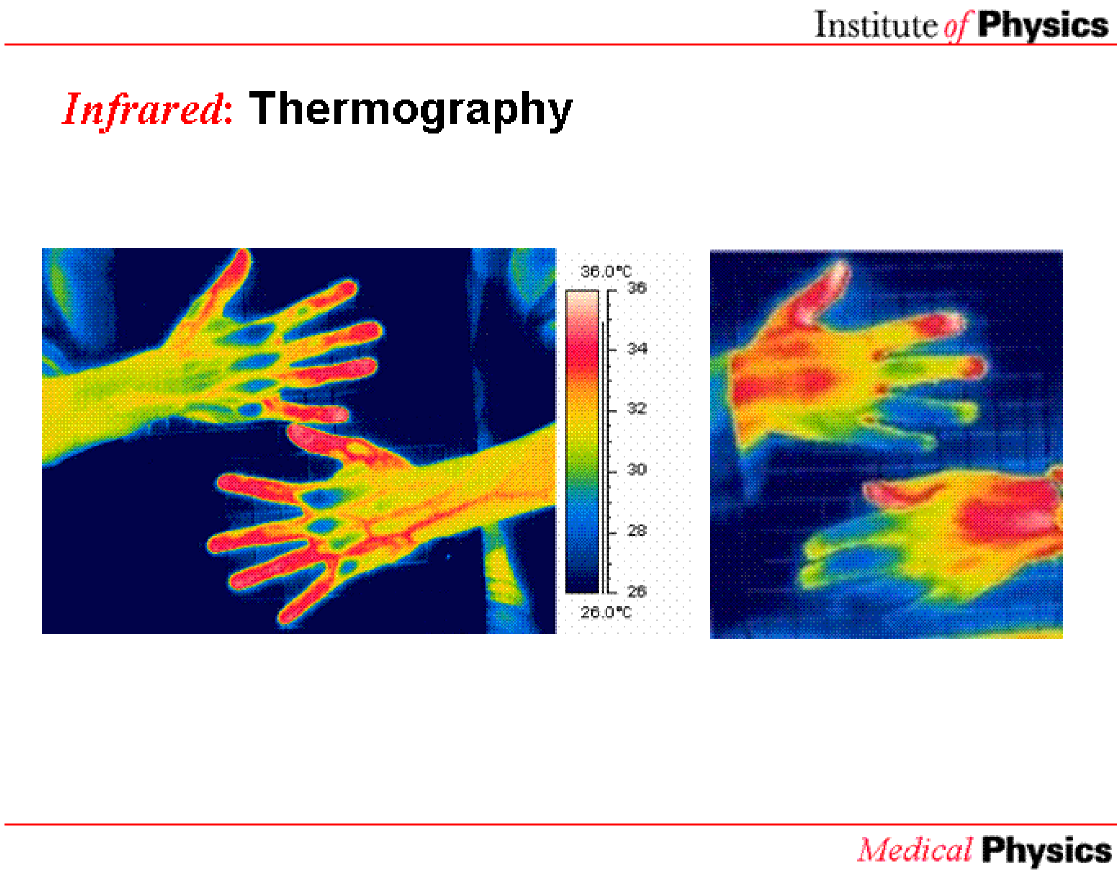
- This is also a carotid artery.
- The flow is not all in the same direction. It is turbulent, like rapids in a river.
- This is usually due to a build-up of fatty deposits in the artery

Medical **Physics**

Figure 3: Slide from the ultrasound lesson. The top part shows an ultrasound image of the carotid artery (in the neck), with the blood flow measured by Doppler ultrasound superimposed in red and blue. The graph below shows the pulse waveform (of velocity against time) in the artery. The flow is turbulent (the red and blue flows are mixed up, and the waveform shows blood travelling at all velocities, even at the peak of the pulse). This is due to a blockage in the artery.

5.4 Recognising a scientific report

Resource 2



Institute *of* **Physics**

Infrared: **Thermography**

Medical **Physics**

Figure 4: Slide from the lesson on the electromagnetic spectrum showing thermal images of the hands. Warm areas are shown in red; cool areas in blue. On the left is a normal volunteer. The fingers on both hands are warm. Note the blood vessels visible on the back of the hand. On the right is a patient with Raynaud's disease, a condition where the capillaries in the fingers and toes may contract, reducing blood flow. The fingers on both hands can be seen to be cold compared to the rest of the hand.

5.4 Recognising a scientific report

Resource 3

Why can we see visible light?

Zdeněk Bochníček,
Department of General Physics, Masaryk University, Kotlarska 2, 611 37 Brno, Czech Republic.

E-mail: zboch@physics.muni.cz

Keywords: high school, advanced, waves/light, laboratory work, physics update

Abstract. Visible light only constitutes a very narrow part of the wide electromagnetic spectrum. This article outlines several reasons why the human eye can see only within this limited range. Solar emissions and low absorption in the atmosphere are determining causes, but not the only ones. The energy of chemical bonds, the optical properties of matter, black body emissions and the wave character of light cause further limitations, all of which have a remarkable congruence.

Since the end of the 19th century, we have known that visible light[1] forms part of electromagnetic radiation. The wave equation for both an electric and magnetic field could be deduced from the Maxwell equation, and the existence of electromagnetic waves was demonstrated experimentally by Heinrich Hertz in 1888.
The frequency scale of electromagnetic waves covers a tremendous 25 orders of magnitude, from radio waves to cosmic radiation. However, visible light covers only a very small part of the scale. The ratio of the frequencies of violet and red light is only about two. Upon considering this, a fundamental question arises: “Why is it that the human eye (and in fact any other animal eye) can discern only this range of electromagnetic radiation? Is it merely accidental, or are there any serious reasons for this?” In this article we aim to demonstrate that there is no chance for any other range of visible light but the existing one.

Solar Radiation

The answer to why visible light is what we can see may be very simply stated: these wavelengths are mostly emitted by the sun. In figure 1 we observe the spectrum of solar radiation. Its maximum value approximately corresponds with the middle of the visible spectrum, and one may assume that evolution could have created light sensors perfected for this range of electromagnetic radiation.

From: *Phys. Educ.* 42 (2007) 37-40 - Copyright IOP Publishing Ltd
http://www.iop.org/EJ/toc/0031-9120/42/1

5.4 Recognising a scientific report

Resource 3

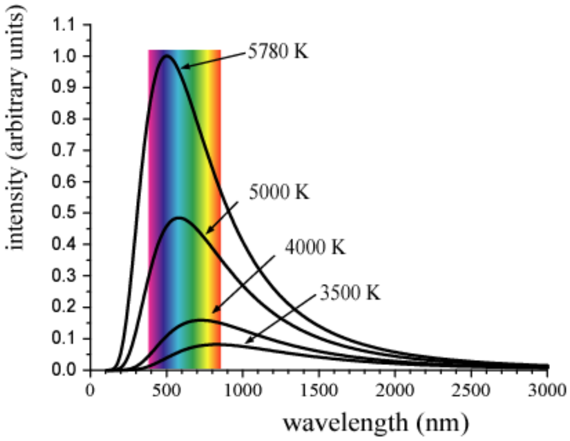


Figure 1: Spectral distribution of black body radiation for different temperatures including the surface temperature of the Sun, 5780K. The visible light range is denoted by the colored band.

Absorption in the Earth's atmosphere

Solar emissions in a particular section of the electromagnetic spectrum are not the only conditions that must be met to ensure a sufficient amount of light on the Earth's surface. The radiation has to go through the Earth's atmosphere, which means that the absorption of visible light must be low. Such is actually the case. The absorption coefficient of the atmosphere is depicted in figure. 2. One can see the "window" in the visible region and larger absorption in both ultraviolet and infrared.
The absorption of electromagnetic radiation in ranges close to visible light could be carried out through two different mechanisms.

1. Mechanical oscillations of molecules. This is true for the infrared region with wavelengths of about 10µm. The absorption by carbon dioxide at 4.26 µm and 15.00 µm would be an example.
2. Changes in the energy state of an electron, or some changes in chemical bonds. This happens in the visible and ultraviolet regions. For example, both creation and annihilation of ozone molecules are caused by the absorption of ultraviolet.

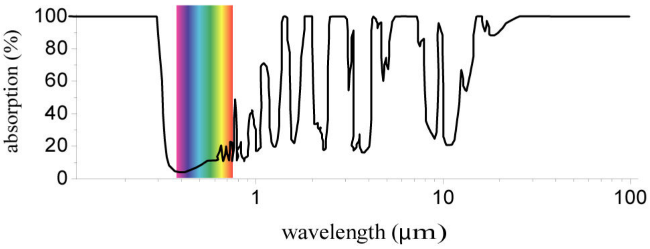


Figure. 2: Absorption of electromagnetic radiation in the Earth's atmosphere.

5.4 Recognising a scientific report

Resource 3

It is interesting to note that absorption at both extremes of visible light is connected with two serious environmental problems. Absorption by ozone molecules protects the biosphere from ultraviolet radiation, and the potential destruction of the ozone layer could represent a grave threat for life on Earth. On the other side of the electromagnetic spectrum, the absorption of infrared radiation by CO_2 molecules can boost the greenhouse effect, leading to serious global climate changes.

We might conceivably conclude our argument at this point, since the reason for the establishment of the visible light range is clear: this radiation has its highest intensity at the surface of our planet. No other points seem necessary. Yet surprisingly, there are still other arguments which may be presented.

Two reasons why we cannot see in the far ultraviolet region

A) Photon detection is impossible

The whole human body is based on chemical bonds, and physiological processes are based on chemical reactions. The same is true for the detection of light at the retina of the eye, where photon energy is absorbed by rhodopsin that changes its geometrical isomerism from trans to cis. The photon must be absorbed as a whole, which means that there must be the possibility to change the energy level of a molecule by the same amount as photon energy does. Moreover this change must be reversible, since the same retina detects light throughout human life. The most effective way to do this is to exploit reversible changes in chemical bonds. This means that the energy of a visible photon must be in the same range as the energy of chemical bonds. This is actually the case. The energy of chemical bonds varies from 0.01eV (van der Waals) to 5eV (covalent), while visible light consists of photons with energies from 1.6eV (red light) up to 3.4eV (violet light).

A photon with significantly higher energy cannot be absorbed by a chemically controlled reversible mechanism, and its absorption leads to large-scale unpredictable destruction. It is well known that ultraviolet or even x-ray radiation is detrimental to human and animal tissues. There is a good example demonstrating how much work is done by our body to heal damage to our skin from exposure to common solar radiation. There exists a rare genetic disease called *xeroderma pigmentosum* that causes the total lack of the mechanism which corrects damage due to ultraviolet radiation. People affected by this disease cannot be exposed to sunlight, even when scattered and coming through an ordinary glass window. They are called “moon children”, because they may only venture outside at night to avoid any risk. As this cannot be maintained at all times, they often die of cancer at a very young age. Thus the human body is somehow sensitive to ultraviolet radiation, though not in a way useful for light detection and vision.

B) The eye lens cannot create an optical image on the retina.

The human eye is an optical system in which a converging lens and a spherical shaped cornea create an optical image on the retina. Rays of light are deviated by refraction and to do this, optical material with a refractive index significantly larger than 1.0 must be available. The refractive index of the human eye lens is about 1.4 in the visible spectrum, but for higher energies the refractive index for practically all materials converges to one. One example – quartz glass – is illustrated in figure 3. The dispersion relation is unique for any individual material but a general trend – convergence towards one for short wavelengths – is valid for any material.

This is why after reaching the diffraction limit of optical microscopy, resolution could not be improved by using ultraviolet or even x-ray radiation. At the same time, this is the reason why a hypothetical ultraviolet eye could never exist.

5.4 Recognising a scientific report

Resource 3

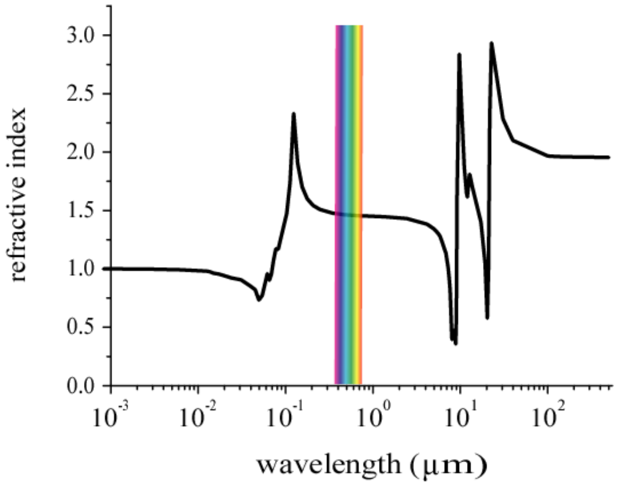


Figure. 3: Refractive index of quartz glass. It is worth mentioning that for visible light (color band) the index of refraction is almost constant, which leads to the slight chromatic aberration of a quartz lens.

Two reasons why we cannot see in the far infrared region

A) The human body itself emits infrared light

Not only the sun or a light bulb, but any body with a temperature above absolute zero emits electromagnetic radiation. For temperatures below 500˚C, the radiation is almost entirely within the infrared region. The human body, with its temperature of about 40˚C, emits infrared electromagnetic radiation with a maximum intensity at a wavelength of 10µm, as seen in figure 4. This makes effective and sensitive infrared vision impossible. The detected radiation signal would be overshadowed by the inner radiation of the human body, eye and retina itself.

It is very interesting to note that infrared vision actually exists in wildlife. Some species of snakes such as rattlesnakes or pythons have a special organ along with the normal eye that is capable of “seeing” infrared light. These organs are said to be more sensitive than any other infrared detector made by man. They are able to detect radiation up to a wavelength of 10µm, which is the region where warm-blooded animals emit. The principle behind their functioning is as yet not fully known. The quality of infrared vision cannot be compared to that of normal eyes however, as we can deduce from the fact that the snake has retained its “visible” eyes together with the infrared one. Eyes for infrared vision are more similar to insect eyes than to the human ones. There are more individual detectors, each of which are able to detect radiation coming from a limited visual angle. In this way, the snake can get approximate information about the sources of infrared light in the vicinity of its head, for instance a small warm-blooded animal. It is able to distinguish a living body from a dead one at a distance of 5 to 10cm. One can see that the capabilities of these eyes are in fact very limited.

5.4 Recognising a scientific report

Resource 3

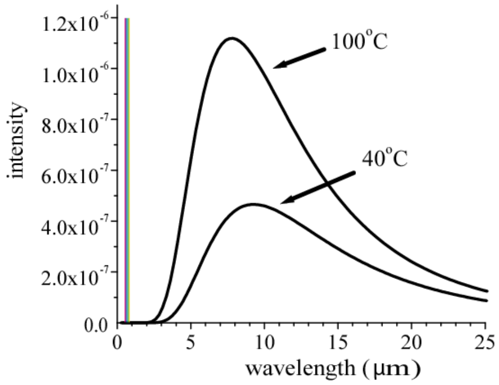


Figure 4: Black body radiation at low temperatures. The visible light range is the narrow colored strip just on the left. The scale at the y-axis is normalized to scale in figure 1.

B) Visual acuity is limited by diffraction

Light has wave characteristics, and as any other wave diffracts when its wave edge is somehow restricted, for instance by passing through a circular hole or a narrow slit. Before entering the eye, light must go through the pupil where diffraction occurs. When a plane wave hits the eye upon diffraction at the pupil, it becomes divergent and the lens is not able to convert the light beam into a single point in focus, as in figure 5. Instead of focusing into a point, light illuminates a small spot with a diameter of *d* approximately rendered by

$$d \cong 1.22\frac{\lambda f}{D},$$

where λ is the wavelength, f focal length and D diameter of the pupil. By applying normal values, one obtains a spot diameter d of about 5μm. This is the size of the image of an individual star, for instance. Visual acuity is thus inversely proportional to wavelength. With a longer wavelength we would have a lower capacity for vision.
The diffraction of light is a major limitation, especially for the small compound eyes of insects. There was no evolutionary driving force to construct a lens eye for insects. If the compound eye had the same size as a human one, its resolution would be much worse. But if the eye must be sub-millimeter in dimension, a compound eye is much better for vision, having other advantages, notably an extremely large visual angle.

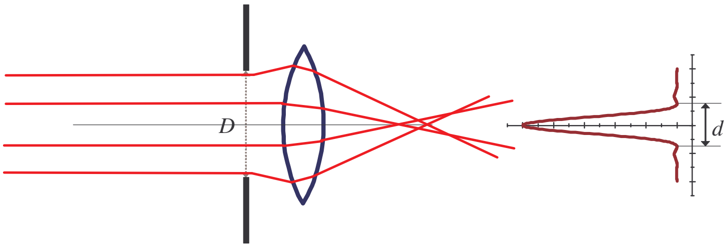


Figure 5: Light diffraction at the pupil of the eye (left) and intensity distribution at the retina (right) when a plane wave hits the eye.

5.4 Recognising a scientific report

Resource 3

Conclusion

We may summarize the above-mentioned facts in these brief statements:

1. Solar radiation is most intense in the visible range.
2. The Earth's atmosphere is effectively transparent in the same spectral range.
3. The energy of chemical bonds is comparable with the energy levels of visible photons, thus visible light can be detected by chemical changes.
4. In the visible range, the refractive index of matter is sufficiently different from unity and therefore the optical system of an effective eye lens may be formed.
5. The human body emits electromagnetic radiation that is far in scale from visible light and does not overexpose the eye itself.
6. Due to the small wavelengths, diffraction of light at the eye's pupil is weak and does not disturb the sharp image on the retina.

All these requirements must be met simultaneously. In fact they are not fully independent. Chemical bonds cannot have the same energy as photons of human body thermal radiation, because stable macromolecules could never exist in such conditions. Nonetheless we observe the remarkable congruence of several different physical states, allowing us to see with fine resolution and sensitivity, and to enjoy the beautiful world around us.

5.4 Recognising a scientific report

Resource 4

From Pythagoras to Sauveur:
Tracing the History of Ideas about the Nature of Sound

Abstract

This paper aims to supplement the scant literature on the history of ideas about the nature of sound. It presents how notions about the production and propagation of sound developed from antiquity up to the 17th century, i.e. from the time of Pythagoras to the time of Sauveur. It will highlight and examine the principles on sound that were formulated by Galileo and Newton, which are some of the less known work of these two giants in physics. The contributions of some familiar names, e.g. Hooke and Boyle, who are usually associated with scientific discoveries unrelated to sound, will also be covered. Some insights for the understanding of the nature of science and for the teaching and learning of physics will also be presented.

Introduction

Historical development of ideas in physics can provide interesting vignettes of information and insights, which can be used to enrich the process of teaching a topic. A recent article in this Journal analysed the historical development of ideas on motion and assessed its implications for teaching [1].

The main goal of this paper is to supplement the scarce literature dealing with the development of ideas about the nature of sound. It intends to bring to light the ideas, be it vague, mystical, erroneous or brilliant, about sound pushed by prominent figures in the history of science, in the hope that valuable lessons can be learned for a better understanding of the concept of sound, of waves, of physics and of science. It is also hoped that the utilization of the historical perspective that will be presented in this paper will put a humanistic touch on the presentation of normally abstract physical concepts in the classroom.

Early Investigation on Sound

Sound is the object of study of both music and physics. Early explorations on sound began as part of music. Music was then more of a mathematical discipline rather than a branch of art. The earliest scientific investigations on the nature of sound are attributed to Pythagoras (about 580- 500 BC), a mathematician and philosopher [2]. Based on the writings of Boethius (480-525 AD), Pythagoras' interest in exploring sound was triggered when he was passing by a blacksmith's forge and heard that the sound of hammers hitting anvils can be at times pleasant (or consonant), and sometimes unpleasant or dissonant [3]. Pythagoras found that the weights of the hammers producing harmonious sounds were in ratios of small whole numbers. He then conducted experiments with other materials, such as glasses, vases, bells, and strings in order to determine if similar ratios can be obtained in creating consonant sounds. He was able to invent a monochord, which comprised a sounding board with movable bridge and a string stretched over it. Using the monochord, he found that two stretched strings with length ratio of 1:2 produced the same note separated by an octave, with the longer string producing the lower note [4]. He concluded that consonant sounds can be produced when the string length ratios involve the whole numbers 1, 2, 3 and 4. It is believed that Pythagoras also extended this conclusion to volumes of air in pipes and volumes of water in vases [5].

From: *Phys. Educ.* 42 (2007) 173-179 - Copyright IOP Publishing Ltd
http://www.iop.org/EJ/toc/0031-9120/42/2

Imelda S Caleon and R Subramaniam

5.4 Recognising a scientific report

Resource 4

The influence of Pythagoras' ideas correlating sound to numbers on the subsequent generations of scientific thinkers should not be underestimated, even if questions can be raised regarding the authenticity of his so-called experiments owing to the scarcity and unavailability during his time of some materials that he is said to have used in such experiments. Pythagoras and his followers, who are labeled as Pythagoreans, should be credited for laying down some fundamental principles on the nature of sound: the generation of sound by vibrating sources, the notion of pitch, and the linking of sound to numbers. Their early investigations became very good springboards for the next generations of scientists in their study of the nature of sound.

Wave versus Particle Views of Sound

Further explorations on the nature of sound branched into two directions: either towards the wave or particulate notion of the nature of sound. These explorations were accompanied by the determination of the mechanism by which sound propagates from source to receiver.

The notion of sound being a wave seems to have originated from observations on water waves. Early explorers of nature viewed a wave as a form of disturbance produced by a vibrating source and which travels through a distance without a net transfer of water particles [6]. Aristotle's (384-322 BC) ideas on the wave nature of sound can be found in *On Things Heard* [7]. He noted that when sound is produced by a source, the air at the source is driven forcibly into the surrounding air for a finite distance – just like wind blowing. On the generation of sound, Aristotle [7] believed that it is produced when air meets with a body – for example, when a stringed musical instrument is played, it produces sound when the air is set in motion.

Aristotle's writings indicate that he recognized the mechanical nature of sound waves, being propagated in a medium, such as air. He had envisaged sound waves like ripples of water when he said that sounds "fill the space around them". He seemed to have also given an early account of the longitudinal nature of sound waves when he wrote '(the air) is set in motion …..by contraction or expansion or compression'[7]; this is somewhat indicative of the definition of longitudinal wave where the wave motion is parallel to the direction of propagation of the vibration.

A long time gap existed before further progress on the nature of sound ensued[1]. In the 16th century, Galileo Galilei (1564-1642), famous as astronomer and physicist, wrote an account of his wave view of sound in the "First Day" of his book, *Dialogue Concerning Two New Sciences* [8], which was first published in 1638. He envisioned sound waves though movements of water waves.

> That the undulations of the medium are widely dispersed about the sounding body is evinced by the fact that a glass of water may be made to emit a tone merely by the friction of the finger-tip upon the rim of the glass; for in this water is produced a series of regular waves.

In 1636, Marin Mersenne (1588-1648), a French mathematician, wrote in *Harmonicorum Libri* that sound is "a disturbance in a medium" (Dear, 2000, p. 268). He

5.4 Recognising a scientific report

Resource 4

also equated sound with movement: “All movements that occur in the air, in water, or elsewhere, can be called sounds, inasmuch as they lack only a sufficient delicate and subtle ear to hear them…” [9]. He empirically determined the speed of propagation of sound to be 316 m/s by finding the time for an echo to return after traveling a known distance [10].

Isaac Newton (1642-1727) provided an elaborate theoretical explanation on the mechanics of the propagation of sound as a wave. In his *Principia* [11], first published in 1687, he explained in Proposition XLVII that pulses propagated in a fluid medium make the particles vibrate back and forth. Using Galileo’s ideas, he noted that the particles in the fluid medium "are always accelerated or retarded according to the law of the oscillating pendulum", which is equivalent to simple harmonic motion in modern usage. He showed that the propagation of sound through any fluid was shown to depend only on measurable physical properties of the fluid, such as elasticity and density. He even calculated the speed of sound in air using theoretical considerations, although the value he got (979 ft/s= 298 m/s) significantly differed from empirical results (1142 ft/s= 348 m/s) owing to an error in assuming that the temperature of the air during its vibrations as the sound propagates remains constant [12]. In 1816, this was corrected by Laplace, who noted that the heating of the air due to its compression and expansion as sound propagates needs to be considered in the calculation; he introduced a factor γ in Newton’s formula, which stands for the ratio of specific heats for air [12].

Although several scientists supported the wave notion of sound, the absence of detectable motion in the air (e.g. sound being observed not to affect the motion of any light body) led other scientists to think of an alternative proposition. Among them was the early seventeenth-century French natural philosopher and astronomer, Pierre Gassendi (1592-1655), who proposed that sound was propagated in a stream of fine, invisible particles from the original source to the ear [13]. This idea sprang from the early works of Epicurus (341-270 BC) and Democritus on atomism. He posited that sound is due to the emission of a stream of atoms from a sound source, with the velocity of sound being the velocity of atoms, and frequency being the number of atoms emitted per unit time [6].

Isaac Beeckman (1588-1637), a Dutch scientist, also envisioned a particulate nature of sound. He postulated that sound travels through air as “globules of sonic data” [14]. He posited that any vibrating object cuts the surrounding air into little spherical corpuscles of air that are sent away in all directions by the vibrating motion of the source, which is then perceived as sound upon reaching the ear [14]. For him, vibration is not even a necessary condition for causing sound: arguing that whenever air is divided into globules, sound is thereby generated [14]. These globules of air in sound generation are reminiscent of Einstein’s concept of photons in the particle theory of light. It appears that a prelude to the quantum theory came in relation to sound way before it has found a better role for light!

The two contrasting ideas on the nature of sound did not experience the same intensity of controversy as that for light. It appears that the large majority of the early

5.4 Recognising a scientific report

Resource 4

thinkers accepted the wave interpretation for sound. This could be due to the fact that sound waves, owing to their mechanical nature, are relatively easier to visualize and comprehend, taking a good analogy from water waves. Light, on the other hand, has a more enigmatic nature - that of being an electromagnetic wave, the comprehensive understanding of which needed to wait until Faraday's theory unifying electricity and magnetism in 1861 and Maxwell's theory of electromagnetic waves in 1865.

The Role of the Medium

Other scientists doubted the role of air in the propagation of sound. Athanasius Kircher (1602-1680) was the first to do an experiment with an air pump [4]. He listened to the sound of a bell in a jar while the air inside was being removed by the air pump. Otto von Guericke (1602-1686), who made a complex two-man pump that drew air from two fitted copper hemispheres [15], popularly known as Magdeburg hemispheres, also conducted a similar experiment. Both Kircher and Von Guericke observed that even if air is removed from a jar, they still could hear the ringing of a bell inside it, leading them to conclude that air is not necessary for the transmission of sound [4]. This observation is perhaps due to air leakage in the pump used.

Robert Boyle (1627-1691), a well known chemist, also attempted to determine how sound propagates in a vacuum. His idea of vacuum came from Evangelista Torriceli's experiment that involved the inversion of a tube filled with mercury, and which left a space at the top, and from the work of Von Guericke [15]. With the help of Robert Hooke (1635-1703), Boyle was able to make a simple, yet efficient, air pump connected to a glass chamber [15]. Using this air pump, Boyle carefully conducted his version of the bell-in-a-jar experiment and observed that the sound of an alarm clock (or bell) placed inside the vacuum chamber faded away as air was withdrawn from the chamber [16]. He concluded that sound cannot travel in a vacuum, thereby supporting the Aristotelian perspective that a medium, such as air, is needed in sound propagation.

A Revival of Pythagoras' Consonance Ratios

During the 16th century, there was a revival of interest in the Pythagorean consonance ratios. Vincenzo Galilei (1525-1591), the father of Galileo, conducted experiments believed to have been done by Pythagoras. The results of Vincenzo's experiments indicated that the musical ratios to generate consonant sound apply only in relation to string and pipe lengths but not to sounds generated using different volumes of water and weights hanging on strings, with all other factors remaining the same [5]. Vincenzo's conclusions partly refuted the long-held belief on the Pythagorean consonance ratios, suggesting that these ratios depended on the properties of the vibrating source, and, thus, not absolute.

Continuing what his father started, Galileo [8] conducted further experiments on sound. He was able to establish the fact that sound produced by a stringed instrument is determined more precisely by the ratios of the frequencies of the sound and not by the ratios defined by the length, size and tension of the strings, as the Pythagoreans had claimed. He noted that frequency, which is "number of pulses of air waves" generated by a vibrating source [8], is the physical cause of pitch that is perceived by the ear - he found

5.4 Recognising a scientific report

Resource 4

this through an experiment involving the scraping of a metal with a chisel. Although this experiment was very realistically described by Galileo in his book *Dialogue Concerning Two New Sciences* [8], slight errors in his account suggest that the experiment was unlikely to have been performed [14]. Real or otherwise, Galileo's experiments led him to an important breakthrough: linking music with the physical reality of motion and associating the consonant ratios with a specific aspect of sound—the frequency. Despite the criticisms on the process he used in deducing these breakthrough principles, Galileo should be credited for "reconciling nature and mechanics, mathematical demonstrations and sensate experiences, while turning the sounding number into sound" [3].

Simultaneous with Galileo's work on sound, Mersenne also conducted an independent study on the vibration of stretched strings. Mersenne discovered that a string's frequency varies inversely with its length [9] and, like Galileo, he associated frequency with pitch. Furthermore, he actually calculated the value of the frequency of vibration of a long, heavy wire that moved very slowly and determined the frequency of a note linked to a particular pitch [10].

Robert Hooke (1635-1703) also indicated his own way of associating frequency of vibration with the pitch of sound. Through his fine mechanical skills, he was able to devise an instrument illustrating his proposition. This instrument was composed of a toothed wheel striking a piece of metal at various speeds, thereby producing musical notes of various pitches [15].

In the late 17th century, French physicist Joseph Sauveur (1653-1716), who first coined the term "acoustics" to refer to the study of sound, carried out detailed investigations on the relationship between frequency and pitch of sound waves. In his book, *Collected Writings on Musical Acoustics* [17], he noted that an organ pipe of about 5 Parisian feet (1.624 metres) gives out sound of frequency equal to 100 cycles per seconds (or Hz)[2]. He made the first frequency table of musical pitches, giving the frequency of the middle C to be 256 Hz, which is rather close to the current value of 261 Hz.

Implications for Understanding the Nature of Science and for the Teaching of Physics

Providing a historical account that details the development of scientific ideas, including the scientists behind these ideas and how and in what context these ideas were generated, can help in humanizing science [18] and in enhancing the significance of the achievements and the nature of science [19]. A historical perspective on the development of ideas about particular science concepts can help teachers understand the difficulties that their students face in giving up their pre-instructional conceptions or misconceptions [1]. The ensuing discussion describes how the history of sound provides a window through which the nature of scientific ideas and the process of knowing science can be viewed and how it can be utilized to motivate students to restructure their alternate conceptions on sound.

On durability and tentativeness of scientific ideas

5.4 Recognising a scientific report

Resource 4

Science is a dynamic enterprise, featuring ideas that are often subject to verification and modification. However, there are also ideas that have withstood rigorous tests and became a relatively durable set of knowledge. In the case of sound, the ideas of Pythagoras about musical harmony and the nature of musical sound have undergone several modifications, but the original formulation, which is about the existence of simple ratios that produce consonant sounds, remains valid up to the present time. In this sense, the history of the nature of sound can be utilized to present both tentative and stable facets of scientific ideas. This helps in addressing the concerns of De Berg [20], who stressed that overemphasizing tentativeness in the nature of science may lead students to perceive that science knowledge need not be taken seriously, and of Wang and Marsh [18], who noted that paying less emphasis on the tentative nature of science will lead students to perceive scientific ideas as the final product of science. When the students' minds are conditioned such that what they study is the final form of scientific research, and thus no longer open for change, their drive to think of alternative ideas and their propensity for creativity will be diminished.

On the personal, psychological and social context of scientific investigation
Scientific investigations are conducted by people neither in a vacuum nor exclusively in a laboratory. They exist in a particular social context. Oftentimes, scientists need to hurdle different obstacles and be ready to stand up for their ideas that may not conform to the accepted ones. One scientist worth mentioning for his courage and determination to challenge the prevailing belief is Vincenzo Galilei. His boldness to verify and challenge a long-held belief on musical ratios has largely contributed to the identification of the key to the underlying mystery behind the "sounding numbers" of Pythagoras. Good filial connections, as that between the father-and-son tandem of Galileo and Vincenzo who had a common interest in music, also helps to facilitate growth of scientific ideas.

On knowing about the process of knowing in science
The path of events leading to the modern view of harmony and consonance provides a framework by which students can experience the process of science and engage in restructuring long held views. The historical development of sound would help students realize that that there must be a good interplay among reason, sense experience, and explanation in order to arrive at the truth about nature, with theory and experiment complementing each other in leading to scientific truths. This was illustrated in the section where the error in Newton's theoretical calculations of the speed of sound was identified after comparison with the empirical results of Mersenne and through reflections of how the personal experiences of Pythagoras, Hooke and Galileo led them to correct generalizations about the nature of sound.

In this paper it was also shown that novel ideas can be generated in various ways. One way is through thought experiments. How Galileo imagined his way through the key principle that links frequency of sound and harmony in music, despite the subtle mental errors he committed, is just amazing. The congruence between Galileo's main finding and that of Mersenne adds credibility to the common idea that they independently discovered. However, the eventual acceptability of Galileo's propositions does not deny the danger that goes with thought experiments. This is a good instance to emphasize to

5.4 Recognising a scientific report

Resource 4

students on the value of careful verification of scientific ideas before they are accepted, citing reproducibility as the hallmark of validity. Another good thing to point out to students is the fact that in the process of verifying ideas, such as during replication of previous experiments, interesting discoveries can also be achieved. When Vincenzo Galilei repeated the so-called experiments of Pythagoras, he not only detected the errors in these experiments but he was also able to deduce that the properties of the source of sound are crucial in musical harmony.

On dealing with alternate conceptions
It has been reported that students' preconceptions about scientific phenomena resemble those of pre-modern science thinkers and the presentation of relevant excerpts from the history of science that mirror the students' difficulties may provide motivation for the students to realize the inadequacy of their ideas, appreciate modern concepts, and eventually restructure their own ideas [19]. Researchers reported that students have difficulty grasping the wave nature of sound, tending to use an object-like mode for understanding sound phenomena [21-22]: This seems to agree with Gassendi's [13] and Beeckman's [14] view of sound. It was also found that students, and even teachers, have difficulty understanding the connection between pitch and frequency of vibration [23]. Noting that it took around 1600 years before the link between pitch and frequency had been fully clarified, this difficulty amongst students is justified. If students are made aware of the aspects of the history of sound that are linked to their preconceptions, they would have a sense of consolation that they are not alone in their struggle. Knowing how Galileo and others derived and reasoned out the correct conceptions may help students in altering their alternate conceptions on sound.

Conclusion
The history of sound, just like the history of any other idea, is a history of dreams, creative imagination, obstinacy, error and enlightenment. It also shows one important facet of science, which is not commonly found in other human activities: the systematic criticism of errors often leading to better version of nature's truth. The history of sound can be used as a window through which the nature of science can be seen and analyzed, and in the process providing flesh to the usually abstract concepts involved in physics.

Endnotes
1. After the time of Aristotle, there was a big gap in the development of ideas about sound. The Roman conquest of the Greek empire began. The works of the ancient Greeks were hidden for protection. During the seventeenth century, the period of the Rennaisance, science was at a crucial turning point, moving from theoretical to practical, emphasizing experimentation over the use of pure reason in investigating natural phenomena. It also helped that the work of the ancient Greeks were translated into other languages and were made available to other scientists.
2. This data was used by Isaac Newton (1995) to determine the wavelength of a pulse of sound produced by the open pipe, using the length of the pipe divided by the sound frequency (Book 2, Scholium in Proposition L, Principia).

5.4 Recognising a scientific report

Resource 4

Acknowledgement

We are grateful to the Nanyang Technological University for the award of a research scholarship to the first author.

References:

[1] Espinoza F 2005 An analysis of the historical development of ideas about motion and its implications to teaching. *Phy. Educ*. **40** 139-146

[2] Dampier W C 1961 *A history of science and its relations with philosophy and religion* (Cambridge: Cambridge University Press) p 18

[3] Gozza P 2000. Number to sound: the musical way to the scientific revolution. (Dordrecht: Kluwer Academic Publishers) p 2 and 41

[4] Lindsay R B 1945 Historical development of acoustics to the time of Rayleigh *The theory of sound* ed J W S Rayleigh (New York: Dover Publications) pp xi-xxv

[5] Palisca C V 2003 Music and science *Dictionary of the history of ideas* Available in http://etext.lib.virginia.edu/cgi-local/DHI/ot2www-dhi?specfile=/texts/english/dhi/dhi.o2w&act=text&offset=12021011&query=music+and+science&tag=MUSIC+AND+SCIENCE p 262-263

[6] Pierce A D 1989 *Acoustics: An introduction to its physical principles and applications* (Woodburry, NY: Acoustical Society of America)

[7] Loveday T and Forster E S 1984 On things heard. *The complete works of Aristotle: The revised Oxford translation, Vol. 1* ed J Barnes, (New Jersey: Princeton University Press) pp 1229-1236

[8] Galilei G 2001 *Dialogues Concerning Two New Sciences* (William Andrew Publishing) Online version available at: http://www.knovel.com.ezlibproxy1.ntu.edu.sg/knovel2/Toc.jsp?BookID=449&VerticalID=0 pp 99-102

[9] Dear P 2000 Marin Mersenne: mechanics, music, and harmony. *Number to sound: the musical way to the scientific revolution* ed P Gozza (Dordrecht: Kluwer Academic Publishers) pp 267-288

[10] Sound 2006 *Microsoft Encarta Online Encyclopedia*. http://uk.encarta.msn.com/encyclopedia_761560639_3/Sound.html#s11

[11] Newton I 1995 *The Principia* (translated by Andrew Motte) (New York: Promethius Books)

[12] Chandrasekhar S 1995 *Newton's principia for the common reader* (London: Clarendon press) pp 579-590

[13] Blood B 2006 *The physics of musical instruments: A brief history*. Available at http://www.dolmetsch.com/poshistory.htm

[14] Cohen H F 2000 Isaac Beeckman *Number to sound: the musical way to the scientific revolution* ed P Gozza (Dordrecht: Kluwer Academic Publishers) pp 223-264

[15] Inwood S 2003 *The Man who knew too much: the strange and inventive life of Robert Hooke (1635-1703)*. (London: Pan Books) pp 19-20 and 224

[16] Murray S R 2000 Robert Boyle (1672-1691). *Science and its times: Understanding the social significance of scientific discovery, Vol. 3 (1450-1699)* ed N Schlager and J Lauer (Detroit: Gale Group) pp 362-363

5.4 Recognising a scientific report

Resource 4

[17] Sauveur J 1984 *Collected writings on musical acoustics (Paris 1700-1713)*, ed R Rasch. (Utrecht: The Diapason Press) p 175
[18] Wang H A and Marsh D D 2002 Science instruction with a humanistic twist: teachers' perception and practice in using the history of science in their classroom. *Sci. and Educ*. **11** 169-189
[19] Monk M and Osborne J 1997 Placing the history and philosophy of science on the curriculum: a model for the development of pedagogy *Sci. Educ.* **81** 405-424
[20] De Berg K C 2003 The development of the theory of electrolytic dissociation. *Sci. and Educ.* **12** 397-419
[21] Barman C R and Barman N 1996 Two teaching methods and students' understanding of sound *School Sci. and Maths.* **96** 63- 68
[22] Wittmann MC 2003 Understanding and affecting reasoning about sound waves. *Int. J. of Sci. Educ*. **25** 992-1013
[23] Menchen K V P and Thomson J R 2004 Pre-service teachers' understanding of propagation and resonance in sound phenomena. *2003 Physics education Research Conference* ed J Max S Franklin and J Cummings (USA: American Institute of Physics) pp 65-68

5.4 Recognising a scientific report

Resource 5

Experimenting with Woodwind Instruments

Michael C. LoPresto, Henry Ford Community College
lopresto@hfcc.edu

Abstract

Simple experiments involving musical Instruments of the woodwind family can be used to demonstrate the basic physics of vibrating air columns in resonance tubes using nothing more than straightforward measurements and data collection hardware and software. More involved experimentation with the same equipment can provide insight to the effects of holes in the tubing and other factors that make simple tubes useful as musical instruments.

Introduction

Exploration of the physics of music and specifically behind the operation of musical instruments is often one of the best ways to make physics seem interesting and relevant to students. What follows are some investigations involving woodwind instruments, specifically the flute and clarinet. The simpler experiments were developed and have proven useful as laboratories in a science of sound and light course for fine-arts students. The more in depth investigations may be more appropriate for physics students with an interest in music and or musical instruments, perhaps as more advanced laboratory projects or independent or directed studies.

Resonance Tubes

Musical instruments of the woodwind family are basically resonance tubes in which a standing wave is generated and maintained in the air column. In the case of the simplest woodwind, the flute, the player generates vibrations in the air column by blowing air against the edge of an “embouchure hole.” The air-column extends approximately from the embouchure hole center to just beyond the first open ”tone-hole” or just beyond the end of the tube if all the tone-holes are closed. See Figure 1.The air column in a clarinet is excited when the player blows over and vibrates a reed which excites an air-column that extends also approximately to the first open tone-hole’s center or to the beginning of a flaring “bell” section that aids in projection of the sound. [1] See Figure 2.

[1] Backus J 1977 *The Acoustical Foundations of Music*, 2nd edn (New York: W W Norton & Company) pp 215-229

From: *Phys. Educ.* 42 (2007) 296-303 - Copyright IOP Publishing Ltd
http://www.iop.org/EJ/toc/0031-9120/42/3

5.4 Recognising a scientific report

Resource 5

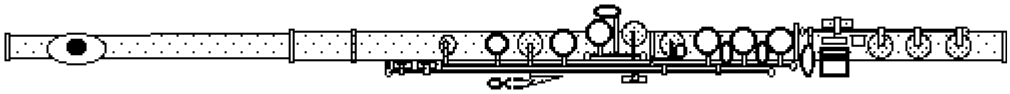


Figure 1-The air column in a flute extends approximately from the embouchure hole (left) to the first open tone hole, or just beyond the end of the tube if all the tone holes are closed.[1]

1-From http://www.phys.unsw.edu.au/music/flute/ used with permission.

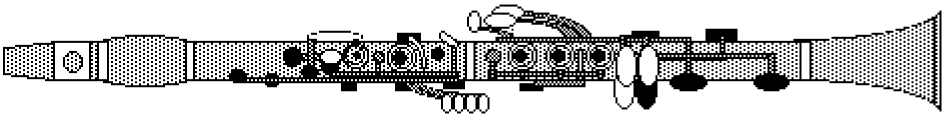


Figure 2- The air column in a clarinet extends approximately from the reed (left) to the first open tone hole, or to the beginning of the flaring bell section if all the tone holes are closed.[2]

2-From http://www.phys.unsw.edu.au/music/clarinet/ used with permission.

The basic physics of vibrating air-columns is well understood. If a tube is open on both ends, which is the case with the flute, there are pressure nodes or displacement antinodes [2,3] on both ends of the air column. It is true that the end of a flute's "head-joint" the piece of tubing that contains the embouchure hole is closed, but the actual vibrating air column that produces the sound begins where the vibrations are initially generated, at the open embouchure hole, not at the closed end of the head joint. The resonant frequencies for an air column open at both ends are given by the expression $f_n=nc/2L$ where L is the length of the tube, c is the speed of sound, approximately 344 m/s at room-temperature, and n is the mode of vibration or harmonic number. The musical "pitch" that is heard when a flute is played comes from the frequency of the first, n=1, harmonic or the fundamental. The higher harmonics add color or "timbre" to the instrument's tone by making the waveform more complex than that of a simple sine wave which is what produces the rather dull sound heard when blowing into a simple tube. See Figure 3.

[2] Hall D E 2002 *Musical Acoustics*, 3rd edn (USA: Brooks Cole) p 232
[3] Benade AH 1960 On the Mathematical Theory of Woodwind Finger Holes The *Journal of the Acoustical Society of America* **32** 1595

5.4 Recognising a scientific report

Resource 5

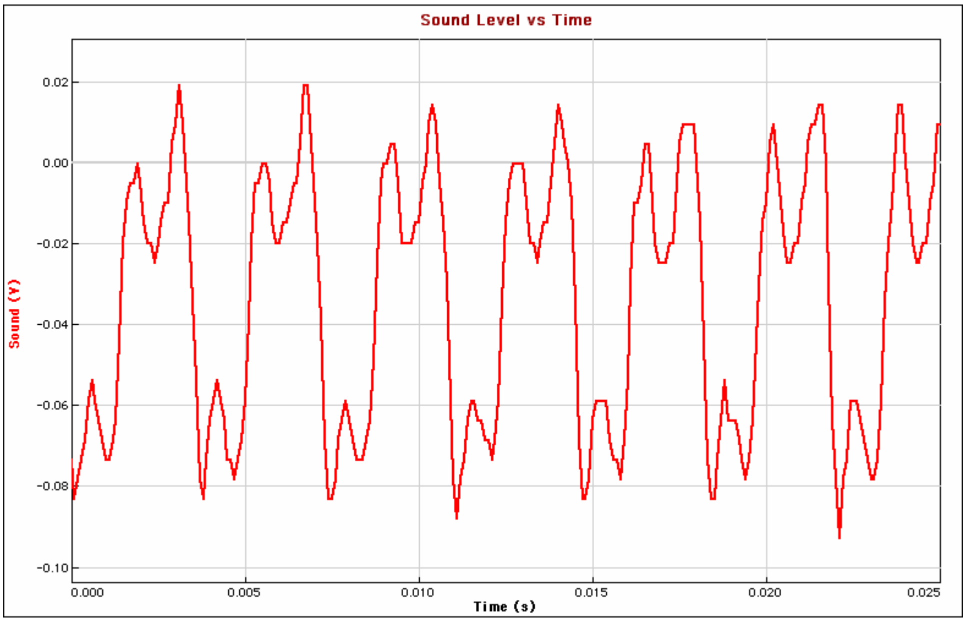


Figure 3-The waveform produced by a flute.[3]

3-The waveforms were captured with a microphone and a Lab-Pro interface and displayed with Logger-Pro; all products of Vernier Software and Technologies, www.vernier.com. Any similar hardware and software could be used such as the Science Workshop Interface and Data Studio by Pasco, www.pasco.com.

When a clarinet is played, the reed-end of the air column is closed by the player's lips creating a pressure antinode or displacement node [2, p265, 3)] at the mouthpiece end and thus an air column open only on one end, giving the frequencies f_n=(2n-1) c/4L, only odd harmonics. As with the flute, the perceived pitch comes from the n=1, fundamental, and the higher, in this case odd only, harmonics add form to the wave, resulting in the characteristic "darker" tone of the clarinet compared to the brighter tone of a flute. See Figure 4.

In practice, the displacement antinode of a standing wave is actually found just beyond the open end of a tube because the air continues traveling as if in the tube for a short distance before spreading out. This results in the air column being longer than the actual resonance tube or in a slightly longer "equivalent-length" of the vibrating air-column. For a simple tube, the equivalent length is longer than the actual length by an "end-correction" equal to about a third of the diameter of the tube [2, p 234; 4]. In the more complicated tubes of real musical instruments, corrections for both open and closed tone holes, embouchure holes and mouthpiece cavities are necessary to determine equivalent lengths. [5]

5.4

Recognising a scientific report

Resource 5

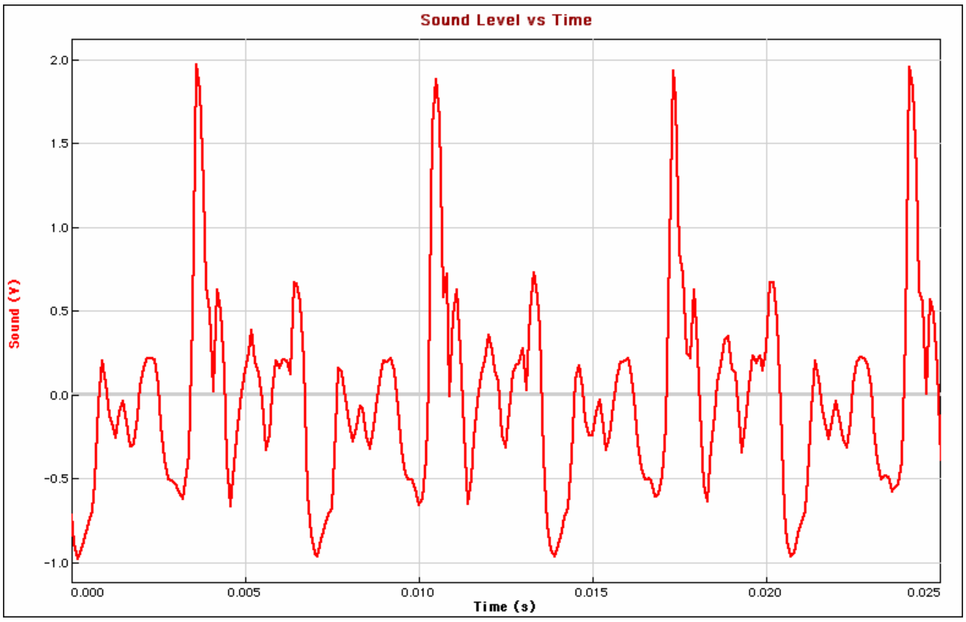


Figure 4-The waveform produced by a clarinet.[3]

[4] Fletcher N H Rossing T D 1998 *The Physics of Musical Instruments* 2nd edn (NY: Springer) p 560
[5] Rigden J 1985 *Physics and the Sound of Music* 2nd edn (New York: John Wiley & Sons) p 175

Observations

Different musical notes are played on both flutes and clarinets by varying the length of the vibrating air column. When all the tone holes are closed, the air column is at its maximum length so, since the length is in the denominator of the above expressions for the frequencies produced by vibrating air columns, the lowest frequency and therefore lowest musical pitches will sound. Higher pitches are played by opening tone-holes to shorten the length of the air column, thus raising the frequency. The instruments are designed so that each successive tone-hole makes the air-column about 6% shorter, raising the frequency by 6%. In the system of "equal-tempered" tuning currently used in Western music, adjacent musical pitches are separated by a frequency ratio of $\sqrt[12]{2} \cong 1.059$, about 6% [1, p 147].

5.4

Recognising a scientific report

Resource 5

Table 1 shows the frequencies sounded by a flute when different musical notes are being played. First with all the tone-holes closed, then with each tone hole in order of increasing distance from the end of the tube open and the corresponding lengths measured from the center of the embouchure-hole to the center of the first open hole or, when all the tone-holes are closed, to the end of the tube. The table also shows the frequency ratios between adjacent pitches and the actual and expected frequency ratios of each pitch with the lowest pitch. Frequencies were determined by using the time axis of the displays shown in Figs. 3 and 4 to measure the periods of the waveforms then reciprocating them.

Musical Note	Frequency Hz	Interval with previous pitch	Interval with first pitch	Expected Interval	Length (measured) L m	Length (equivalent) L_e m	L -L m
C-4	260	1.00	1.00	1.00	0.600	0.662	0.062
C#-4	275	1.06	1.06	1.06	0.550	0.625	0.075
D4	291	1.06	1.12	1.12	0.524	0.591	0.067
D#-4	310	1.07	1.19	1.19	0.490	0.555	0.065
E4	328	1.06	1.26	1.26	0.457	0.524	0.067
F4	348	1.06	1.34	1.33	0.428	0.494	0.066
F#-4	369	1.06	1.42	1.41	0.401	0.466	0.065
G-4	392	1.06	1.51	1.50	0.376	0.439	0.063
G#-4	415	1.06	1.60	1.59	0.350	0.414	0.064
A-4	441	1.06	1.70	1.68	0.327	0.390	0.063
A#-4	472	1.07	1.82	1.78	0.304	0.364	0.060
B-4	493	1.04	1.90	1.89	0.284	0.349	0.065
C-5	529	1.07	2.03	2.00	0.264	0.325	0.061
C#-5	573	1.08	2.20	2.12	0.233	0.300	0.067

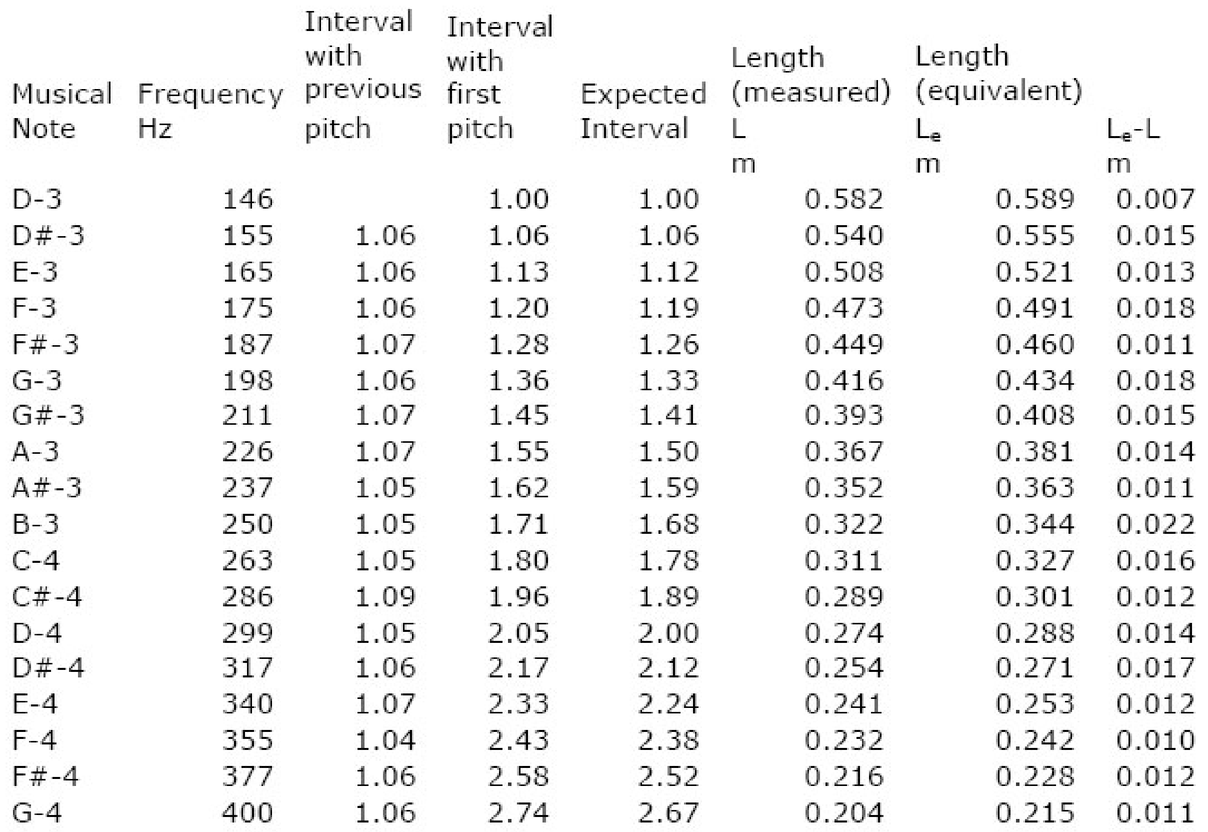
Table 1-The measured frequencies of the musical notes played on a flute, the musical intervals between the measured frequencies and the measured lengths compared to the equivalent lengths calculated from the measured frequencies.

Table 2 is the same as Table 1 but for the clarinet. Air column lengths were measured from the tip of the reed to the center of the first open tone-hole. The maximum length was measured to the beginning of the flaring bell section. The standing waves for lower harmonics tend to terminate near the beginning of a flaring bell section while higher harmonics penetrate further into the bell. [6] Since the frequency of the fundamental is what determines the pitch of a clarinet, for purposes of comparing frequency and length, the air column can be approximated as ending at the beginning of the flaring section. [5]

[6] Rossing TD Moore FR Wheeler PA 2002 *The Science of Sound* (New York: Addison Wesley) p 232

5.4 Recognising a scientific report

Resource 5



Musical Note	Frequency Hz	Interval with previous pitch	Interval with first pitch	Expected Interval	Length (measured) L m	Length (equivalent) L_e m	L_e-L m
D-3	146		1.00	1.00	0.582	0.589	0.007
D#-3	155	1.06	1.06	1.06	0.540	0.555	0.015
E-3	165	1.06	1.13	1.12	0.508	0.521	0.013
F-3	175	1.06	1.20	1.19	0.473	0.491	0.018
F#-3	187	1.07	1.28	1.26	0.449	0.460	0.011
G-3	198	1.06	1.36	1.33	0.416	0.434	0.018
G#-3	211	1.07	1.45	1.41	0.393	0.408	0.015
A-3	226	1.07	1.55	1.50	0.367	0.381	0.014
A#-3	237	1.05	1.62	1.59	0.352	0.363	0.011
B-3	250	1.05	1.71	1.68	0.322	0.344	0.022
C-4	263	1.05	1.80	1.78	0.311	0.327	0.016
C#-4	286	1.09	1.96	1.89	0.289	0.301	0.012
D-4	299	1.05	2.05	2.00	0.274	0.288	0.014
D#-4	317	1.06	2.17	2.12	0.254	0.271	0.017
E-4	340	1.07	2.33	2.24	0.241	0.253	0.012
F-4	355	1.04	2.43	2.38	0.232	0.242	0.010
F#-4	377	1.06	2.58	2.52	0.216	0.228	0.012
G-4	400	1.06	2.74	2.67	0.204	0.215	0.011

Table 2- The measured frequencies of the musical notes played on a clarinet, the musical intervals between the measured frequencies and the measured lengths compared to the equivalent lengths calculated from the measured frequencies.

Initial inspection of the data in Tables 1 and 2 shows that adjacent pitches for both the flute and clarinet are indeed close to 6% apart and that the musical intervals, the frequency ratios that each successively higher pitch makes with the lowest pitch are also close to what is expected. [1, p 146]

The end corrections for each individual playing frequency and corresponding tube-length shown in Tables 1 and 2 were calculated by taking the difference between the actual length, L, of a tube and the equivalent length of the air-column given, for a flute, by $L_e = c/2f$ or $Le=c/4f$ for a clarinet. Both the equivalent air column lengths and end-corrections, $\Delta L=L_e-L$ for a flute and clarinet are in Tables 1 and 2.

Another observation that can be made from inspection of the data in Tables 1 and 2 is when playing the same musical notes. C-4 through G-4, the measured flute tube lengths are about twice the clarinet tube lengths. This is because the fundamental frequencies produced by tubes open on both ends $f=c/2L$, a flute, are twice $f=c/4L$, those produced by tubes closed on one end, a clarinet.

5.4 Recognising a scientific report

Resource 5

The software[3] used to capture the sound waves and display the waveforms has a sampling rate that can be varied to a minimum of ΔT=0.02 ms between data points. The expressions used to calculated the equivalent lengths in Tables 1 and 2 could be written for a flute and clarinet respectively as L=cT/2 and L=cT/4 which would give uncertainties in the calculated equivalent lengths of ΔL=(c/2)ΔT and ΔL=(c/4)ΔT, 3mm for the flute and 1.5 mm for the clarinet. These values are only about 5% of the calculated end-corrections for the flute in Table 1 and about 10% of those for the clarinet in Table 2. Measuring the actual lengths of the air-columns was straightforward with an error of at most ΔL=1mm.

Graphical Investigations

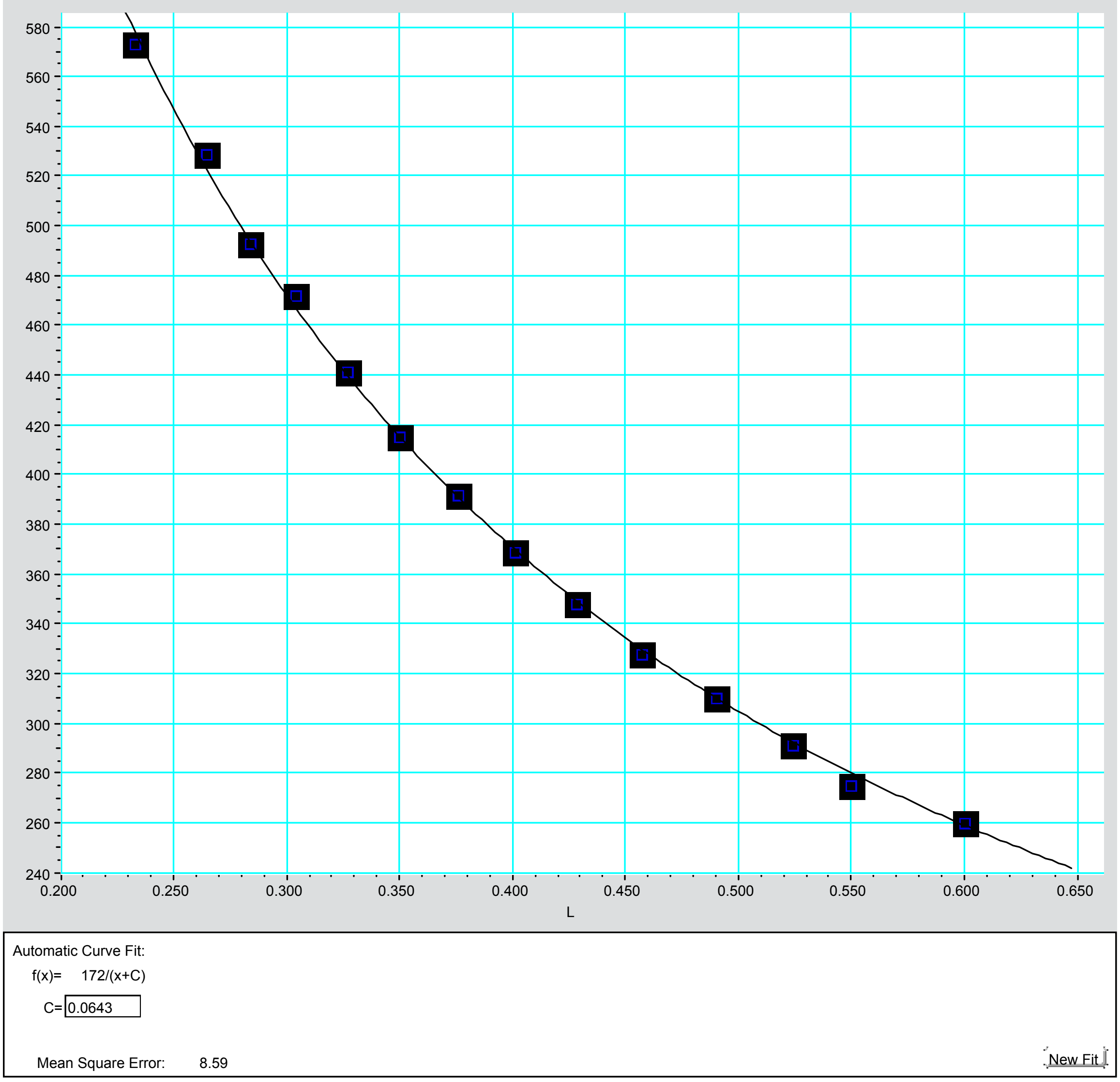
Figure 5 is a plot of the measured playing frequencies and corresponding measured tube lengths for a flute (data from Table 1). An equation of the form f=A/(L +C)^B should fit the plot. 'A" should equal c/2, c being the speed of sound, 'B' should be close to 1, since a flute's tube is considered open on both ends and 'C' is the necessary end-correction added to the tube-length L to equal the equivalent length of the air column.

A curve fit to the plot shown in Figure 5, taking A=344/2=172 as a known, gave B=1.06. Taking B=1 as the known gave A=171 or c=342 m/s for the speed of sound. The best agreement with the average value of end-correction from the flute data in Table-1 6.5 +/- 0.4 cm, was 6.43 cm obtained from the fit shown in Figure 5 where A=172 and B=1 were both considered knows.

5.4

Recognising a scientific report

Resource 5



Automatic Curve Fit:
f(x)= 172/(x+C)
C= 0.0643
Mean Square Error: 8.59

Figure 5-Plot of playing frequencies vs. air column length for a flute.[4]

4-Plot and fits done with Graphical Analysis by Vernier Software and Technologies, www.vernier.com

A plot of the clarinet data from Table 1 was similar to Figure 5 and curve fits, this time with A=c/4 because the clarinet is closed on the mouthpiece end, gave comparable values for the speed of sound and the exponent, B.

5.4 Recognising a scientific report

Resource 5

It can be instructive to plot and analyze the frequency vs. length data for both instruments in the manners of both Figure 5 and 6. Figure 5 directly shows the inverse proportion between frequency and length, which could be the main objective of the investigation in a less mathematical, more descriptive course, like many physics of music or science of sound courses. The linear plot in Figure 6 is a more sophisticated analysis and gives not only the end-correction, but also the speed of sound. This analysis would be appropriate in a course of higher mathematical level, such as introductory physics.

More on Flutes

As mentioned above, the equivalent-length of the vibrating air-columns in woodwind instruments can be calculated by considering the effects of both open and closed tone holes as well as the mouthpiece. Just as the anti node of a standing wave is found just beyond the end of a tube it is also found just a beyond the end of an open tone hole by an amount that depends on the dimensions of the hole and the tube it is in.

An expression for a the distance beyond the center of a tone-hole that the vibrating air-column actually ends is

$$\Delta L_H = s\left(\sqrt{1+2(t_e/s)(a/b)^2}-1\right) \qquad (1)$$

where 2s is distance between adjacent tone-holes or "tone-hole spacing", a is the inside radius of the tube, b is the inside radius of the tone-hole and t is the thickness or height of the tone hole, t_e=t+1.5b, is a corrected tone-hole height [7]

[7] Benade AH 1990 Fundamentals of Musical Acoustics (New York: Dover Publications Inc) p 450

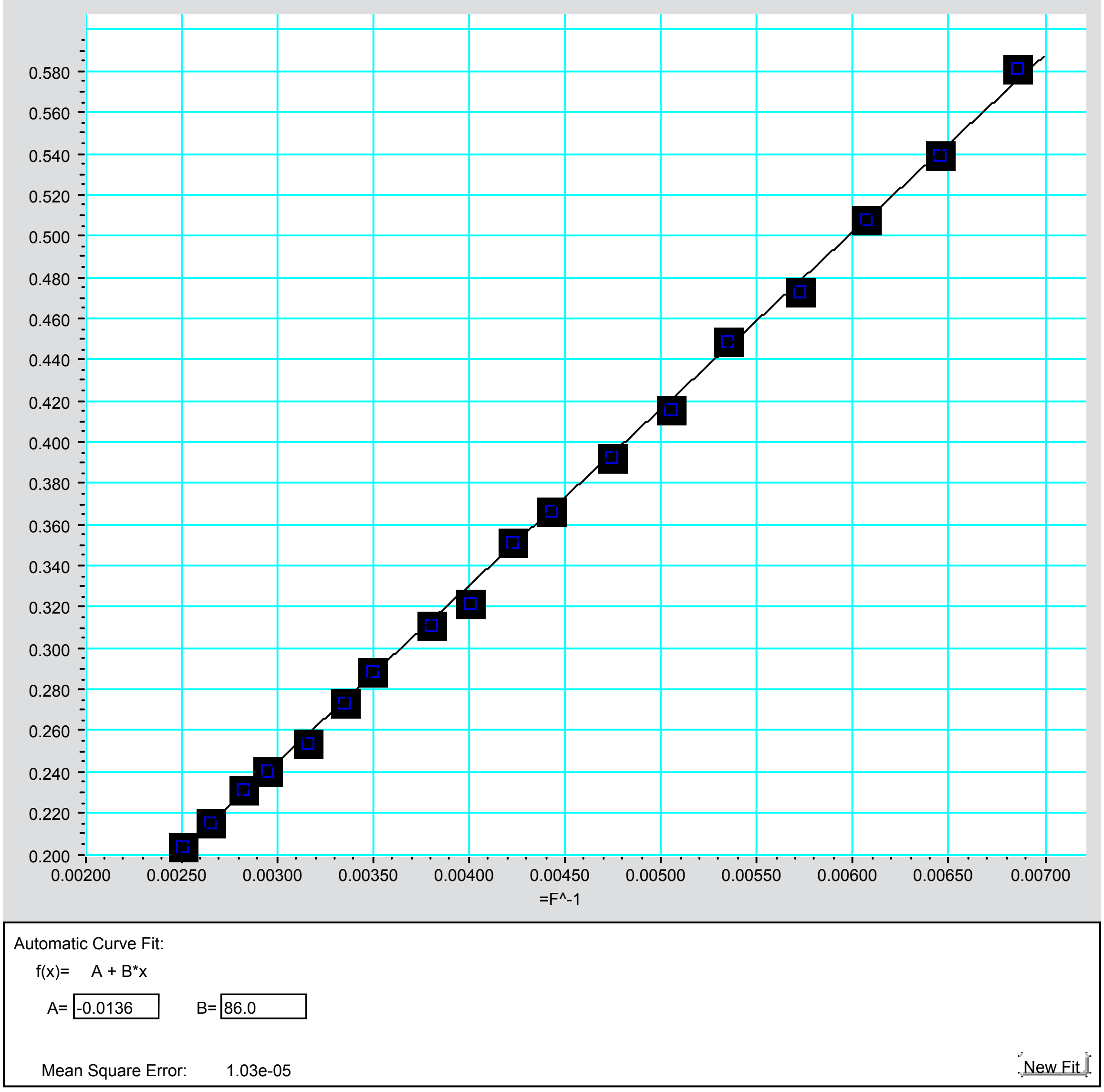
The equivalent length, L_e, of an actual tube of measured length L in a flute vibrating at a frequency f=c/2 L_e can be calculated if the embouchure hole is also accounted for. Empirical measurements over a wide range of frequencies have shown the embouchure hole of a flute adds about ΔL_E=5 cm of equivalent length to a tube [8, 9]

[8] Neverdeen CJ 1973 Blown, passive and calculated resonance frequencies of the flute *Acustica* **28** p 16
[9] Forester CML 2007 Musical Mathematics: A practice in the mathematics of tuning instruments and analyzing scales-Simple Flutes: Equations for the Placement of Tone Holes on Concert Flutes and Simple Flutes http://www.chrysalis-foundation.org/flute_tone_holes.htm Chapter 8: Section 4

5.4 Recognising a scientific report

Resource 5

The average end-correction for the clarinet data in Table 2 was 1.37 +/- 0.35 cm. The best agreement with this value came from combining the previous two expressions, which gives $\Delta L = c/4f - L$ or $L=(c/4)*(1/f) - \Delta L$, the equation of a line with slope c/4 and a y-intercept equal to the negative of the end-correction. A linear-fit to a plot of L vs. 1/f for the clarinet data from Table 2 is shown in Fig. 6. c/4=86 gives a speed of sound of 344 m/s and the y-intercept gives an end-correction of 1.36 cm.



Automatic Curve Fit:
f(x)= A + B*x
A= -0.0136 B= 86.0
Mean Square Error: 1.03e-05

Figure 6-Plot of air column length vs. the inverse of playing frequencies for a clarinet with a linear fit.[4]

5.4 Recognising a scientific report

Resource 5

Table 3 compares the equivalent lengths of the flute tubes of actual lengths, L, vibrating at a frequencies f, calculated by L_e =c/2f to effective lengths calculated from $L_e = L + \Delta L_H + \Delta L_E$. For each tube of successively shorter length ΔL_H is calculated from equation (1) for the first open hole, the one furthest “up” the tube or closest to the embouchure hole. The dimensions of the flute and tone holes are 2a=1.87 cm, 2b=1.61 cm, t=0.43 cm and 2s, which can vary somewhat from hole to hole, is taken for each hole as the length of a tube segment that extends the sum of the distances from the center of a tone-hole halfway to the next tone hole in either direction.[5] See Table 3 for results.

5- Using this average tone hole spacing is considered permissible [3, p 1598]

Note the large error in the shortest tube length. The tone hole for this length is smaller than the others. In general the smaller the tone hole, the further down the tube the antinode is found. [5, p 170; 10] This assertion is verified by use of equation (1) as the value of ΔL_H for this hole is larger than for the others, but this resulted in the largest discrepancy in calculated equivalent lengths.

[10] Benade AH 1960 *The Physics of Woodwinds* Scientific American -*The Physics of Music* (San Francisco: W H Freeman and Company) p 40

When all the tone-holes are closed ΔL_H is replaced with the standard end-correction of 0.6a. and a correction for all the closed tone holes in the tube. Since they add volume to a tube [7, p 448], closed tone-holes tend increase the effective length of a tube by and amount based on their dimensions. Closed holes increase the effective length of their segment of a tube by an amount $\Delta L_C = 2s(E-1)$, where (E -1) is a percentage increase, usually between 2 and 5% [7, p449] in the segment of the tube 2s, which is equivalent to the tone-hole spacing. E is a numerical factor;

$$E = \left[1 + \frac{1}{2}\left(\frac{b}{a}\right)\left(\frac{t}{2s}\right)^2\right] \qquad (2)$$

ΔL_C was calculated for each tone-hole in the “lattice” using the lengths of each segment and Equation (2). The sum of all the closed tone-hole corrections [3, p 1597] and 0.6a for the correction at the end of the tube was used to determine the equivalent length of the flute with all the tone-holes closed, the longest length, playing musical note C-4. Note that equation (2) was only used when all the tone-holes were closed because equation (1) calculates the position of the anti node, how far beyond the center of the tone hole that it is located, not just an amount to add along with the correction for the embouchure-hole to the measured length of the tube. [9, Chapter 8: Section 5] It should also be noted that the above mentioned smallest tone hole and two others present further up the tube have values very close to E =1 from equation (2) so therefore do not contribute significantly to the equivalent length of a flue when all the tone-holes are closed.

5.4 Recognising a scientific report

Resource 5

Musical Note	f Hz	L_e-L (table 2) m	ΔL[6] m	L + ΔL m	L_e (from f) m	% difference
C-4	260	0.062	0.076	0.676	0.662	2.25
C#-4	275	0.075	0.064	0.614	0.625	-1.79
D4	291	0.067	0.064	0.588	0.591	-0.47
D#-4	310	0.065	0.065	0.555	0.555	-0.005
E4	328	0.067	0.065	0.522	0.524	-0.41
F4	348	0.066	0.065	0.493	0.494	-0.27
F#-4	369	0.065	0.065	0.466	0.466	-0.12
G-4	392	0.063	0.064	0.440	0.439	0.34
G#-4	415	0.064	0.064	0.414	0.414	-0.06
A-4	441	0.063	0.064	0.391	0.39	0.27
A#-4	472	0.060	0.064	0.368	0.364	0.94
B-4	493	0.065	0.064	0.348	0.349	-0.38
C-5	529	0.061	0.063	0.327	0.325	0.66
C#-5	573	0.067	0.087	0.320	0.300	6.67

Table 3-Comparison between equivalent lengths for a flute's air column calculated from the playing frequencies to those calculated with corrections for the embouchure hole and tone holes.

6-For all air column lengths other than that of C-4, ΔL is the sum of the embouchure and tone hole correction. For the length at note C-4, the entire length of the instrument, ΔL is the sum of the embouchure hole correction, the sum of all closed tone hole corrections and the standard 0.6a end correction.

More on Clarinets

Comparisons like those shown Table 3 are more difficult for a clarinet than a flute because the dimensions of the clarinet tone-holes are more difficult to determine without removing the keys. This is of course possible, but once removed they are difficult to put back on correctly. This should be left to experts in the playing and/or maintenance of clarinets.[7]

7-The author speaks on this point from unfortunate experience.

5.4 Recognising a scientific report

Resource 5

Note in Table 2, that the end-corrections for a clarinet are smaller than those for the flute. This is because the correction for the clarinet mouthpiece, where the reed is attached to the tube, at the closed end, is much less than the correction for the flute embouchure-hole. The mouthpiece cavity adds an equivalent length to the cylinder to which it is attached equal to that of a cylinder of the same diameter, having the same volume as the mouthpiece [11; 5, p 174] and furthermore the volume is not the actual volume of the mouthpiece cavity, it is an equivalent volume that is very difficult to determine, however experimentation has shown that for frequencies below 700 Hz the equivalent volume of a clarinet mouthpiece and reed combination is about $V'=13.25\ cm^2$ [7, p 472] a small amount more than a measured value of about $V=11\ cm^2$ for the clarinet used. The volume of the mouthpiece can be measured by taping the hole that is usually covered by the reed shut and filling the mouthpiece with water. The difference in the mass in grams between the mouthpiece filled with water and empty will be numerically equal to the mouthpiece volume, V, in cubic centimeters. Since the diameter of the mouthpiece decreases in direction of the actual end of the tube, the equivalent length will actually be *less* than the measured length of the mouthpiece by a small amount, therefore subtracting equivalent length from that provided by tone-holes resulting in the observed overall smaller end-corrections.

[11] Benade AH 1959 On Woodwind Instrument Bores *The Journal of the American Acoustical Society* pp 140-141

Several of the tone-holes on a clarinet are not covered with keys; the effective length of air columns ending with these holes can be determined by adding a correction from equation (1) and a correction for the mouthpiece to the measured length of the air column. The effective volume of the mouthpiece along with the radius of the clarinet tubing to which it is attached, b can be used to calculated the mouthpiece effective length, $\Delta L_M = V'/\pi b^2$. This length can be added to the length of the tube after the actual length of the mouthpiece is subtracted.

For example, the first uncovered clarinet tone-hole (G-3, see Table 4) was a measured distance of 41.6 cm from the closed end of the tube. The actual length of the mouthpiece portion of the tube of 9 cm was subtracted and $\Delta L_M = 8.36$ cm, calculated from the equivalent volume $V'=13.25\ cm^3$ and tube radius $b=0.71$ cm was added along with a tone-hole correction of $\Delta L_H = 2.2$ cm calculated with equation (1). Note that the equivalent length for the mouthpiece is actually negative. This gave an equivalent cylinder length of 43.2 cm compared to 43.4 cm calculated from the playing frequency of 198 Hz, a difference of about 0.6 %. See Table 4 for results for other uncovered clarinet tone holes. The differences between effective lengths are similar in all cases resulting in higher percentage errors for the shorter air column lengths.

5.4 Recognising a scientific report

Resource 5

Musical Note	f Hz	L_m m	ΔL_H m	L_e m	L_e (from f) m	% difference
G-3	198	0.416	0.022	0.432	0.434	-0.607
G#-3	211	0.393	0.0283	0.415	0.408	1.83
A-3	226	0.367	0.0283	0.389	0.381	2.24
C-4	263	0.311	0.0246	0.329	0.327	0.700
C#-4	286	0.289	0.0287	0.311	0.301	3.55
D#-4	317	0.254	0.0409	0.289	0.271	6.40

Table 4 -Comparison between equivalent lengths for a clarinet's air column calculated from the playing frequencies to those calculated with corrections for the mouthpiece and tone holes.

Conclusion

These experiments or a combination there of could be useful for students of various physics courses. Graphically verifying that the air columns in flutes and clarinets behave similarly to simple open and closed resonance tubes can be completed in a laboratory period and could be useful even in a general introductory physics course showing real-world examples of standing waves in air columns. The former experiments as well as those comparing the musical pitches and intervals produced by the instruments to those that are expected and those comparing actual and equivalent lengths may be more appropriate for a musical acoustics course, but can also be easily completed in a single laboratory period.

If the computer hardware and software necessary to measure the playing frequencies produced by the instruments are not available, or time does not allow it, an alternative is to use an electronic tuner to tune the instruments. If not available in a student physics laboratory, one could be borrowed from the music department. The experiments can then be carried out with the assumption that the playing frequencies of the instruments are those of the musical pitches when the instruments are played precisely in tune. [8] The more in-depth investigations involving tone holes may only be appropriate for more advanced laboratory students or perhaps as individual or independent study projects.

8-[1, p 153] has a table of the frequencies of the notes in the tempered scale.

5.4 Recognising a scientific report

Resource 5

Acknowledgements

I thank professional flute and clarinet player, Jan LoPresto, student flute player Sarah LoPresto and student clarinet player Emily LoPresto for providing data for these investigations as well as several former students from “Sound and Light in Fine-Arts” at HFCC for the same and also for actually performing the experiments. I also thank Joe Wolfe of the Musical Acoustics research-group at the University of New South Wales for permission to use Figures 1 and 2 from their website and the anonymous *Physics Education* reviewer for his/her comments. Finally I thank Dr. Charles Jacobs, Associate Dean of Science at HFCC, for his support of the above-mentioned course and reassembly of a clarinet dismantled by the author and some of his students.