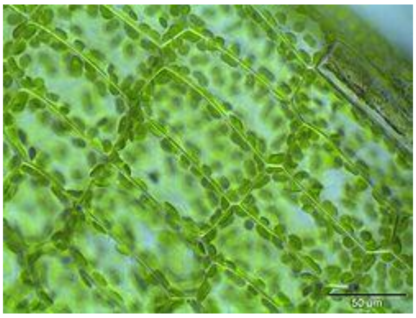
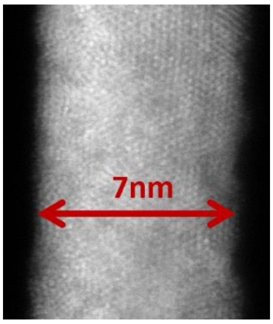
2018





Measuring and making on the nanoscale [Microscopy, Nanoscience and Physics]

Student:

Tutor: Pierce Maguire, BA(Mod.), Ph.D.

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Measuring and making on the nanoscale

Course Rationale

Length scales and orders of magnitude represent a challenging but vital step in the education of almost any scientist or engineer. From galaxies down to elemental particles, a thorough understanding of orders of magnitude underpins all physical sciences. To perform an initial experiment in say defect engineering, I need to know to the nearest ten how many ions I need to hit my device with to get the desired number of defects. A good guess comes from knowing the size of my device.

My PhD research covers a few slices on the spectrum of size. I will deal with things that can be barely seen with the naked eye right down to atoms, electrons and ions. This is information that nearly every chemist, biologist, physicist and many engineers deal with all the time but need to work at to really understand well.

The first tutorials will introduce scale and orders of magnitude in size, electromagnetic radiation and energy. We will investigate how to measure and make objects and devices on these length scales. In this course, more than anything I want to instil an interest in nanoscience, some of its uses and methods and most of all its applications on different length scales.

Final Assignment

Small solutions to a big problem. A 2000-word essay covering three key points:

A human problem which could be solved or mitigated using nanotechnology. I want you to investigate nanotechnology-based solutions to this problem and argue for (or against if you like!) the proposed solutions. Some ideas are

- Environment/pollution/climate change/energy
- Human health
- Screen Technology
- Sports Technology

Some of the fabrication methods that would be used to make the devices from starting materials.

Microscopy or other methods that might be used in investigating the materials and the performance of the devices used.

Feel free to be creative or stick to conventional thinking. Either is perfectly fine here.

Mark Scheme

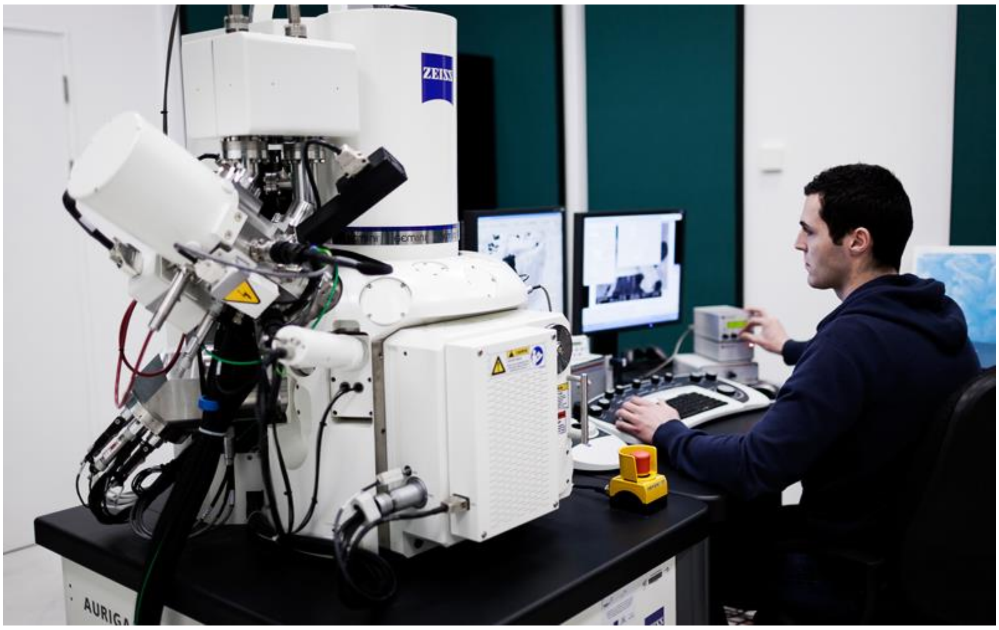
The marks will all be awarded for the final assignment. Addressing the three above points thoroughly will gather up to 25% of the marks each. Getting top marks will require demonstrating a reasonable amount of literature review on each of the points and the use of references to back claims. The remaining 25% will be awarded for clear writing, logical argument and the conclusion. Late submission will be punished by 2 marks per day. Plagiarism will be punished according to severity.

Grade	Percentage	Description
First class	≥70%	Making a strong and well-informed argument in favour/against a nanotechnology as a solution to a well-researched problem
Upper Second Class	60-69%	Making a solid and informed argument in favour/against a nanotechnology as a solution to a researched problem
Lower Second Class	50-59%	Making a supported argument in favour/against a nanotechnology as a solution to a clear problem
Third Class	40-49%	Making an unsupported argument in favour/against a nanotechnology as a solution to an unclear problem

Glossary of Keywords

Word	Definition
Orders of Magnitude	
Scales	
Electron	
Microscope	
Optical Microscope	
Scanning Probe Microscope	
Electron Microscope	
Resolution	
Macro	
Nano	
Micro	
Dimensions	
Experiment	
Theory	
Hypothesis	

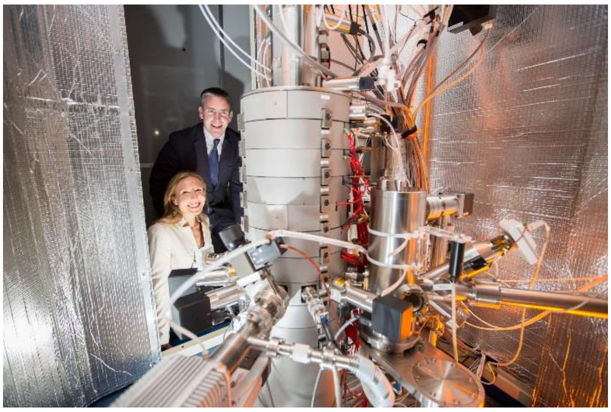
Tutorial 1 – Tour of the Advanced Microscopy Laboratory, TCD



What is the Purpose of Tutorial 1?

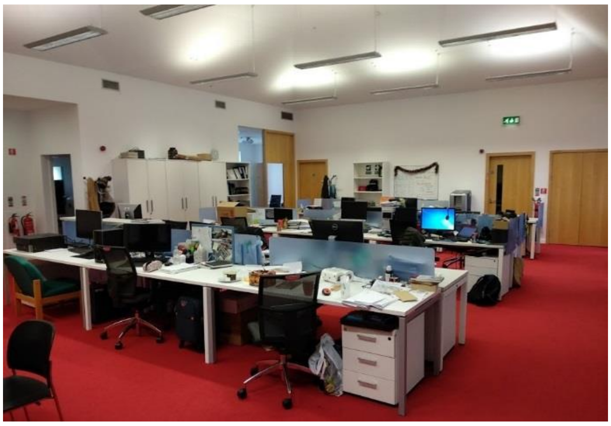
- Convey the type of environment that scientists work in, showing lab and office space, technical and academic staff etc.
- Show what high energy electron/ion microscopes look like and what it is like to operate them.

There is a variety of rooms: some of which we don't usually go into because the equipment is so sensitive.



There are some rooms, we have to go into sometimes so we can do our experimental work.

Then there is office space where we do most of our data analysis and writing of papers and reports.



Homework 1 – Baseline Test: Understanding the Language of Nanoscience

The homework assignment for the first tutorial is a baseline test to see your initial level of attainment in this subject area. The assignment will test for some of or all the subject specific skills that are required later in the final assignment. However, it is shorter than the final assignment and will be an introduction to the subject as well as a challenge!

Do not worry too much about doing 'well' or 'badly' on the baseline test, it takes into account the fact that you may not be familiar with the subject area. It is designed to help you and your PhD tutor identify where you are at the start of the programme and to help you measure your progress along the way.

- **Doing your own research, fill in the definitions of the course keywords. Record your references (see the referencing guide in this handbook).**

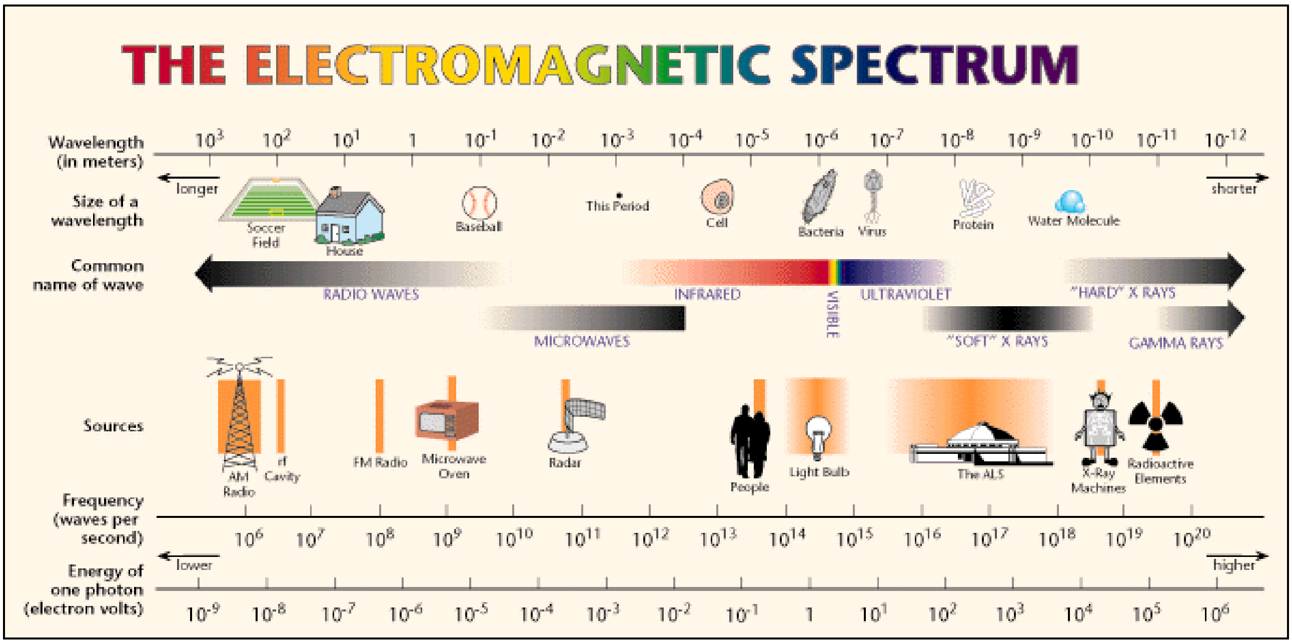
Recommended Further Exploring:
Prof. Valeria Nicolosi, TCD

https://www.youtube.com/watch?v=w0mdUKv90OA

Dr. Danny Fox, TCD

https://www.youtube.com/watch?v=SGRp87FuMls

Tutorial 2 – Scale in Space and Energy



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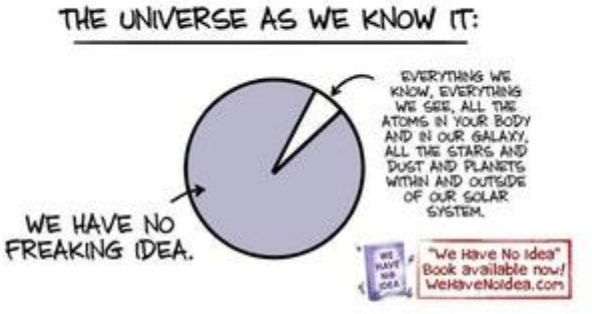
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

*	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
**	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

What is the Purpose of Tutorial 2?

- The purpose of tutorial 2 is to provide a sense of the relative sizes of things -both physical lengths and energies. It is only a few centuries since we invented the telescope and the microscope and we still have an enormous amount of research to do understand the things that we can see with them.

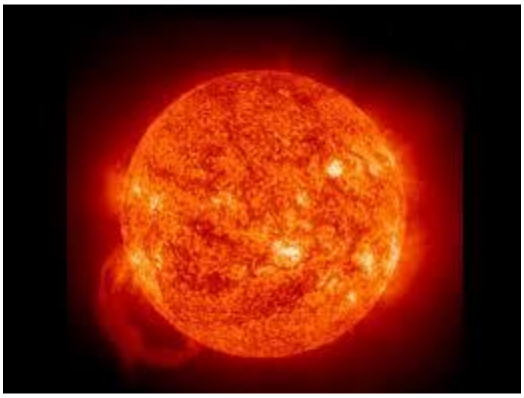


- The first part will focus on scales in space, from galaxies at the large end to electrons and other particles at the other, we will cover a vast range of size and objects
- The second part will (much more briefly) build on the first by covering energy and the way it too changes on different scales.

Very large things
(Below left) Galaxies (radius = 500,000,000,000,000,000 km)

(Below right) Pillars of Creation – Clouds of gas and dust that give birth to stars

Large things



(Left) The Sun (radius = 695,700 km)

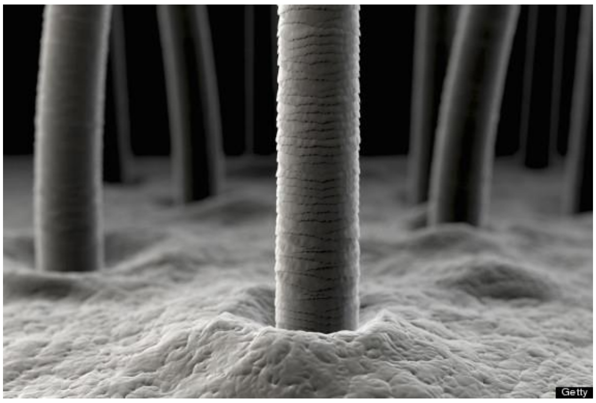
(Below left) The Earth (radius = 6,371 km)

(Below right) Ireland (if it was a circle, it's radius would be 260 km)

Human scale things
(Left below) A Car (if it was a sphere, it's radius would be 3 m)

(Right below) Soccer ball (radius = 22 cm)

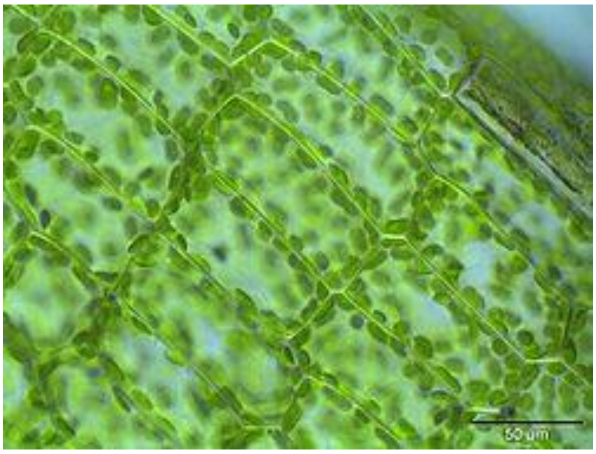
Small things

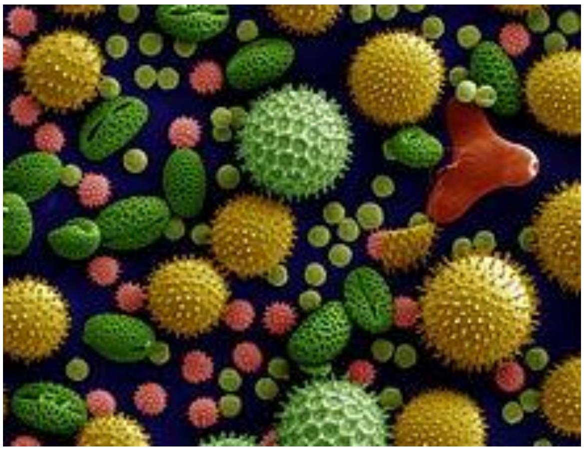


(Left) Human Hair (width = 100 µm)

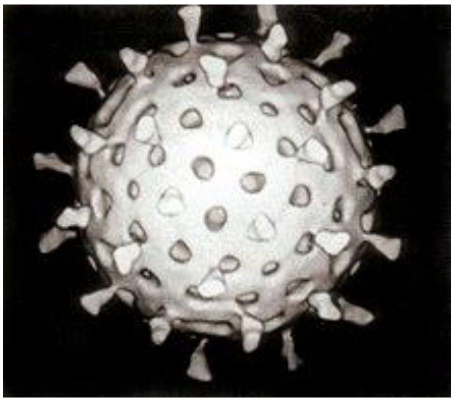
(Left below) Plant cells (about 10-30 µm)

(Right below) Pollen (about 6 µm)





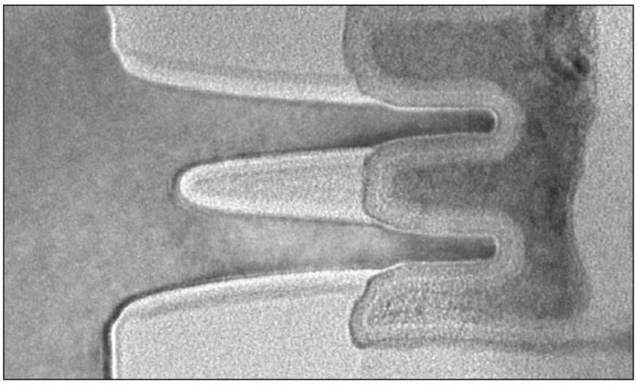
Very small things

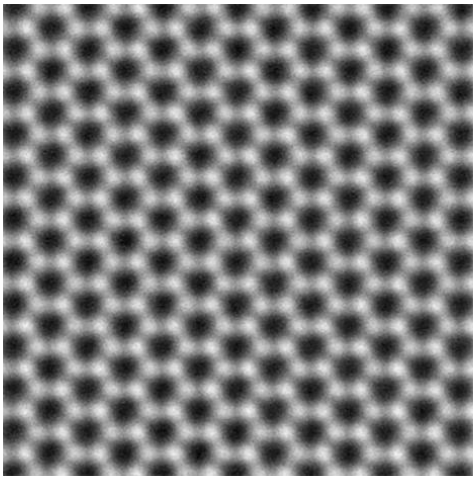


(Left) Virus (40-400 nm)

(Left below) Transistor (10 nm)

(Right below) Graphene atoms (0.3 nm)





Homework 2 – Units and What Can Nanoscience Do?

Two parts to this homework. The first is to fill in this table:

Symbol	Full name	In terms of metres?
km	e.g. kilometres	e.g. 1 km = 1000 m
m		
mm		
µm		
nm		

The second task is to fill in 200 words on the subject of a big problem you think might be solvable in the future using nanotechnology.

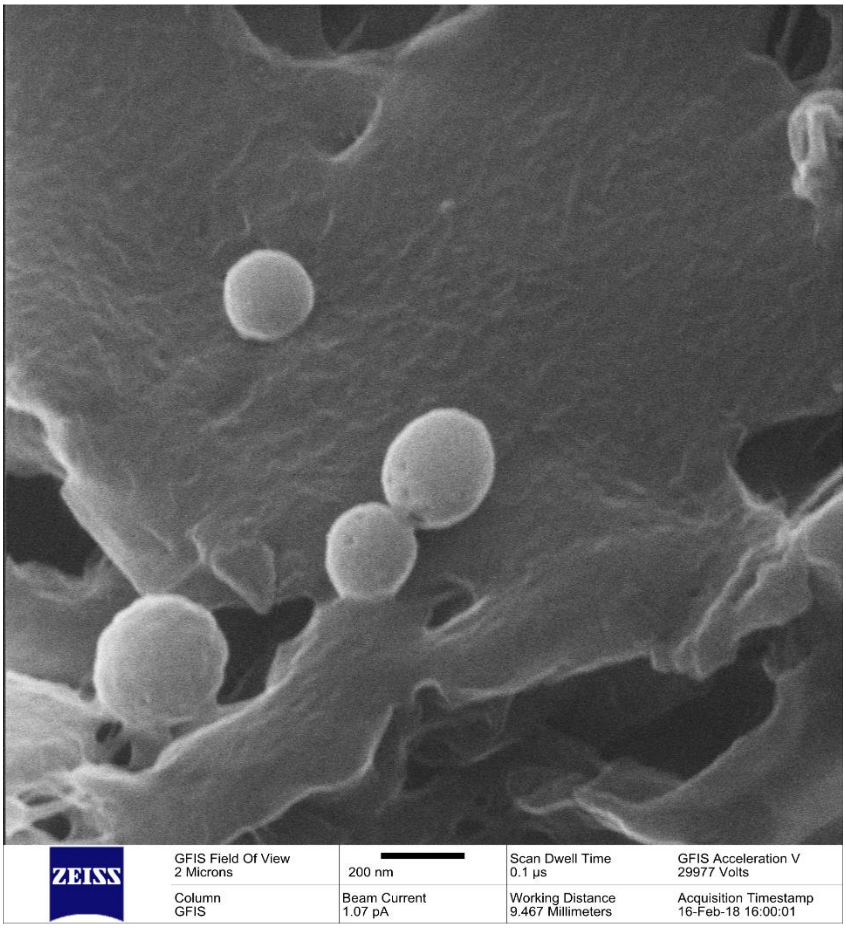
- Describe the causes of the problem
- Describe attempts to solve it so far without nanoscience

Recommended Further Exploring:

Powers of Ten: https://www.youtube.com/watch?v=0fKBhvDjuy0

List of humorous units (note the beard-second!): https://en.wikipedia.org/wiki/List_of_humorous_units_of_measurement

Tutorial 3 – Measuring Distances and Imaging on the Nanoscale



What is the Purpose of Tutorial 3?

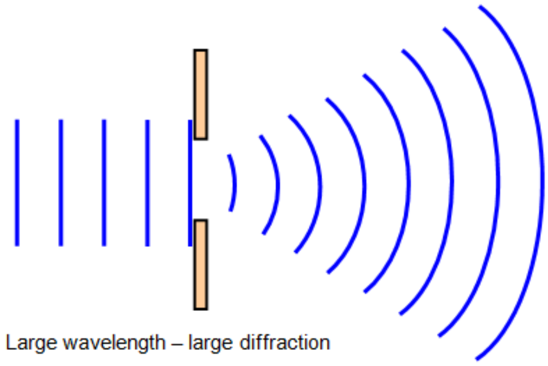
- Understand sizes in images (a.k.a. micrographs)
    - What is the approximate size of the features in this image? (HINT use the scale bar).
- What different kinds of information can different microscopes provide?
- Why is it difficult to really understand what we see with our eyes or with a microscope?
    - What are some drawbacks with this type of image (think about what the actual information in this image means)?

Introduction to Microscopes and Optical Microscopes

A Microscope is sometimes defined as any instrument which can provide information beyond the resolution of the human eye (resolution ~0.1mm).

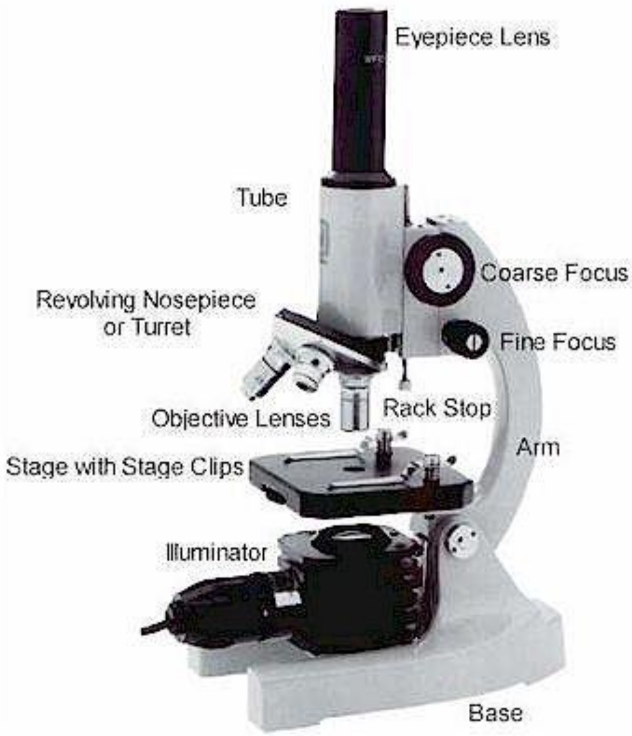
An optical microscope uses light, the same as we see with our eyes. A lamp sends a lot of light at the sample and the reflected light is collected and magnified by the lenses. Light is a wave and has something called a wavelength. The wavelength of light is measured in hundreds of nanometers.

Diffraction occurs over the length scale of the wavelength which means that any features that we want to measure in our microscope have to be the same size or larger than the wavelength (for further reading look up the Abbe diffraction limit or the Rayleigh criterion).



Highest useful magnification governed by resolution limit. What does this mean?

When we zoom in too much, everything gets blurred just like cameras on phones.

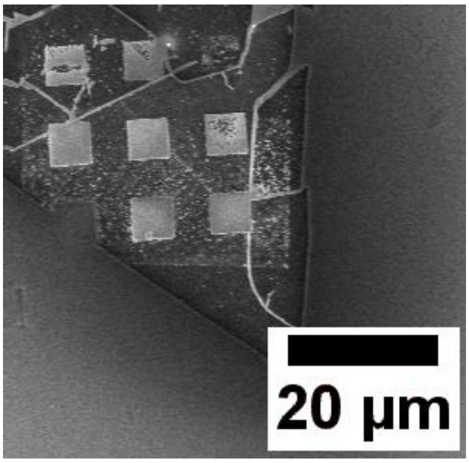


So we have to use different methods than in an optical microscope to measure nanoscale features. One thing we can do is use a mechanical tip and drag it across the sample. We can then measure the bumps.

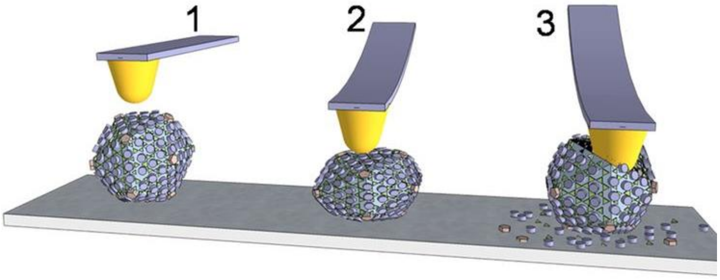
Another thing we can do is use a shorter wavelength. However, making the wavelength of light shorter (to x-rays and gamma rays) is very difficult to control, so we use electrons instead.

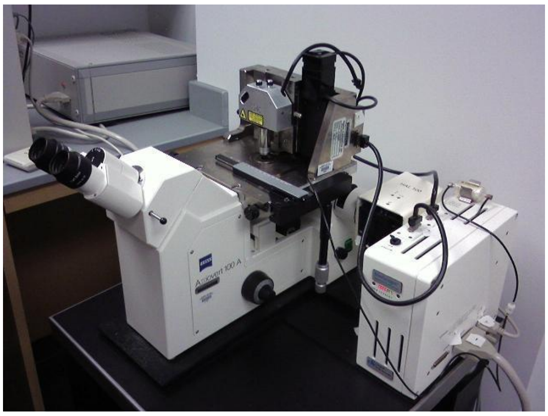
Why is it difficult to control? Glass doesn't bend short wavelengths well so we have no lenses!

From my work: an optical image which is limited by diffraction (blurriness) and an SEM image which is not.



Scanning Probe Microscopes

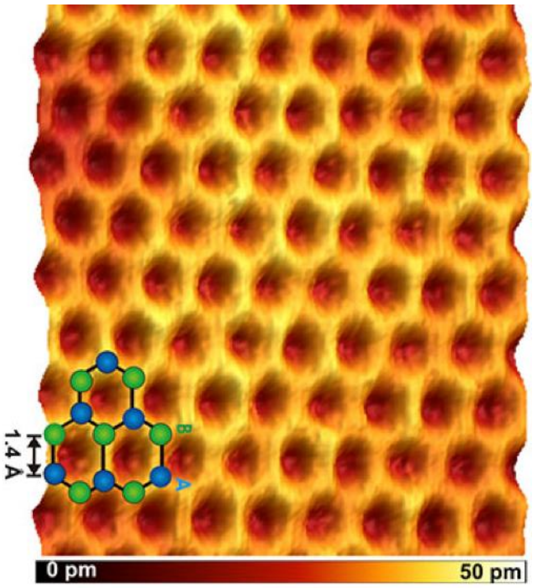




We scan tiny mechanical probes (tips) to go very close to or touch the sample surface.

What kind of information do you think this gives?

One very cool use of SPM was to measure the force required to make germs explode!

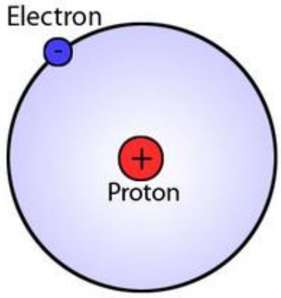


Scanning Electron Microscopes

A focused beam of electrons of very high energy hits the sample.

Other electrons are excited and shoot off the sample.

These “secondary” electrons are collected on a detector



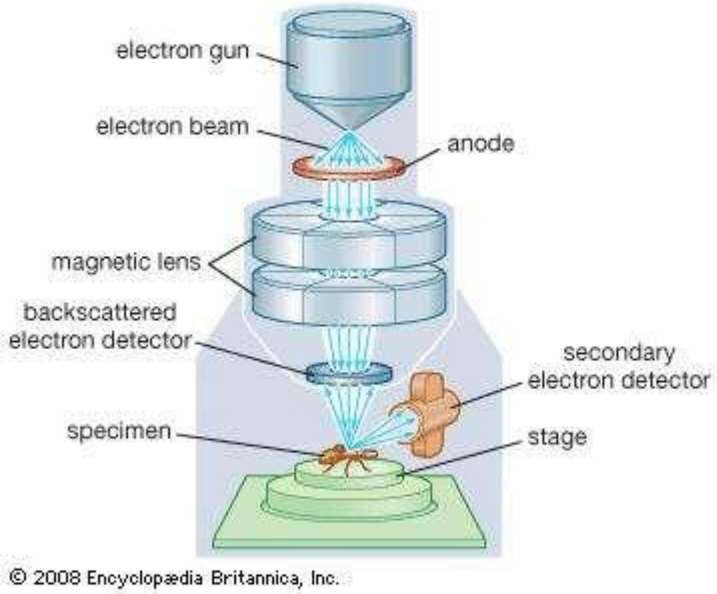
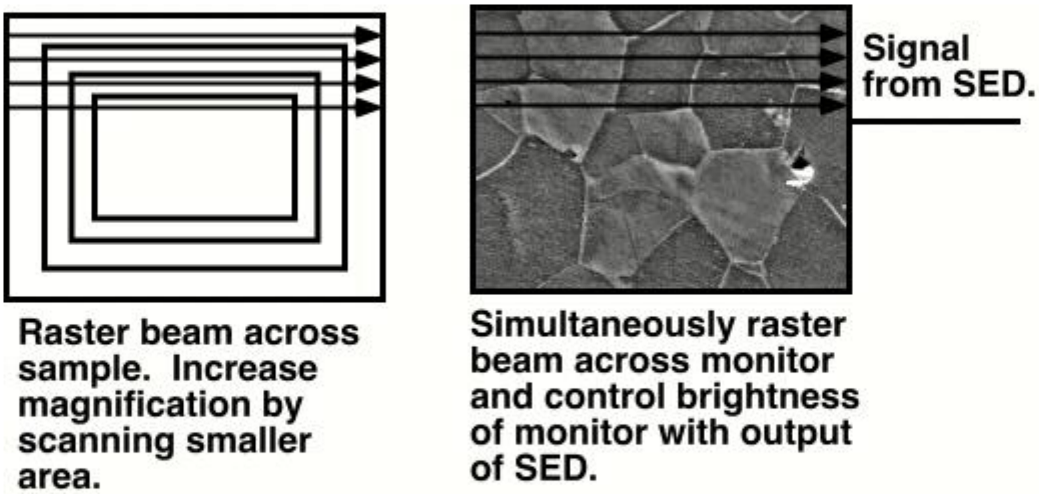


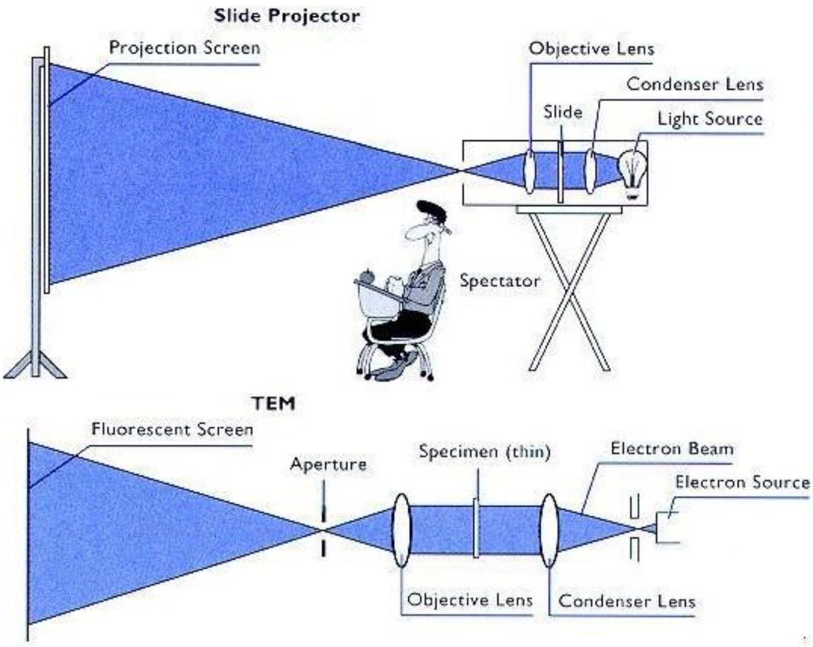
Image Formation

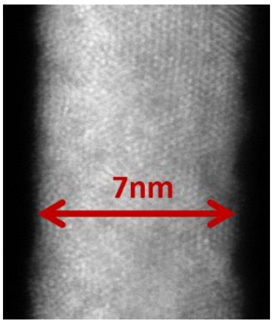
Just like the probe in SPM, the electron beam is scanned across the sample to create the image



Transmission Electron Microscopes (and Scanning Transmission Electron Microscopes)

While an SEM is kind of like a camera that uses electrons, a TEM is kind of like a projector. The electrons pass through the sample (which is like the slides) and the “primary” electrons are collected on a screen or in a detector.





Homework 3 – Comparing Microscopes

Write 200-300 words on two or three of the microscopy methods listed here and compare to one other method of your choice. Focus on the information (electrical properties, height, mechanical properties etc.) that each method provides and when you might choose one over the other.

Recommended Further Exploring:

Atomic Force Microscope

https://www.youtube.com/watch?v=s6KqJS1GZNE

Scanning Electron Microscope

https://www.youtube.com/watch?v=GY9lfO-tVfE

Transmission Electron Microscope

https://www.youtube.com/watch?v=fQJYuTpK8Fs

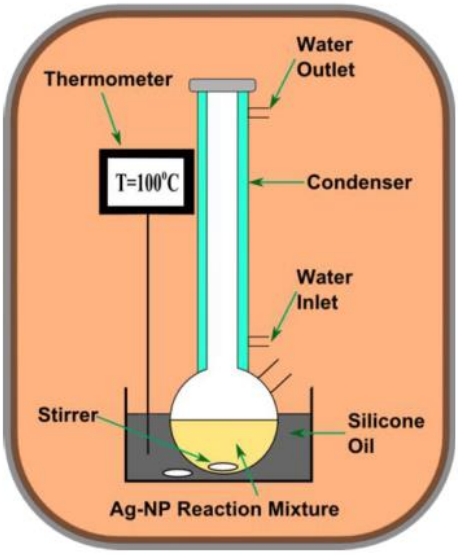
Tutorial 4 – Making and Breaking things on the Nanoscale

What is the Purpose of Tutorial 4?

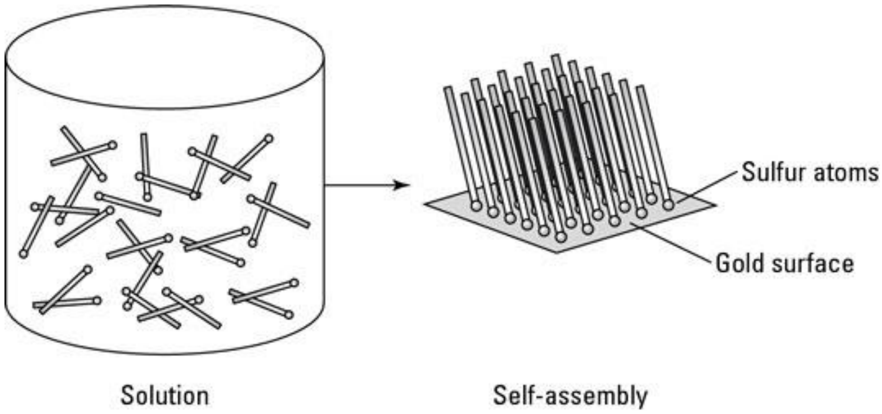
- The purpose of tutorial 4 is to talk about some ways to make and modify nanoscale objects and features.

List of Synthesis Methods

- Wet chemical methods e.g. silver nanoparticles are made "by the reduction of silver nitrate with sodium borohydride" (in other words, mixing a bunch of chemicals and boiling them).



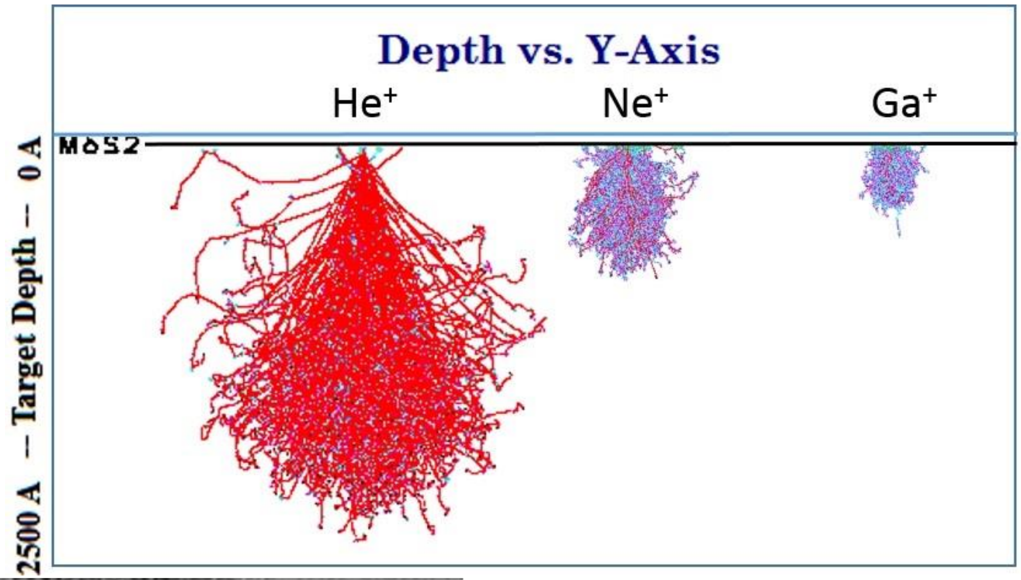
- Self-assembly. Some Nanoscale features form on their own when you control them carefully. Some polymers (which plastics are made from) self-assemble into complex shapes called block co-

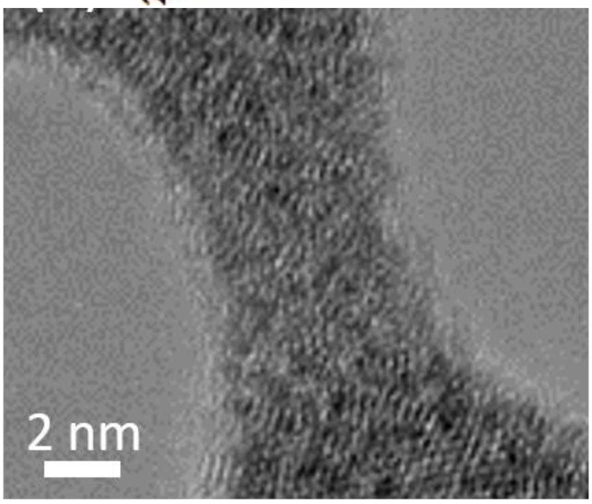


polymers. Sulfur wires can assemble on gold too.

- Using the microscopes described previously:
  - Electron beams have a weak interaction with matter but if you use enough of them at a high energy you can change the shapes of things. This is very precise but very slow.
  - Scanning probe microscopes are even more precise but even slower and less efficient. Check out the further exploration material at the end of this tutorial.
- Focused Ion beams: are the main method in my research. Ions are much heavier than electrons and can transfer a lot more momentum. This makes them far more destructive i.e. much better at cutting things into desirable shapes. They come in a wide variety with some using light ions like

helium and some using heavy ions like gallium. Depending on their mass, the ions behave differently. Here is a map of how far they go into the surface of your sample:





- From my work, a TEM image of a "nanoribbon" which was cut into shape using a helium ion beam

Homework 4 – Making a Small Device to Solve a Big Problem

For the previous big problem that you identified, consider a nanotechnology which could be used to help with this problem. Write 200-300 words on the methods used to make/modify such a thing. I suggest you include: the minimum feature size that this method can make (i.e. the resolution, also known sometimes as the "pitch"); the drawbacks such as cost and inefficiency, maybe environmental costs, toxicity to humans etc.

Recommended Further Exploring:

Light: A boy and his atom https://www.youtube.com/watch?v=oSCX78-8-q0

Medium: Making of the boy and his atom https://www.youtube.com/watch?v=xA4QWwaweWA

Heavy: Nano, the next dimension https://www.youtube.com/watch?v=eCpkq_AeX50

Tutorial 5 – Nanomaterials

What is the Purpose of Tutorial 5?

- Tutorial 5 places the methods discussed previously into their greater context. The methods are designed to be used on nanomaterials. Now that we know a little about how they are made and studied, nanomaterials themselves are discussed in detail.

Nanomaterials

There is an enormous variety of chemicals, shapes and arrangements that make up what we call nanomaterials. Their large surface-to-volume ratio and the effects of quantum physics mean that they have extraordinary properties.

Surface-to-volume ratio: Think, what happens if I cut bread into thin slices instead of thick?
I need different amounts of butter to cover it! This is the phenomenon behind flour explosions!

10 DUST EXPLOSIONS

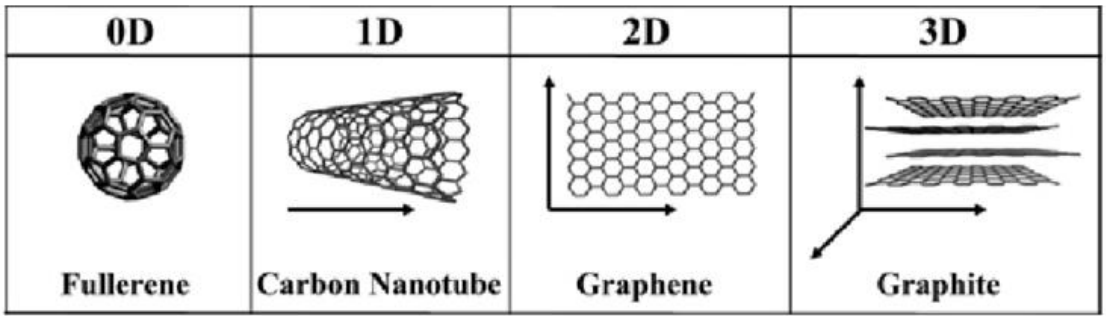
Flour dust explosion, Hutchinson, Kan., May 1, 1947. — Improper training of employees for fire emergencies was responsible for the disastrous explosion. Instead of calling the fire department on discovering a belt fire, employees attacked the blaze with solid stream extinguishers and pails of water, thereby stirring up dust that exploded.

Quantum physics: On very small scales, classical physics starts to breakdown. As electrons in a nanomaterial are more confined, they behave differently. (A little complicated to cover in this course!)

A common way to class these materials is by the number of their dimensions which are not on the nanoscale. Thus:

- A 0D material has all three spatial dimensions less than 100 nm. Such materials include quantum dots and nanoparticles.
- A 1D material has two spatial dimensions less than 100 nm. Such materials include nanowires and nanoribbons.
- A 2D material has one spatial dimension less than 100 nm. Such materials include graphene and layered forms of other materials like MoS_2.
- A 3D material has no spatial dimension less than 100 nm and is sometimes called a “bulk” material.

Carbon, for example, can exist in all of these classes:

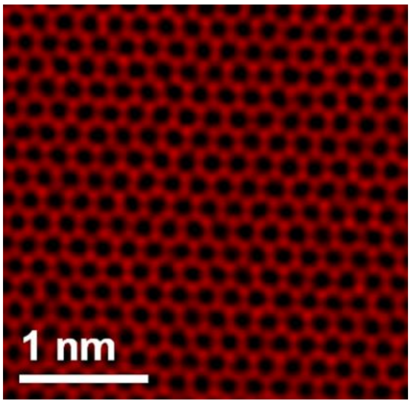


Usually we consider nanomaterials to mean those deliberately engineered. However, nanosized features also regularly occur in nature and are also studied heavily.

What makes nanomaterials so special? Their extraordinary properties.

As optical emitters, nanoparticles produce different light depending on their size:

Graphene consists of a single layer of carbon atoms in a honeycomb-shape. A high resolution STEM image of the hexagonal structure is shown here:



Graphene, for its size, is supreme in mechanical properties. It deforms very little when strained, it is very strong, it carries a large current extremely quickly and it carries heat incredibly quickly. Some of the most promising applications of graphene include its use in supercapacitors for energy storage; flexible electronics for display technology and more.

Homework 5 – [Draft Assignment]

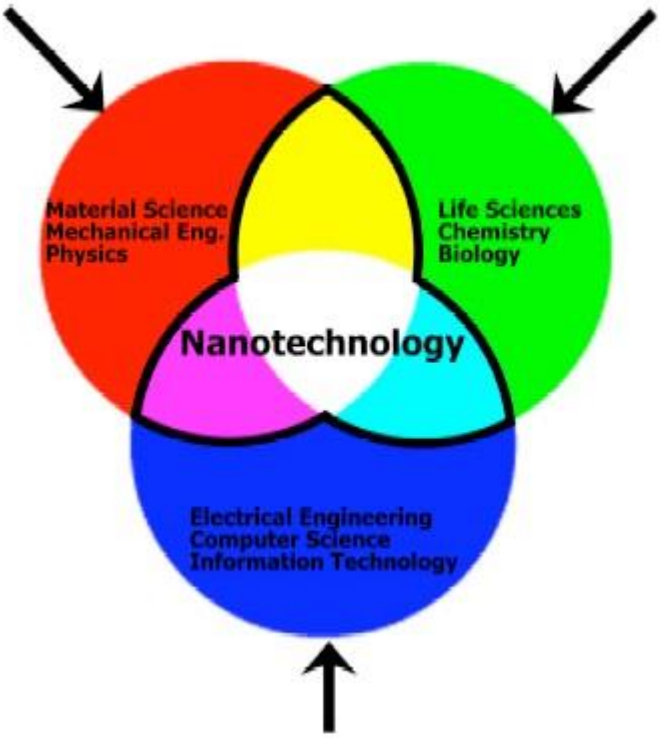
Begin work on your final assignment. We can discuss the usual format of a scientific paper to help with this. Use full sentences if you like or bullet points to form a structure.

Recommended Further Exploring:

Stephen Fry Documentary

https://www.youtube.com/watch?v=70ba1DByUmM

Tutorial 6 – Further Exploring and Assignment Workshop



What is the Purpose of Tutorial 6?

- Tutorial 6 is for further exploring. There are a number of available options depending on student feedback including:
    - What working in research is like
    - What might happen in nanoscience in the next 5-10 years or more
    - When spectroscopy and microscopy combine
        - Energy Dispersive X-ray Spectroscopy
        - Raman Spectroscopy and more
    - Any other sub-topic
- Finally, in the second half of this tutorial, students will work on their assignments and ask any questions they may have.

Homework 6 – [Final Assignment]

See the details at the start of the handbook.

Recommended Further Exploring:

Websites

Khan academy

https://phys.org

Books

Bad Science by Ben Goldacre (or anything by him!)

A Brief History of Time by Stephen Hawking

(Maybe once you have studied a little more physics, look up the Feynman lectures either in book or audio)

Podcasts

Note: most science podcasts can be a little bit cringey but once you get over that, these are some of the good ones!

Guardian Science Podcast

The Science Shed

The Skeptic's Guide to the Universe

Talk Nerdy

Star Talk

More or Less: Behind the Statistics (BBC)

Nature Podcast

The Curious Cases of Rutherford and Fry

Radiolab

The Infinite Monkey Cage

And many more

Tutorial 7 – Reflection and Feedback

What is the Purpose of Tutorial 7?

- To reflect on the programme including what was enjoyed and what was challenging.
- To receive feedback on final assignments.
- To share examples of best practice with the other students in your group.
- To write targets for improvement in school lessons.

Reflecting on the Programme

What did you most enjoy about the programme?

What did you find challenging about the programme?	How did you overcome these challenges?

Sharing Reflection

Final Assignment Feedback

What I did well…	What I could have improved on….
•	•

• •	• •

My target for future work is…

Appendix 1 – Referencing Guide

When you get to university, you will need to include references in the assignments that you write, so we would like you to start getting into the habit of referencing in your Brilliant Club assignment. This is very important, because it will help you to avoid plagiarism. Plagiarism is when you take someone else's work or ideas and pass them off as your own. Whether plagiarism is deliberate or accidental, the consequences can be severe. In order to avoid losing marks in your final assignment, or even failing, you must be careful to reference your sources correctly.

What is a reference?

A reference is just a note in your assignment which says if you have referred to or been influenced by another source such as a book, website or article. For example, if you use the internet to research a particular subject, and you want to include a specific piece of information from this website, you will need to reference it.

Why should I reference?

Referencing is important in your work for the following reasons:

- It gives credit to the authors of any sources you have referred to or been influenced by.
- It supports the arguments you make in your assignments.
- It demonstrates the variety of sources you have used.
- It helps to prevent you losing marks, or failing, due to plagiarism.

When should I use a reference?

You should use a reference when you:

- Quote directly from another source.
- Summarise or rephrase another piece of work.
- Include a specific statistic or fact from a source.

How do I reference?

There are a number of different ways of referencing, and these often vary depending on what subject you are studying. The most important to thing is to be consistent. This means that you need to stick to the same system throughout your whole assignment. Here is a basic system of referencing that you can use, which consists of two parts:

A marker in your assignment: After you have used a reference in your assignment (you have read something and included it in your work as a quote, or re-written it in your own words) you should mark this in your text with a number, e.g. [1]. The next time you use a reference you should use the next number, e.g. [2].

Bibliography: This is just a list of the references you have used in your assignment. In the bibliography, you list your references by the numbers you have used, and include as much information as you have about the reference. The list below gives what should be included for different sources.

Websites – Author (if possible), title of the web page, website address, [date you accessed it, in square brackets].

E.g. Dan Snow, 'How did so many soldiers survive the trenches?', http://www.bbc.co.uk/guides/z3kgjxs#zg2dtfr [11 July 2014].

Books – Author, date published, title of book (in italics), pages where the information came from.

E.g. S. Dubner and S. Levitt, (2006) Freakonomics, 7-9.

Articles – Author, 'title of the article' (with quotation marks), where the article comes from (newspaper, journal etc.), date of the article.

E.g. Maev Kennedy, 'The lights to go out across the UK to mark First World War's centenary', Guardian, 10 July 2014.

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