Vignette 1: **Marie Curie**

Marie Curie is one of the most famous scientists ever. She won two *Nobel prizes* – one for chemistry and one for physics.

Curie worked on a new area of science - **radioactivity**.

She studied minerals that were radioactive because they were *compounds of radioactive elements* (**uranium** and **thorium**). However, she found that the minerals were more radioactive than they should have been given their chemical makeup, and the activity of the radio-isotopes they contained.

Curie had the idea that the minerals contained small amounts of impurities that were highly radioactive. To test this idea she had to use careful chemical techniques to separate out the impurities. Curie's results suggested that the minerals contained very small amounts of *unknown elements* that were *very* strongly radioactive – she had to process tonnes of minerals to extract tiny quantities of the new substances.

Curie isolated substances that are now known as **polonium** (after Curie's homeland) and **radium**. Radium was so radioactive, its compounds glowed in the dark.

Curie's work involved long hours working 'at the bench', with large quantities of radioactive materials – materials now known to be very dangerous. Mary Curie's work involved the difficult task of isolating radioactive elements that were present in very low concentration in minerals such as pitchblende.

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Vignette 2: **Albert Einstein**

Einstein is one of the most famous scientists ever, and most people would recognise his iconic image, and one of his formulas: **$E=mc^2$**.

A lot of people also know that the work that made Einstein's reputation was not completed in a laboratory, but while he was working as an office clerk (checking patent applications). This was possible because Einstein was a *theoretical* physicist: using pencil and paper to work out his ideas. Einstein's most important apparatus of course, was his brain, and he carried out '**thought experiments**'.

When he tried to imagine what it would be like to move alongside a beam of light, he decided that it was not possible to travel at the speed of light. Before Einstein's work, most scientists believed in a simple principle of **relativity** that had been discussed by Galileo: that relative speeds can be worked out by simple arithmetic: e.g. if two beams of light pass each other in opposite directions, each travelling at 3.0×10^8 ms^{-1}, then the speed of one beam, relative to the other should be 3.0×10^8 ms^{-1} + 3.0×10^8 ms^{-1} = 6.0×10^8 ms^{-1}.

However Einstein decided to build up a new model by starting with the assumption that the speed of light (in empty space) is *invariant* –always measured to be 3.0×10^8 ms^{-1} relative to any observer no matter how fast they were moving.

Einstein developed a range of models, mostly using mathematics to work out the consequences of his ideas. He developed a mathematical model that fitted data about what happens when light is shone on different metal surfaces; and another about the effects of the random movement of molecules. He is most famous, though, for his theories of relativity.

Einstein's theories fitted with some recognised problems in science. For example, a well-known idea suggested that light needed a *medium* to travel (called the **ether**, or ***æther***) but experiments had been unable to detect it. Einstein's ideas fitted the experimental data, and we now say that light *can* travel through a vacuum.

Another known problem was that the observed orbit of the planet **Mercury** did not quite fit the prediction of astronomers who used the well-established theories of Newton. Astronomers had known for many years that calculations based on Newton's theories led to predictions that were close, but were not as accurate as they would have expected. Newton's ideas were used as they were the best available – but Einstein's theories of gravity were found to better a better fit with the observations.

Einstein's ideas were also used to make new predictions: e.g. predictions about the path of light being deflected by mass ('*gravitational lensing*' - later tested by observing solar **eclipses**), and about the passage of **time** being different for observers at different speeds (later tested by flying clocks into space). These predictions were considered as the basis for crucial tests of the theory

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Vignette 3: **William Harvey**

William Harvey was a *physician* working long before modern medical techniques (X-rays, microscopes etc.) were available. In 1635 he carried out an **autopsy** on a man who had lived (it was believed) to 152 years and nine months. Harvey described the state of all his internal organs, and suggested that he might have lived even longer if he had not changed his lifestyle in his old age (from being an agricultural labourer, to being a celebrity living in the polluted city, eating too much fatty food and not taking enough exercise. Some medical advice has not changed much over the years!)

Harvey is famous for arguing for the theory of **the circulation of blood**. According to Harvey, the heart pumped blood to and from the lungs, and all around the rest of the body:

> *"the pulsation of the left ventricle of the heart forces the blood out of it and propels it through the arteries into all parts of the body's system…further, that **the blood flows back again** through the veins and the vena cava and right up to the right auricle…"*

This was a brave claim, as there was a long accepted view that the blood only moved *from* the heart *to* the organs, not back again. Indeed, centuries of anatomical investigations had not suggested *any* means by which blood could circulate, as there did not appear to be any way that veins and arteries were connected. (Capillaries are too small to be seen without magnification, and microscopes had yet to be invented.)

Harvey based his view on a wide range of observations and experiments, carried out on people and a range of other animals "*through ever wider and more meticulous inquiry, involving frequent examinations of the insides of many different living animals and the collation of many observations*". For over a thousand years medical ideas and investigations had been based on the work of Galen, and Harvey begins his arguments by listing problems with Galen's ideas: where they did not seen logical, or where they *did not fit* his anatomical observations

Harvey argued strongly for his theory of blood circulation, for example by suggesting **calculations** that showed that the amount of blood pumped by the heart in half-an-hour was more than the total amount of blood in the body. This did not prove he was right, but showed that the blood must be constantly produced by the body at a very high rate if it was *not* being recycled – something that seemed ridiculous.

Harvey suggested **experiments** that would support his theory – for example that when cut the arteries "*spout relatively freely and abundantly a rushing torrent of blood"* – suggesting his readers *"should put the matter to the test in a sheep or a dog*" by cutting the neck artery.

One "*special experiment*" Harvey recommended to his readers concerned opening up a snake - and then squeezing off the blood vessels either side of the heart between finger and thumb, and then watching to see how the heart either swells and turns purple (if blood is prevented from leaving) or turns pale and stops beating (if the blood is prevented from reaching it from the veins).

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Vignette 4: **Robert Millikan**

Millikan was an American (US) physicist. He is best known for his ***'oil drop' experiment***. At the time when Millikan did his experiments (around 1910), it was not known if electrical charge could take any value ('continuous') or whether it only existed in discrete *quanta* ('packets').

Millikan's **experiment** was quite difficult and 'fiddly'. The principle was simple – a small drop of oil would fall under gravity, but if the oil drop was electrically charged the weight of the drop could be countered by an electrical force attracting the drop upwards. In practice, his apparatus required observing tiny oil drops as they slowly fell through electrical fields, and making careful measurement. He also had to use X-rays to charge his drops, and his **calculations** had to allow for other forces that might have an effect – air resistance when the drop was moving, and the *upthrust* due to its *buoyancy*.

Because each of the measurements was subject to ***experimental error*** (the limit on how *precisely* one can measure something), Millikan had to *average* results from many runs to get a reliable result. However, because the apparatus was very difficult to operate, the experiments sometimes had to be abandoned before any results were obtained. Millikan worked on refining his apparatus, and collecting data, for several years,

Millikan eventually reported that his results showed that electrical charge is **quantised**, although the basic unit of charge was very small*. Other scientists working at the time were doing **experiments** that they thought suggested that the electrical charge could take any value. The different scientists disputed each other's conclusions, and sometimes suggested that the other's results could fit their findings! We now accept Millikan's work gave a **reliable** answer, and we now accept that the electronic charge = 1.6×10^{-19} C.

When Millikan's laboratory notebooks were examined many years later, it was found that he had run his experiment about 140 times. However, he had rejected about 80 of these experiments and *excluded* them in drawing his conclusions - because he believed he could tell which results were reliable, and which derived from times when something must have gone wrong with his apparatus.

* **e ≈ -0.000 000 000 000 000 000 2 Coulombs**

p.s. – one re-examination of Millikan's notebooks suggested that had he not excluded so many results, his best value for the electronic charge would be approximately $^{e}/_{3}$. Scientists now believe that **subatomic particles** called *quarks* may carry charge of value $^{e}/_{3}$, and so the charge on an electron is not the smallest possible charge. However, according to accepted scientific theories, **quarks** are always joined into groups, and single **quarks** are only found in extreme conditions (such as powerful particle accelerators), - so Millikan's oil drops could not have had charges of $^{e}/_{3}$ ...

...or could they?

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Vignette 5: **Barbara McClintock**

Barbara McClintock studied cells and the **genetics** of plants – and in particular maize (sweet corn). When she was a young researcher, her work won her a lot of respect, and she was recognised as a capable biologist.

However, over time McClintock's research led to ideas that other scientists found unconvincing. In particular, McClintock interpreted the results of her experiments to suggest that **genes** were not always fixed to a single location, but could sometimes move along the **chromosome**, or even to a new **chromosome** - *transposition*. The notion of *'jumping genes'* (*transposons*) seemed an odd and unlikely finding to other scientists who were study genes. Most geneticists believed that genes are arranged in fixed places on chromosomes, and it did not seem possible that they could move about (except during **sexual reproduction** when some 'shuffling' occurred).

For many years McClintock was seen as something of an eccentric. It perhaps did not help that McClintock seemed to focus on individual plants in great detail rather than using **statistical** approaches to average out individual differences:

> *"the important thing is to develop the capacity to see one kernel that is different, and make that understandable".*

Worse, perhaps, McClintock admitted to relying on what might be called '**insight**', or even '**intuition**', to carry out her science. She saw her brain as being like the 'black box' processor in a computer: she did her experiments, made observations, and drew conclusions (she "understood" the plant), without understanding how her brain was "*integrating*" the information.

As other scientists carried on their studies into genetics over many years, they discovered that the way genes work was more complicated than they had first expected. Some genes control other genes – effectively turning them on or off – and it is not always possible to assign a single simple role to a particular gene without considering what else is going on in the organism, or in the cell, at that time. It is *as if there are several layers* to the way genetics works, and it is not possible to understand what is going on by only paying attention to one layer of the system at a time.

It is now realised that McClintock's approach, even if she did not always fully understand how it worked herself, provided insights into the complexity of genetics that other scientists only recognised many years later. McClintock is now recognised as an important pioneer in genetics.

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Vignette 6: **Crick, Franklin, Wilkins and Watson**

Although some scientific discoveries are largely down to one scientist, modern science is usually a **collaborative** process, with groups of researchers working together.

One of the most important discoveries of the 20th Century was the basic structure of **DNA** – the so-called '*double helix*'. It was not realised quite how important this 'problem' was until it was solved: Crick and Watson published a paper proposing a structure, and pointed out that it suggested a way that genetic material was copied in cell division and reproduction.

Crick and Watson 'discovered' the likely structure by building a **molecular model**, rather than doing any experiments on DNA. Watson worked on the model, *like a jigsaw puzzle*, until he found a way to get the pieces *to fit*. Watson did not actually know very much chemistry, as he was a biologist with a particular interest in ornithology. However, he was able to bring together a range of different ideas and information in order to build the model that was soon accepted being substantially the 'correct' structure. It was not possible to build the model until a great deal of data was collated, and understood. Indeed Crick and Watson's first attempt to build a model was a failure - as colleagues from another laboratory soon pointed out how it did not fit the experimental data available. Wilkins and Franklin from King's College London travelled up to Cambridge to see the model, but Rosalind Franklin told them the model did not match her experimental results. Franklin, who was much more familiar with the latest experimental data, could immediately see that the model could never fit the available evidence.

Wilkins, and particularly Franklin, were working on a difficult experimental technique called **X-ray diffraction** that can give some information about structures of substances that can be **crystallised**. Franklin worked long hours on careful experiments, and then had laborious **calculations** (without machines to help in those days) to undertake before she should estimate some of the dimensions of the DNA structure. Because Franklin's colleague Wilkins was a friend of Crick, information about Franklin's research reached Crick and Watson. Their work depended on information from other scientists as well. The physicist **Schrödinger** had written a book that alerted Crick and Watson to the area of research. Various chemists had undertaken experiments showing what the *chemical components of DNA* were, and how much of each of the different components were present. The idea of building a **model** had been copied from Linus **Pauling** who had used a similar approach to explore protein structures. Finally, Crick himself made a major contribution when he worked out the **mathematical theory** that predicted the X-ray diffraction pattern produced by crystals of *helical* molecules.

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Vignette 7: **Galileo Galilei**

Galileo is most famous for his argument with the Catholic Church, about *whether the Earth moved* around the sun. At the time most people believed that the Earth was still at *the centre of the world* (i.e. the Universe) and that the sun and stars moved in circles around the earth - although some of the stars 'wandered' a bit (i.e. the planets). The Church believed that this was the meaning of some of the passages in the Bible.

The story goes that:

Galileo had evidence from his scientific investigations to suggest that the earth moved round the sun, and that he opposed the Church view. Eventually he was arrested by *the inquisition* (the religious authorities), and made to 'confess' that he was mistaken. He is supposed to have confessed, but then mumbled 'under his breadth' that he actually knew the earth did move through space.

Galileo was a clever scientist who undertook many important studies, at a time when laboratory apparatus was rather primitive (for example, he used his **pulse** to time things).

It was not surprising that people thought the earth was stationary – it does not feel or look like it is moving at very high speeds, even though we now think it is. The *orthodox* view was that *everything in the heavens moved in circles (if sometimes circles within circles) around the earth*. Galileo used the newly invented **telescope** to see 'heavenly bodies' in much more detail than earlier observers, and *discovered* four **moons** that moved around Jupiter rather than the earth. It seems strange now that many people refused to believe Galileo, even though he tried to show them what he could see thought his telescope. Some looked, but *did not see* the moons, and others refused to look! Of course, the first telescopes were crude with imperfect **lenses**, and where some saw a new star, others saw smudges or other artefacts of the apparatus. Some of those who refused to look were not being obstinate, but not understanding the theory of how a telescope works, they did not know how they were meant to interpret the patterns they might see through it.

Galileo was brave to hold to his views against strong opposition, but he was also a political operator who tried to get powerful people on his side (dedicating the new moons to an important prince) and trying to take advantage of his long-standing friendship with the Pope. However, he also annoyed many people by being arrogant and argumentative - and eventually agreed to confess his 'mistake' after being shown the inquisition's instruments of torture. Most prisoners would agree to cooperate with the authorities when taken on a tour of the torture chamber, before the various instruments actually needed to be used! Galileo was not as 'brave' as Bruno, a scientist with similar ideas, who 'decided' to be burnt at the stake for his *heresy* rather than admit to being wrong!

Another famous story about Galileo is that he dropped a cannon ball and a musket ball from the leaning tower of Pisa as an experiment **to prove** that they would fall at the same rate. This was not really an *experiment*, as he already knew what would happen from many earlier tests in his laboratory: rather he used this as a dramatic way to **demonstrate** his findings.

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Vignette 8: **Lise Meitner**

Austrian scientist Lise Meitner was so keen to study physics that she managed to persuade the University teachers to let her attend their classes – even though she was female! She attained her doctorate in 1906.

Despite being an exceptional student, Meitner was only able to find work as a research scientist by working for many years without any pay. She was not allowed to work in proper laboratories where the male (paid) scientists worked, and had to set up her work-bench in a disused workshop. However, over time, Meitner was recognised as a brilliant scientist, and eventually she was even paid for her work! Meitner explored **radioactivity** with Otto Hahn and Fritz Strassman, in Berlin, and her research group undertook experiments that led to important discoveries in the new science. They did this by developing ideas and techniques that derived from the work of the Curies and others. These theories showed that radioactivity involved the **atomic nucleus** ejecting small particles, leading to new elements being discovered. Because the rules by which radioactive changes occurred had been established, careful experimental work could identify which *elements* were present before and after radioactive changes.

Meitner fled Germany when the Nazis started persecuting scientists and others who were Jewish (or considered to be Jewish under Nazi laws) – but she continued to communicate, with Hahn and Strassman about the experimental work.

Hahn and Strassman's experiments started producing very strange results, which did not fit with the known mechanisms of radioactive decay (known as α**–decay** and β**–decay**), which led to elements changing into others that were very close in the **periodic table**: so an element with **atomic number** 92 should change into one with atomic number 93 or 90. Hahn and Strassman found their experiments were producing elements that were much, much lighter than the uranium they started from! Other scientists had previously obtained the same results, but dismissed them as impossible - and due to impurities. Hahn and Strassman found that no matter how careful they were in preparing pure samples, they still found that uranium (atomic number 92) *seemed to be changing into* barium (atomic number 56).

Lise Meitner discussed the strange results with her nephew (another scientist) Otto Robert Frisch, and she came up with the idea that a totally **new mechanism** caused the result. Meitner and Frisch proposed that some large nuclei can sometimes split into parts. This became known as *nuclear fission*, and Meitner's idea was soon found to be very useful in physics (and is now well accepted). When Meitner came to England and gave a lecture on cosmic physics, a newspaper misreported the topic as *cosmetic physics*.

The importance of nuclear fission was recognised in 1944, when a Nobel Prize was awarded to Otto Hahn. For many years, Meitner's work-bench was displayed in a German museum labelled as the work-bench of Otto Hahn (it has since been reassigned to include Meitner and Strassman).

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Vignette 9: **Jane Goodall**

Goodall is a **primatologist -** a **naturalist** who studies primates (monkeys and apes). Goodall has spent many years closely studying the behaviour of chimpanzee in Africa. Goodall studied the animals in their **natural habitat**, and *observed* how they behaved in their 'natural groups'. This involved spending long periods watching the animals, getting to recognise individuals, learning about their relationships, and developing an appreciation for their social groupings.

Because Goodall was interesting in how these animals behave in their usual environment, she based her work on *observations*, rather than on *experiments* (interventions, trying to *control the 'variables'*). To understand the way chimps organise socially she had to watch the animals for many years, to see how different chimps took on and lost roles in chimp 'society'.

As she did not use an experimental approach, Goodall had to build her models on the observation data that became available over time, and accept that her findings my have to be reviewed in the light of further evidence.

Goodall found examples of chimps using tools (something previously thought to be characteristic only of humans). In her early reports of chimp 'society' Goodall described how chimp 'communities' were *largely peaceful*, and *mostly vegetarian*. However, she later found evidence of chimps hunting other animals for meat. She even found examples of chimps killing other chimps for food. She also observed a '*war*' break out in one of the groups she observed. The group split into two, and - over time - all the animals in one of the new groups were killed by members of the other group.

Goodall has therefore had to change some of her ideas about what is typical in chimpanzee society, as new evidence has become available. However, over time, she has been able to build a well-supported account of the structure of chimp groups, and the changing roles animals take in the group as they mature and grow old.

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Vignette 10: **Johann Kepler**

Johann or Johannes Kepler or Keppler or Khepler or Kheppler or Keplerus, was not very consistent in giving his name. However, he reported that he had been born on 27th December 1571, *at 2.30 in the afternoon*, having been conceived on the previous 16th May, *at 4.37 in the morning*. Kepler was very careful in recording numbers precisely. His life's work concerned producing an accurate model of the solar system, using mathematics. Kepler believed the general principle of the **heliocentric** (sun-centred) model of Copernicus, which had the earth, and the other known planets, travel around the sun. At that time, most people believed the sun moved around the earth - the **geocentric** model. But neither Copernicus, nor astronomers supporting the geocentric view, were able to present *a simple model* of the paths of the heavenly bodies *that matched observations*. Most of the models involved assuming complicated patterns of planets moving in circles, that themselves move around other circles…

Kepler believed that the planets would be organised into a simple geometric arrangement, and made it his life's work to study this. As producing mathematical models of 'the world' did not pay very well in those days, he and his family made great sacrifices for his calling – and Kepler did a lot of grovelling. Kepler moved from his native Germany when he managed to get himself a position working for the metal-nosed Danish astronomer Tycho Brahe at his island observatory – where the *most accurate observations* of the night sky were bring made. Brahe had developed his own model of the solar system, and only allowed each of his assistants access to the data they needed for the job assigned to them. Kepler was given the job of making sense of the **Mars** data. Later, when Brahe died (after a short illness, apparently initiated by drinking too much wine at banquet where it would have been considered rude to leave the room to empty the bladder), he left all his observations to Kepler, believing that Kepler was the person most likely to be able to *interpret* them.

Kepler's first *assumption* was that planets moved in perfect **circles**. He could not fit the data to such a model, no matter how **eccentric** (off-centre) he assumed the Sun. He had to reject his preferred idea. He thought about various possibilities, including the ellipse, but decided instead to calculate what an **oval** (egg-shaped) orbit would be like - on the reasonable basis that the planet was likely to follow a different shape path when nearer the sun, than when further away. However, he could not produce an oval orbit that fitted the data either, and rejected this idea. Eventually he tried the **ellipse** (even though it seemed too symmetrical), and found that it could fit with the data if he assumed that the planet moved around the ellipse *faster* when nearer the sun. (Newton's gravitational theories later explained why this was). Kepler found that he could get ellipses *to fit observations* for all the planets.

Kepler's other great project was to try a find a pattern in the distances the different planets were from the sun. He developed a complicated model based on the series of **regular solids** (tetrahedron, octahedron etc. – solids where all the faces were identical) acting like a set of Russian dolls. However, he could not find any way to get the *observations to fit* his model. Kepler wrote up his work in detail, explaining how he constructed his model, and showing why it did *not* fit the available evidence.

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