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Using a scanning electron microscope in physics STEM education

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Abstract

This paper describes the use of a tabletop electron microscope in teaching college level physics. The workings and use of an electron microscope encompass many aspects of science, technology, engineering and mathematics (STEM). A sequence of activities was constructed to compliment the instructional material in the physics course of the University of Queensland Foundation Year. A Hitachi TM4000 scanning electron microscope was used to obtain images to measure the track spacing of CD, DVD and Blu-ray discs. The nominal track spacings are 1.6 μm, 740 nm and 320 nm for CD, DVD and Blu-ray discs, respectively, comparable to the wavelength of visible light and therefore give rise to visible diffraction effects. The track spacing for a CD and DVD was measured using red, green and blue laser pointers with an accuracy well under 10%. The experiments described in this paper demonstrate how a scientific instrument such as a scanning electron microscope can be used to integrate the teaching of different STEM areas.

S Supplementary material for this article is available online

Introduction

A central idea behind science, technology, engineering and mathematics (STEM) education is the integration of STEM subjects in a syllabus. This paper describes the use of a scanning electron microscope (SEM) in STEM teaching. A Hitachi TM4000 tabletop SEM was used in teaching physics, chemistry and biology. The SEM was temporarily installed at IES College in Brisbane, which teaches the foundation year for the University of Queensland to international students. The SEM was used over the course of a month to compliment the teaching of physics to a group of students in the high achievers STEM program (https://iescollege.com/stem/program-info.html).

An Australian company, NewSpec, has partnered with Hitachi High Technologies and the University of Queensland (www.uq.edu.au) in the production of a program called 'Inspire STEM Education'. Schools and colleges are able to hire a TM4000 a week at a time. (www.inspirestemeducation.com.au/). Between loans, the SEM is kept at the Centre for Microscopy and Microanalysis (https://cmm.centre.uq.edu.au/) at the University of Queensland.

Figure 1. STEM students using a Hitachi TM4000 electron microscope at IES. The SEM is the beige box in the centre of the field of view.

The TM4000 is shown in figure 1, which gives some idea of the small size of the unit. Prior to use of the SEM at IES, the inspire STEM education team provided basic training to teachers on how to use the TM4000.

This paper describes how the SEM was integrated into teaching a section of the STEM physics course of the University of Queensland foundation year. The material presented in this paper would also be suitable for inclusion in the high school physics curriculum.

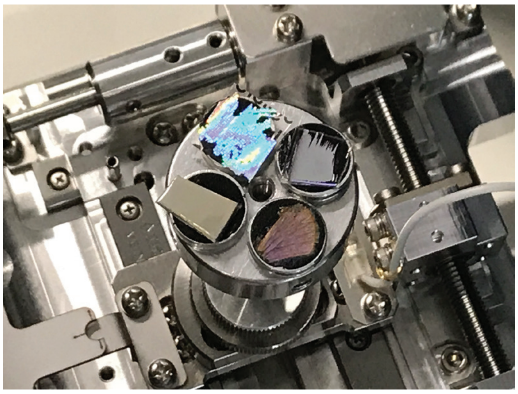

Figure 2. Sample of a CD, DVD, Blu-ray disc and butterfly wing on the sample table of the Hitachi TM4000 SEM. Top: CD, left: Blu-ray, Right: DVD, bottom: butterfly wing (not discussed in this paper). Note the structural colour of the CD.

Using a SEM to teach physics

The SEM is an instrument that encompasses a range of academic disciplines, for example, physics, chemistry, biology, engineering and mathematics. At IES, the TM4000 was used to teach physics, chemistry and biology in the STEM High Achievers program. This paper focuses on the use of the SEM in teaching the basic principles of diffraction, electromagnetism, quantum mechanics and wave-particle duality.

All these concepts feature in the operation of a SEM. The rationale behind an electron microscope is that electrons have a de Broglie wavelength much smaller than visible light and are therefore able to resolve structures much smaller than can be seen in a conventional light microscope. The teaching of the operation of an electron microscope can be supported by articles describing the operation, for example Ponting (2004). A Crookes tube is a helpful device to demonstrate the effect of magnetic and electric fields on electrons, principles essential to the operation of an electron microscope.

Scanning samples of CD, DVD and Blu-ray discs

The STEM physics students prepared and scanned samples of a CD, DVD and Blu-ray disc. Scissors were used to cut samples from unwanted discs and a scalpel to dissect the reflective layer

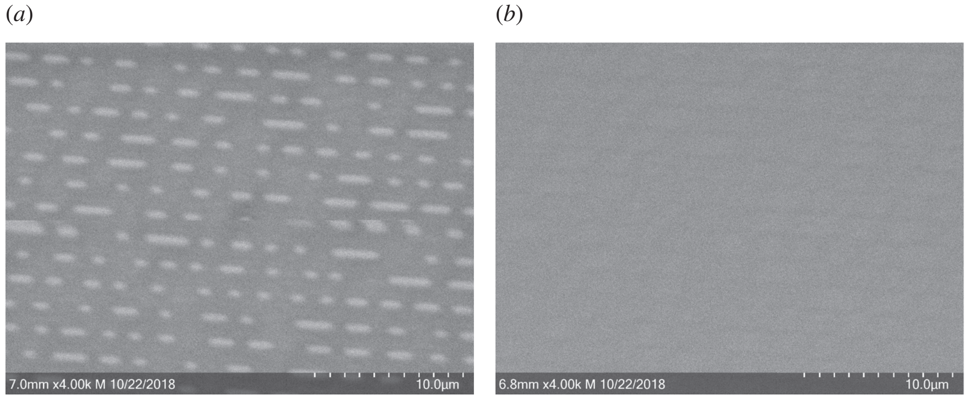

Figure 3. (a) CD magnified 4000 times imaged with 15 keV electrons. (b) CD magnified 4000 times imaged with 5 keV electrons.

so it could be directly exposed to the scanning electrons. Each sample was held in place on the sample holder by an adhesive disc as shown in figure 2.

SEMs and wave-particle duality

A key part of the foundation year physics course is quantum mechanics, an essential feature of which is wave-particle duality, which states that photons can behave like particles and particles like waves. In the class, students calculate the de Broglie wavelength of electrons with an energy similar to electrons in an SEM, for example 15 keV. The students then get to see 15 keV electrons in use, which takes wave-particle duality from abstract to concrete. The wavelength (λ) of an electron, known as the de Broglie wavelength, is given by

$$\lambda = \frac{h}{mv}.$$

Where h is the Planck constant (6.626×10^{-34} kg m^2 s^{-1}), m the rest mass of the electron (9.1×10^{-31} kg) and v the velocity of the electron. Electron kinetic energy (KE) is specified in electron volts (eV). By definition, an electron that is accelerated through a potential difference of 1 V gains (or loses) 1 eV. A value is converted from eV to J by multiplying by 1.6×10^{-19}. The KE can be used to calculate the electron velocity and hence the de Broglie wavelength,

$$v = \sqrt{\frac{2\text{KE}}{m}}.$$

The de Broglie wavelength of 15 keV electrons is found by first calculating the velocity.

$$v = \sqrt{\frac{2 \times 15 \times 10^3 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}}$$
$$= 7.26 \times 10^7 \text{ ms}^{-1}.$$

This is 24% of the speed of light and the Lorentz factor is 1.0301, not large enough to have a significant effect on the de Broglie wavelength. However, this point is a useful connection with relativity. It can be mentioned that in high energy electron devices, such as linear accelerators used to treat cancer, electrons are accelerated to very close to the speed of light and therefore relativity must be taken into account when calculating electron energy. If relativity were not taken into account, patients would receive a radiation dose different from that prescribed.

The de Broglie wavelength is

$$\lambda = \frac{6.6 \times 10^{-34}}{9.1 \times 10^{-31} \times 7.26 \times 10^7}$$
$$= 9.99 \times 10^{-12} \cong 10^{-11} \text{ m}.$$

This is smaller than the hydrogen atom. In practice, the resolution of an electron microscope is much larger due to imperfections in the magnetic optics etc.

To complement the theory presented in the lessons, a CD sample was scanned using 15 keV and 5 keV electrons to look directly at the influence of the de Broglie wavelength on image resolution, as seen in figure 3. Clearly, electron energy has a profound influence on image resolution.

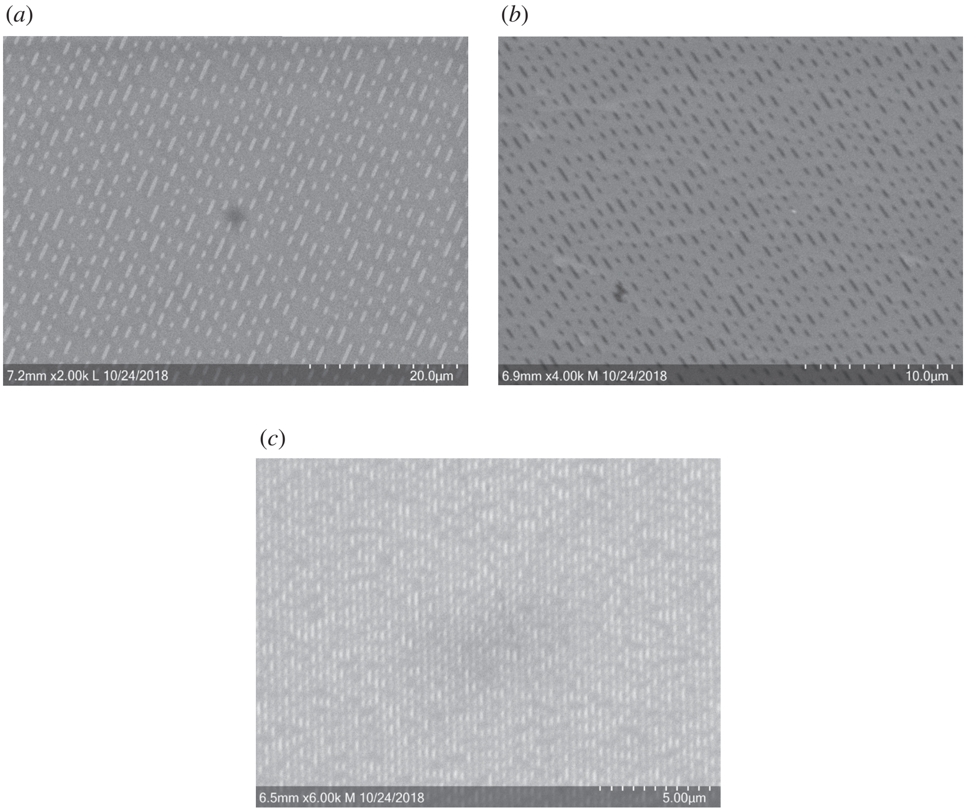

Figure 4. (a) CD magnified 2000 times. (b) DVD magnified 4000 times. (c) Blu-ray magnified 6000 times.

Measuring disc track spacing

To measure the track spacing, the SEM images were loaded into ImageJ, a free image analysis program that can be downloaded from https://imagej.nih.gov/ij/. The program is available for Mac, Windows and Linux computers. The STEM students downloaded ImageJ onto their laptops. The TM4000 produces TIFF images, which can be loaded directly into ImageJ with no conversion required.

Figure 4 shows the three images used to measure track spacing. Each image was loaded into ImageJ and the line tool used to mark the scale at the bottom right of each image. The Analyze/Set Scale option was used to set the length of the scale line in pixels to the appropriate number of μm. Five measurements were made for each image—one in the centre and one at each corner. In each case, a line was drawn at right angles to the track direction between 10 pits. To obtain the mean distance, the total distance was divided by 10. Note that the scale at the bottom right is about the same horizontal length for each image and so the three images together show the relative pit density of each disc type. The spacing measurements are shown in table 1.

Table 1. Track spacing measurements.

Measurement	CD ×2k	DVD ×4k	Blu-ray ×6k
1	1514	736.3	319.3
2	1666.4	741.7	316.6
3	1514.6	743.2	315.1
4	1501.4	737.6	316.5
5	1496.5	736.5	318.3
Mean	1538.6	739.1	317.2
sd	71.9	3.2	1.6
Nominal (nm)	16 000	740	320
% difference	−3.84	−0.13	−0.89

The electron microscope measurements are accurate to less than 4% for the CD and less than 1% for the DVD and Blu-ray discs.

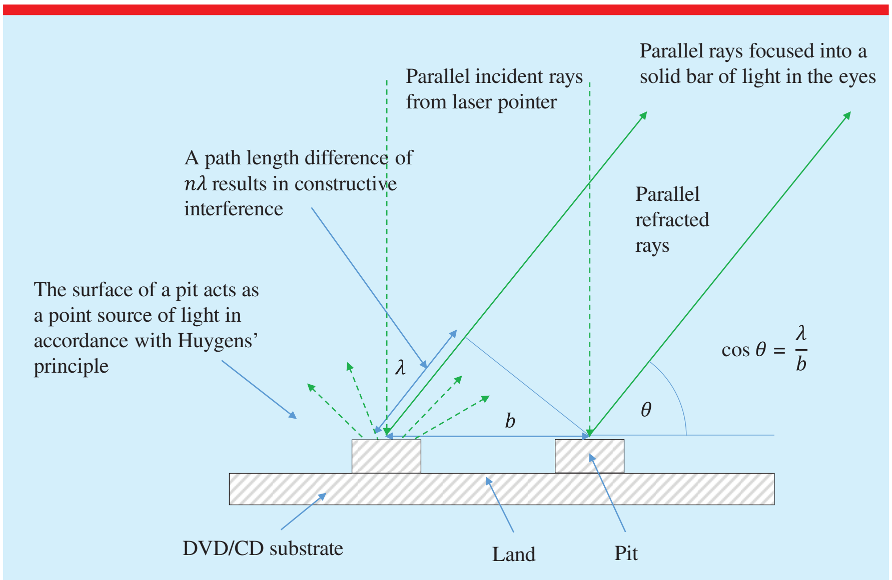

Figure 5. A laser beam shining on the surface of a CD or DVD is reflected from the pits in all directions in accordance with Huygens' principle. At certain angles, rays of a particular wavelength are parallel and so interfere constructively.

Using laser pointers to measure track separation

Laser pointers were used to measure the track spacing and crosscheck the EM measurements. Using multiple techniques to make a measurement increases confidence that a particular measurement is correct. The physical principle is summarised in figure 5. Laser light is reflected in multiple directions from the pits. (N.B. the pits are bumps on the reflective side of the disc). Constructive interference occurs at an angle where the path difference is an integral number of wavelengths.

Inside a CD, DVD or Blu-ray reader the laser beam is confined to a region only slightly larger than the pit, so reflections from adjacent pits do not confuse the signal. In an 'open disc' laser experiment, such as the one discussed in this paper, the beam is much wider than the pit separation, and so multiple pits acts as a source in accordance with Huygens'principle. Close to the laser pointer, the beam is at least 1 mm wide, so when the surface of a CD is illuminated, the laser beam is diffracted by about 600 tracks.

This particular exercise also affords the opportunity to discuss how disc players work (Cope 1993), and origin of the iridescence (Cornwall 1993), which brings in the engineering and technology component of STEM.

A schematic diagram of the experimental setup is shown in figure 6.

The angle (θ) is used to calculate the track spacing (b) using,

$$b = \frac{\lambda}{\sin\left[\tan^{-1}(x/y)\right]}.$$

The laser pointers used for this project had a wavelength of 405 nm for blue, 532 nm for green and 650 nm for red, with an uncertainty of $\pm$ 10 nm in each case. Each laser was attached to a retort stand using a bulldog clip and oriented vertically downwards, as shown in figure 7. The bulldog clip was used to keep the on button of the laser pressed during the time it took to take a photo of the diffracted laser dots. A black felt tip pen was used to mark a dot on the discs 3 cm from the edge of the CD and DVD. The discs were abutted against the wall, which was assumed to be vertical. A rule was attached to the wall using Blu-Tack. If there is doubt about the verticality of a wall, a bubble level can be used to check the wall.

A smartphone was used to photograph the diffracted dots for the three lasers for the CD and DVD. The photo for CD blue laser diffraction is shown in figure 8. The ImageJ line tool was used

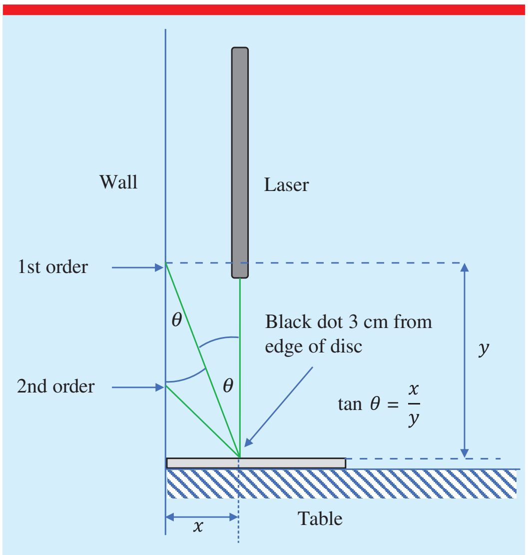

Figure 6. Schematic diagram of the set up to measure disc track spacing using laser diffraction. The laser beam is projected vertically downwards and the height of the diffracted dots on the wall above the disc measured.

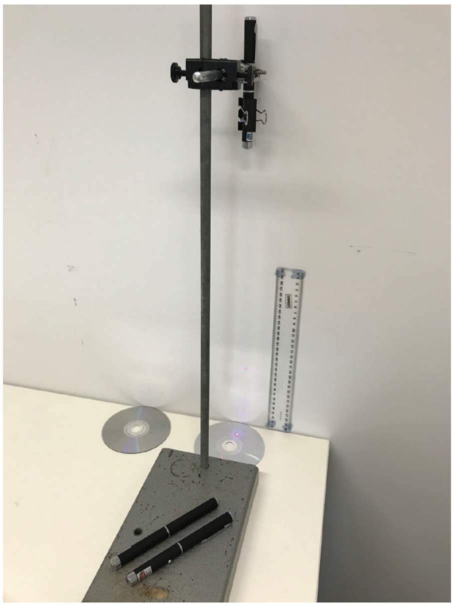

Figure 7. Overview of the experimental setup. The laser is oriented vertically using a retort stand clamp. A bulldog clip was used to keep the laser on while the dots were being photographed.

to measure the vertical distance of each diffracted laser dot above the level of the disc. The height in pixels was recorded and in ImageJ a line drawn

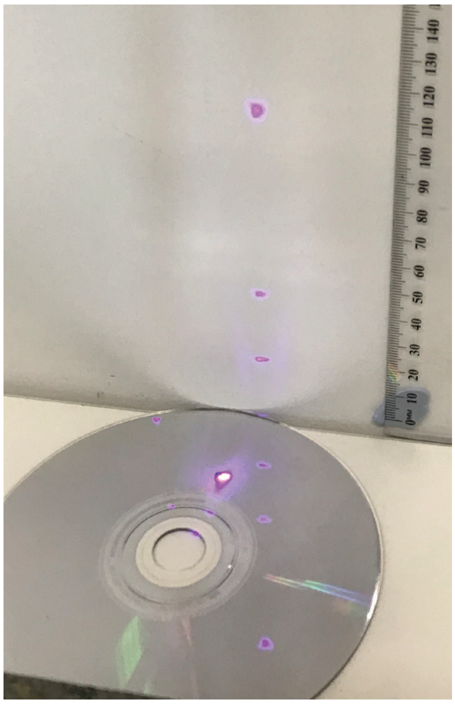

Figure 8. Diffraction dots produced by a blue laser (405 nm) shining onto a CD. Three diffraction orders are seen on the wall. The three sets of diffraction dots are also seen reflected in the surface of the CD.

on the rule the same length in pixels. This was surprisingly easy, taking just a few iterations. Distances were measured to the nearest 0.5 mm.

A key point to impress on students is that diffraction used to measure microscopic spacings makes use of similar triangles, a direct link between physics and maths. The angle of a macroscopic triangle is measured and applied to a microscopic triangle. In the class, x-ray and neutron diffraction can be referred to as practical examples of diffraction.

The experiment described in this paper enables students to see second and third order diffraction with their own eyes, normally only ever seen through the eyepiece of a spectrometer. In fact, many students may find the experience of seeing diffracted laser spots perplexing—how can a laser beam pointing at right angles to a smooth, reflective surface reflect off axis? This appears to be a clear violation of the law of reflection, i.e. that the reflection angle is equal to the incident angle with respect to the normal.

Table 2. Track spacing vales obtained from laser diffraction.

	Dot height (cm)	Angle (rad)	Angle (degrees)	Order	Spacing (μm)	% difference from nominal
CD blue	11.1	1.31	74.9	1	1.552	−3.0
	4.7	1.00	57.2	2	1.494	−6.6
	2.1	0.61	35.0	3	1.483	−7.3
CD green	8.0	1.21	69.5	1	1.517	−5.2
	3.0	0.79	45.0	2	1.505	−6.0
CD red	6.05	1.11	63.6	1	1.463	−8.6
	1.75	0.53	30.3	2	1.505	−5.9
DVD blue	4.7	1.00	57.4	1	0.753	1.7
DVD green	2.85	0.76	43.5	1	0.734	−0.8
DVD red	1.5	0.46	26.6	1	0.727	−1.8

Table 3. Propagated errors for track spacing measurements.

	Measured	Propagated error	Difference	% difference
CD blue	1.552	1.656	0.103	10.3
	1.494	1.593	0.099	9.9
	1.483	1.563	0.080	8.0
CD green	1.517	1.610	0.093	9.3
	1.505	1.587	0.082	8.2
CD red	1.463	1.547	0.084	8.4
	1.505	1.566	0.061	6.1
DVD blue	0.753	0.803	0.050	5.0
DVD green	0.734	0.773	0.039	3.9
DVD red	0.727	0.754	0.027	2.7

Students will notice that the laser diffraction experiment does not work with Blu-ray discs. On reflection, they will realise the reason is because Blu-ray track spacing is smaller than the wavelength of blue light. This will teach students that there are mathematical reasons for limitations in the physical world.

The Bragg equation is,

$$n\lambda = b\sin\theta$$

$$\sin\theta = \frac{n\lambda}{b}.$$

$\sin\theta$ can only vary between 0 and 1, therefore $n\lambda \leqslant b$. The track spacing of a Blu-ray disc is 320 nm, less than the wavelengths of the red, green and blue lasers. For the CD, three diffraction orders are seen with the blue laser, and two orders with the green and red lasers. For the DVD, only first order is seen with the three lasers.

This is a powerful way of teaching students the connection between physics and mathematics. The Bragg equation gives the condition for constructive interference. The sine of any angle is always between 0 and 1, which means interference is impossible if the wavelength is greater than the grating spacing. It is a good idea to include a Blu-ray disc with the CD and DVD discs and let students discover that no diffraction dots are seen with any of the lasers and get them to think about why.

This experiment is also good at getting students to think laterally. Students studying high school, college, or first year university physics will be familiar with diffraction gratings. However, students will not be so familiar with the concept of a reflection grating, or *echelle* grating. Echelle is the French word for ladder. Echelle gratings are used in astronomical spectrometers, for example, a high-resolution echelle grating spectrometer is available on the Keck Telescopes in Hawaii www2.keck.hawaii.edu/inst/hires/. In an echelle grating, narrow reflective ridges act as Huygens sources just as effectively as the gap in a diffraction grating. Echelle diffraction gratings are in essence high tech versions of a CD or DVD.

Table 2 shows the CD and DVD track spacing obtained with the red, green and blue lasers.

The results are surprisingly accurate considering the laser dots were photographed next to a rule stuck on a wall. All of the CD values are within 10% of the nominal track spacing and DVD values less than 2%. The error could probably be reduced by sticking graph paper on the wall to read dot height directly.

Propagated errors

If desired, a more vigorous error analysis can be performed. This can be done by adding measurement errors to the spacing formula,

$$b = \frac{\lambda + \Delta\lambda}{\sin\left[\tan^{-1}\left((x+\Delta x)\,/\,(y-\Delta y)\right)\right]}.$$

With $\Delta\lambda = 10\,\mathrm{nm}$, $\Delta x = 1\,\mathrm{mm}$, $\Delta y = 1\,\mathrm{mm}$, the propagated errors were obtained as shown in table 3, comparable to the difference between measured and nominal track spacings.

Discussion

The challenge of STEM is to integrate subjects traditionally taught separately. The SEM is a scientific instrument that appears to be ideally suited to integrating the teaching of STEM subjects. At IES, the SEM was used to compliment the teaching of a range of topics including Huygens' principle, diffraction, constructive and destructive wave interference, wave-particle duality and the de Broglie wavelength of electrons, magnetic and electric fields, relativity (science), operation of the SEM and disc players (engineering), use of image analysis software (technology), trigonometry and similar triangles, mean and standard deviation, least squares fitting and the correlation coefficient (mathematics).

The laser part of the experiment could be used without access to a SEM. Coloured lasers and CDs, DVDs are readily available and therefore the equipment costs very low. The CD, DVD and Blu-ray SEM images have been included as supplementary material (stacks.iop.org/PhysEd/54/055018/mmedia) to be freely used for teaching.

The use of the SEM at IES, enabled students to link classroom theory with practical applications, in-context learning. Tytler (2007) emphasises the need for a practical component in the high school science curriculum to encourage and maintain interest and engagement in science.

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