IPM component 3, week 6
Ways of thinking and scientific paradigms

Introduction

Here we will look at ways of thinking about science using specific episodes in the history of science, and we will also look at the idea of scientific paradigms. My opinion is that the only way to understand these two ideas is to trace the historical development of one's discipline in order to see how

- that discipline evolved over the decades and centuries in the way it perceived the nature of the physical world;
- perception of the natural world influenced the experiments and theories which were developed to explain the physical world.

Questions to consider: As you read these notes consider the following questions;

- What ways of thinking are used in your discipline? What paradigms are used in your discipline?
- What is rational thought in your discipline? How does your discipline demonstrate rational thinking? To help you answer this question consider your own responses to the following: Is it rational to think that
  - water can contract when heated? Think of an ide cube in a glass of water.
  - there is some invisible force, which acts at a distance, pulling objects back to Earth?
  - it is not possible to find out both the position of an object and its speed at the same time?
  - if the planets revolve around the Earth in a circular motion, then Mars will, at some point, move backwards in the sky?
  - the motion of light can both be particle motion and wave motion (given that particles and waves are two fundamentally different and incompatible forms)?
  - $\sqrt{2}$ is not a number?
  - The only geometry that exists is that of Euclid, i.e. the geometry of rectangular planes otherwise known as Cartesian geometry?

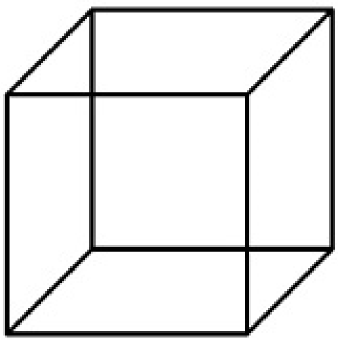
- Are there any seemingly wild or fringe theories in your discipline? If so, how can they be understood as rational theories? Look at any controversial ideas in your discipline; multiple (and possibly conflicting) perspectives on a theory/idea.

Let us start with two exercises.

Exercise 1: Images

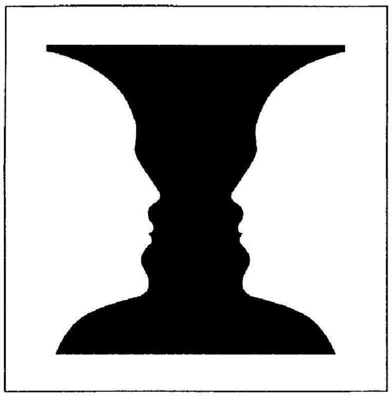
Spend some time looking at these diagrams. Notice that you have to shift your perception in order to see the alternative version of each diagram.

- Pay attention to the subtle shift in perception you need to go through in order to change from one view of the image to the other view of the image.
- If you stay looking at one particular version of a diagram are you aware of the other version? In other words, for each diagram, can you see both versions at the same time?



(a)

(b)



(c)

There are two ways to look at each diagram. For diagram (a) which direction is the cube pointing in? For diagram (b) is the woman you are looking at young or old? For diagram (c) what are you looking at? What can you see? (suggested answers on the last page).

Exercise 2: Water

Describe all the possible things you can about water.

Water is

- something which boils, something which freezes, something which flows,
- ice
  - cold, hard, makes your fingers stick to it, breaks, compressible, floats on water, conducts electricity, Sticks to surfaces;
- liquid
  - incompressible, liquid between 0C and 100C, drinkable, conducts electricity, expands when heated above 4C, contracts when heated between 0C and 4C, sticks to surfaces;
- gas: something floats in air;

etc. But these only describe the effects of water, what water does or how it "works". Is this really what the nature of water is? Can we only know water by its effects and processes?

We now look at some examples in detail. There are five examples. The first is related to physics, and the remaining four are related to maths

Example 1: The paradigms of physics

1. *Gravity*: Newton's conception of gravity was that it was a force which acted at a distance. This force was described as being invisible because there was no known mechanism for describing how this force worked or took effect. For example, when you throw an object into the air it will always fall back to Earth. But how? There is nothing connecting the object to the Earth. Newton used the analogy that gravity was like an invisible rubber band pulling things back to Earth.

   Einstein's conception of gravity was that it was not a force but curved space (actually, curved spacetime). In his theory space is described geometrically, and gravity is the curvature of space caused by a mass (i.e. a planet, a star, a galaxy, a black-hole). Here gravity is the effect of the mass on space.

This is a radical change in conception about what gravity is. The change in paradigm was to move away from the idea that gravity was some unknown mysterious force which acted over a distance and move towards the idea that gravity could be represented as geometry, as the curvature of space-time, where it is the mass of the object which creates the curvature of space (i.e. gravity), and where lighter masses follow the curvature of space (i.e. the curved geometric lines) created by heavier masses. The classical physicist before the 20^{th} century would never had conceived of this because to him force was something which was inherently a part of the mass whereas in relativity force is created outside of the mass by the interaction of the mass with space.

2. *Classical mechanics vs quantum mechanics*: In classical mechanics the model of the atom was originally that of the smallest unit of matter. Later it was found that the atom contained smaller discrete particles such as electrons, protons and neutrons. Furthermore, classical mechanics thought that the position and speed of orbiting electrons could be found exactly. In other words, it was possible to know exactly where the electron was at any moment in time *and* also know how fast it was going at that specific moment. This meant that the atom could be viewed in the same way the solar system was seen, namely as discrete electrons orbiting a central nucleus, as illustrated in diagram (i) below.

   The quantum mechanical perspective of the atom is that the electron, proton and neutron are all composed of even smaller particles. This in itself might not be so difficult to accept for the classical physicist of the early of the 20^{th} century. But then imagine being told that you can never find out

   - the exact position of an electron if you know its exact speed

   or

   - the exact speed of an electron if you know exactly where it is.

Such a situation can be seen in diagram (ii) below.

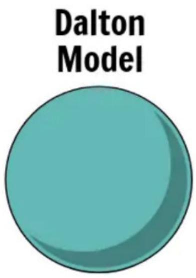
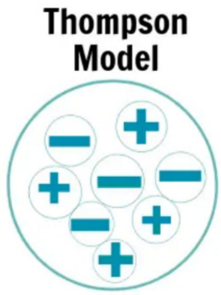
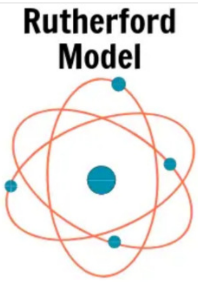
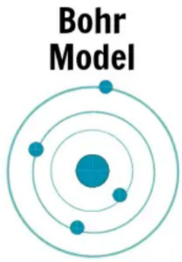
 Matter is made of indivisible atoms.	 Thomson proposed this model in 1903 when only electrons and protons were known to exist. Here the atom was considered to be a sphere of positively and negatively charged particles.
 Rutherford's work on the atom suggested to him that electrons orbited the nucleus.	 The Bohr suggested that electrons orbit the atom at discrete position around the atom, in the same way planets orbit the sun. Each orbit represents different energy levels of the electrons.

Diagram (i)

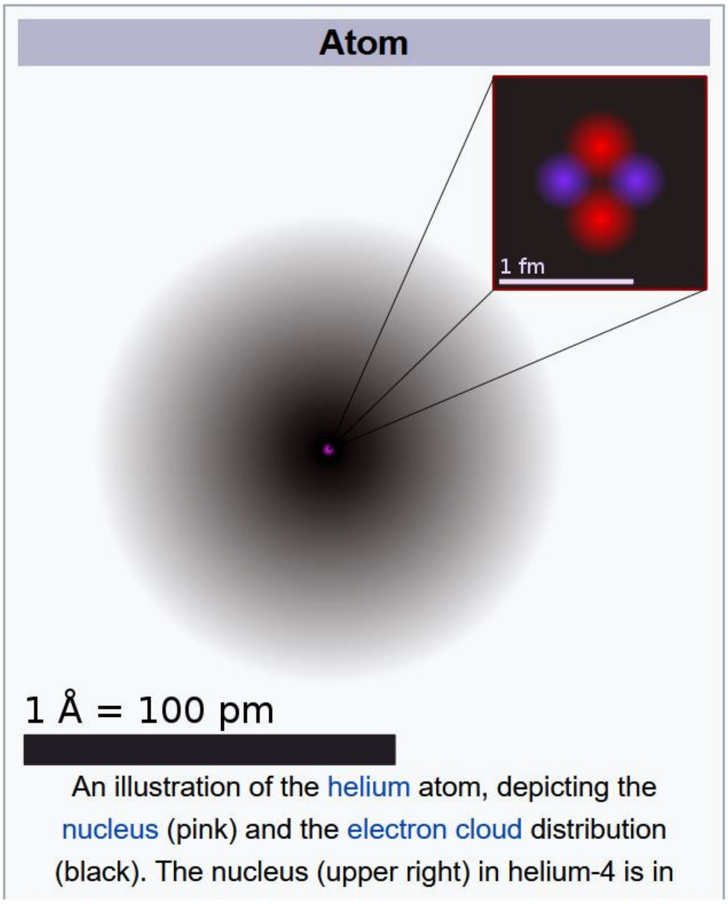


Diagram (ii)

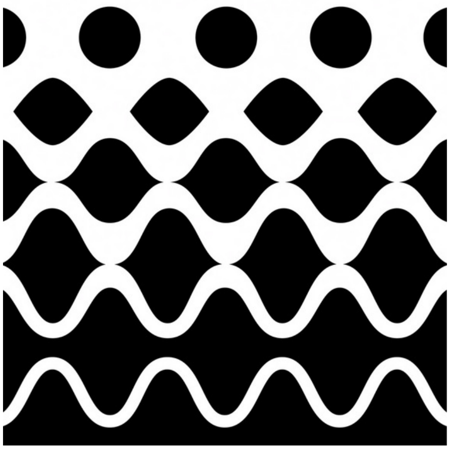
The change in paradigm was to move from representing the electron as having an exact position and speed to representing it as having only a probable position (if we know the speed) or speed (if we know the position). That is why modern diagrams of the atom show a *cloud* of electrons surrounding the nucleus (as shown in diagram (ii) above) and not a clear cut, discrete orbits. So, for a given speed of the electron this cloud is supposed to represent the *probable* position of the electron, not the exact position. Einstein could not accept this conception of physics. He once told Paul Dirac (###), one of the founders of quantum theory that the mathematics in one of his (Dirac's) papers was beautiful but that his physics was awful.

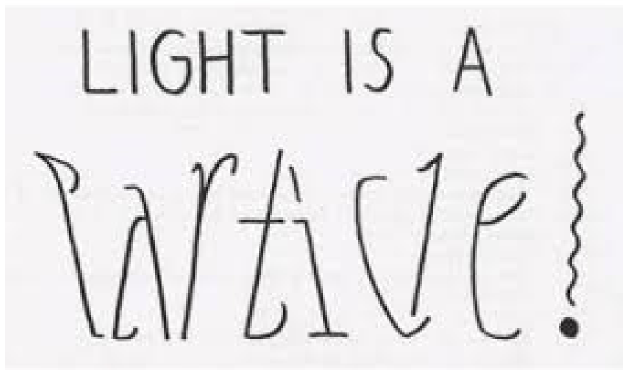
3. Newton (1642-1726) thought that light was made of particles because he saw that light travelled in a straight line and, by his owns laws of mechanics, straight line motion only occurs for discrete objects such as particles.

   Christiaan Huygens (1629-1695) thought light was a wave, an idea he first suggested in 1678, and which Thomas Young (1773-1829) proved was true by an experiment (called the double-slit experiment) in 1801. Young's experiment showed a pattern which could only occur if light behaved as a wave form.

The change in paradigm was to move from seeing light as only made of particles or as only a wave form, to seeing light as behaving both as particle or wave (the famous wave-particle duality). This was a radical shift in perspective of the nature of light that had to wait until the advent of quantum mechanics before it could be described and understood clearly.

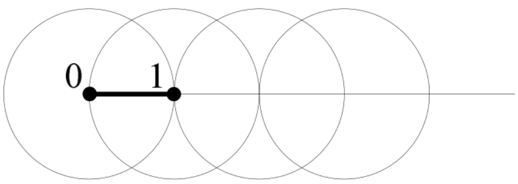
A nice visual illustration of wave-particle nature can be seen in the two diagrams below. Can you see the "particle" nature of the diagrams? Can you see the "wave" nature of the diagrams?

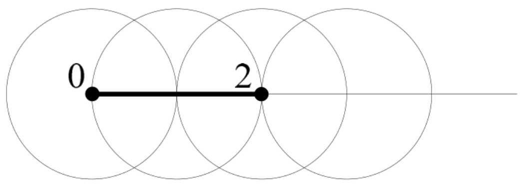




<u>Example 2: The paradigm of mathematics before the 20th century</u>

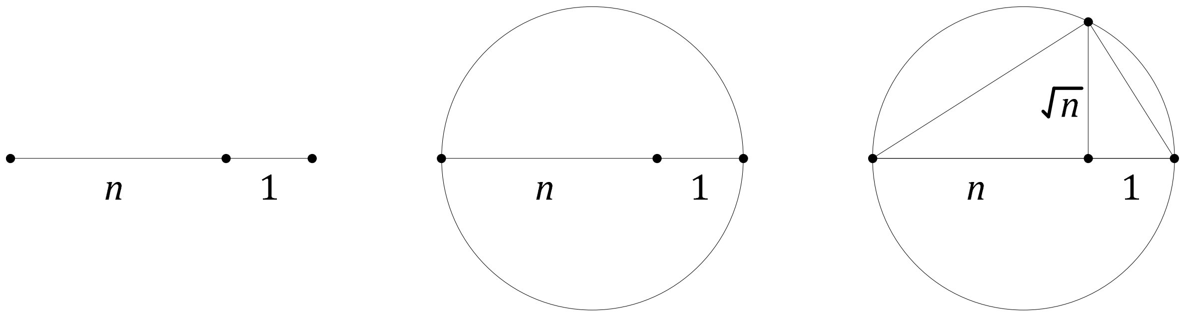
From the time of Euclid (4th to 3rd century BC) to approximately the end of the 18th century mathematics was considered to be fundamentally about geometry. Every aspect of mathematics could be represented by geometry. As such it was believed that geometry was more general than number and arithmetic. In fact numbers and arithmetic were defined geometrically. By using a ruler and compass geometric figures would be constructed in such a way as to define numbers and arithmetic. So, starting with two points one could construct he following geometric figures, where the intersection of circles and lines is what defined each integer.





Fractions could also be constructed by geometry, as well as things such as $\sqrt{2}$ (I say “things” because in those days $\sqrt{2}$ was not considered to be a number). In fact it was possible to construct any square root via geometry as follows:

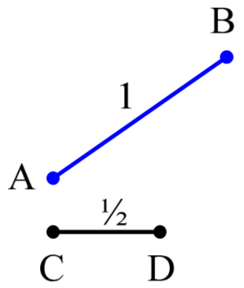
- we start with two points and then we construct a line segment of any length joining these two points. Call this line n. Onto line segment n we then add a unit line, as shown in diagram (i) below;
- using $n + 1$ as diameter we construct a circle of radius $(n + 1)/2$ as shown in diagram (ii) below;
- then we construct a perpendicular from the end of line n to the circumference of the circle. This creates a point on the circumference;
- we then join one end of the diameter to the point on the circle and the other end of the diameter to that same point on the circle, as shown in diagram (iii);



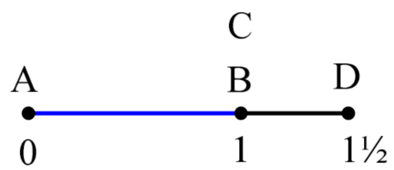
(i) (ii) (iii)

We now have three triangles (the large one and the two internal ones). By the side-angle-side aspect of geometry they are all similar to each other. Letting the perpendicular line in diagram (iii) be x we have $a/x = x/1$ implying $x = \sqrt{a}$.

In terms of arithmetic the case of performing addition can also be done geometrically. For example, given two lines AB and CD (diagram (a)) we can perform a sequence of steps using a straight-edge and compass to add CD onto the end of AB at point B (diagram (b)). Subtraction can be performed in a similar manner. Geometric multiplication and division is more tricky, but can still be done.



(a)



(b)

All of this is designed to illustrate the point that mathematics was all about geometry. Today mathematics is considered fundamentally numeric and arithmetic, not geometric. Numbers are constructed not as points created by the intersection of lines and curves but by some other non-geometric way (principally via set theory or Peano's axioms, and the principle of induction). I won't go into this since it is quite technical and will takes us beyond the purpose of these notes.

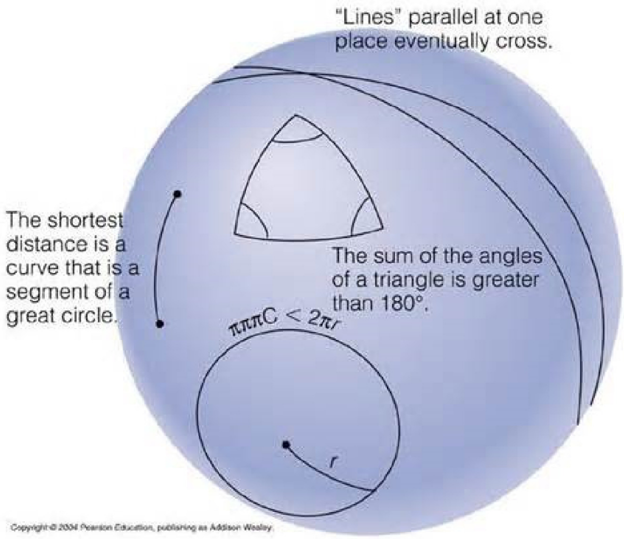
The point to note is that for approximately two and a half thousand years the paradigm of mathematics was geometry (say up until the mid- to late 1800s), and only for the past 150 years or so has the paradigm of mathematics been numerical and arithmetic.

Example 3: The paradigm of Euclidean geometry

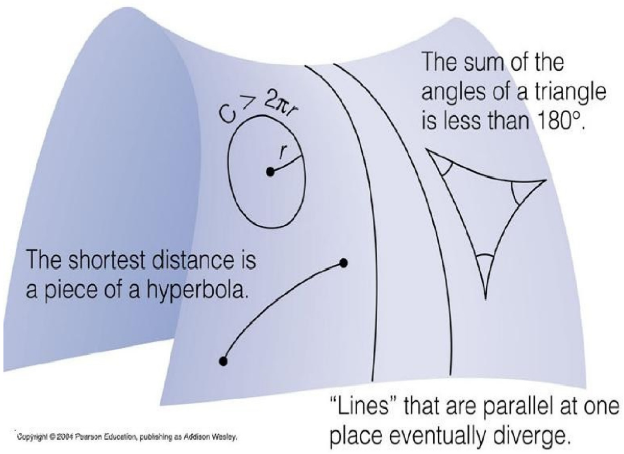
The previous example mentioned that the paradigm of mathematics was geometry. But this geometry was a very specific type of geometry, namely Euclidean geometry. This is the geometry we all learn at school. Euclidean geometry was considered to be the only geometry that existed. However, over the 19th century other "geometries" were discovered such as hyperbolic geometry and spherical geometry. What is the difference between these and Euclidean geometry? Well

- In Euclidean geometry all angles in a triangle add up to 180^0, and all lines which are parallel at some point remain parallel at other points further down the line;
- In spherical geometry all angles in a triangle add up to greater than 180^0, and all lines

which are parallel at some point will ultimately intersect at some other point, as illustrated below:



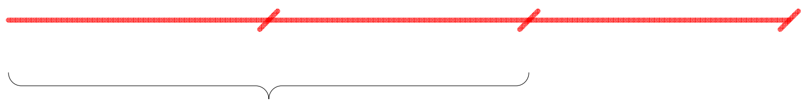
- In hyperbolic geometry all angles in a triangle add up to less than 180^0, and all lines which are parallel at some point will ultimately diverge, as illustrated below:



Up until the 19th century it was inconceivable to think of a geometry other than Euclidean (plane) geometry. So it was thought that there was only one paradigm to geometry, the paradigm of Euclidean plane geometry. Now it is known that there are several different types of geometries.

Example 4: The paradigm of numbers – part 1

Since the time of Pythagoras every phase in mathematical history has had its own beliefs and conceptions about what numbers are. Over the centuries and millennia these conceptions have changed to what we have today. But Pythagoras (approx. 570BC – 495BC) and his followers (the Pythagoreans) had a very specific conception of what numbers were. They believed that the only numbers which existed were integers, i.e. 1, 2, 3, 4, ... and ratios of integers, i.e. 1 : 2, 3 : 5, etc (where these are not considered as fractions but merely comparison of two integers). Negative numbers did not exist. Fractions as we know them did not exist. So, imagine if you can, living in a world where you only believe integers exists. Imagine a world where you have no conception of the number 2/3. For us this can be represented geometrically as



Two-thirds of a line

But the ancient Greeks only had the idea of 2 : 3, and this only meant that they were comparing a whole line of length 2 to another whole line of length 3, as illustrated below.

2 : 3

To us this means not only the ratio 2 : 3 but can also mean the fraction 2/5 and 3/5 of a line made up of 5 parts. So in the first diagram the number 2/3 is a description of parts compared to the whole (our modern conception of fractions), whereas in the second diagram 2 : 3 is a description of a whole compared to another whole (the Greek understanding). So, there is no way the Greeks would have thought in terms of the concept “one line can be cut in half” since cutting a line in half simply produces two other (shorter) whole lines.

And, with the idea of “cutting” in mind there is no way they could conceive of $\sqrt{2}$ as a number because, given a line “2” long it is impossible to cut it down to a length $\sqrt{2}$ long since this would require an infinite number of cuts, each one shorter and shorter until they would end up having to cut an infinitely short line. To see this in more detail, the line below is finite in length and can therefore be measured exactly. An integer can then be assigned to it to numerically represent the length of the line.

A line

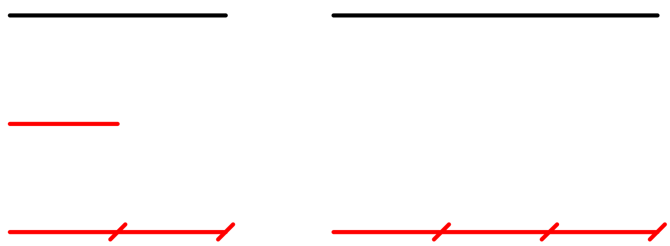
In terms of comparing the lengths of two different lines (or areas or volumes) the ancient Greeks would then speak of ratios. Today we write ratios numerically such as 2 : 3. But, to the Greeks this would mean that two lines were being compared not numerically but simply geometrically for their span/extension. In that case what we interpret as “lines in the ratio of 2:3” the Greeks would interpret as a line comprising twice a reference line of a given length, and another line comprising three times the reference line. In other words, the numbers in a ratio represented the comparison of spans or extent of lines (or other geometric objects).

And this is the crux of the matter: In order to compare the length of two lines a reference line had to be found whose length was common to the two original lines (this idea also applies to finding a common area or volume when comparing areas or volumes), as illustrated below.

Two lines

Common measure

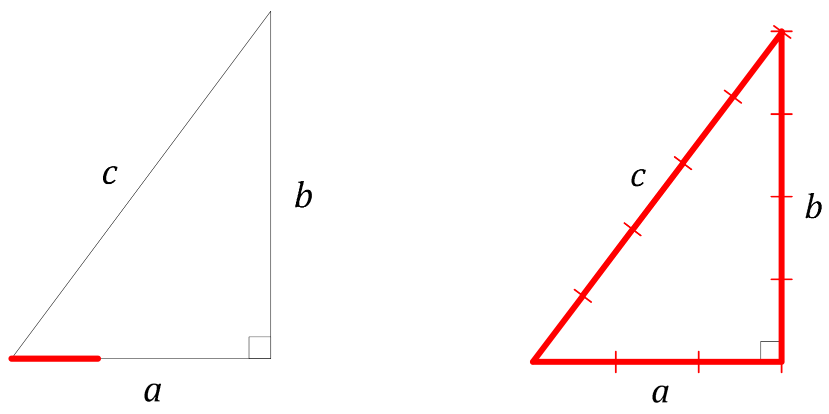
Confirmation of co-measurability



Ratio: Using numbers as a short-hand for lines of different magnitudes. 2 : 3

In comparing the ratio of two lines the ancient Greeks spoke in terms of lines being commensurable. The word commensurable comes from the latin: *co-* meaning “together with”, and *mensura* meaning “a measuring”. So, the two black lines above are commensurable because they have a common measure.

As another example of commensurability consider the right-triangle shown below in (i):

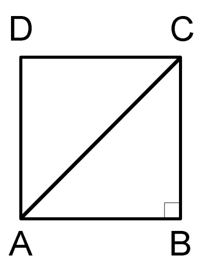


(i) (ii)

Let us take the red line of diagram (i) as our reference line or unit measure. Can this be used to measure all the lines of the triangle an integral number of times? Another way of asking this is, does our unit measure fit an integer number of times into the lines of length a, b, and c? By diagram (ii) above we see that it does. Hence, lines a, b, and c are commensurable.

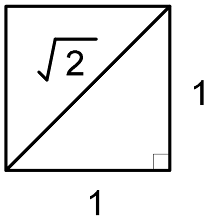
Incommensurability

Incommensurability is the opposite of commensurability. In other words, there exist two lines whose lengths are such that no reference/unit line will fit into them an integer number of times, *irrespective of how short we make our unit line*. It is the impossibility of making our unit line as short as we need which is key here. Our two original lines are therefore said to be incommensurable with respect to each other. The classic example of this is illustrated by unit square as shown below.

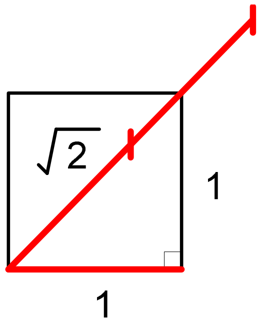


Given the Greek's idea of commensurability the question now is, Can the diagonal of the square above be expressed as an integer ratio p: q? To find out we try to construct a line which will act as a common measure to the side and diagonal of the square.

The first obvious thing to do is to use the side of the square as a common measure. However, in trying to fit this line to the diagonal the side of the square is not commensurable with the diagonal, as shown in diagram (b) below.



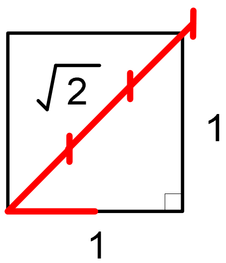
(a)



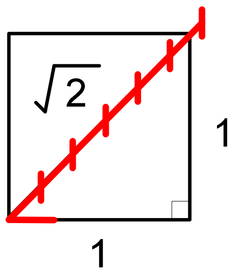
(b)

From the perspective of geometry it cannot be denied that the diagonal of the square exists. It also cannot be denied that the number "1" can be used to represent the magnitude of the sides of the square. But we have found in diagram (b) that, geometrically speaking, the side of the square does not fit an integral number of times into the diagonal.

Maybe we can overcome this problem by choosing a smaller unit line, as shown in red in diagrams (c) or (d) below. It turns out this even these unit lines will not fit an integral number of times into the diagonals of the respective squares.



(c)



(d)

It so happens that we would have to forever cut our unit line into ever smaller pieces, none of these ever being sufficiently short enough to fit an integral number of times into the diagonal. As such, the diagonal is incommensurable with the sides of a square.

What has this to do with paradigms and paradigm shifts? Well,

- the ancient Greeks' paradigm of numbers was that they were only positive integers. Nothing else. So total and complete was this attitude and belief that they had no conception of negative numbers and square roots;
- the ancient Greeks had no conception of fractions or parts-to-wholes. They compared whole one whole line with another whole line;
- they did this using a common measure, and believed that all lines could be compared with a common measure, however small this common reference line might be;
- then they encounter a line which does not have a common measure with any other line, i.e. the diagonal of a unit square. This diagonal clearly exists because it can be drawn and is finite in length. But it cannot be expressed using integers (i.e. finite numbers);
- the paradigm shift would have to be made whereby things like $\sqrt{2}$ would be seen and accepted as numbers.

Example 5: The paradigm of numbers – part 2

Another example of the Pythagoreans attitude towards numbers was that "1" was not a number at all. Instead it was the originator of all numbers in the sense that every other number could be constructed from it, for example: 1 + 1 = 2, 1 + 1 + 1 = 3, 1 + 1 + 1 + 1 = 4, etc. Also, subtraction had the effect of decreasing all numbers but since 0 and negative numbers did not exist "1" could not be considered a number since it could not be decreased. Yet more definitions of "1" were that it was i) the least number (remembering that all numbers were only natural numbers), or ii) that thing which is common to all numbers 2, 3, 4, 5….

So the Pythagoreans had a very specific perspective on numbers none of which we use today (except for the idea of even and odd numbers, which they also recognised). That was their paradigm.

Our paradigm today consists of the natural (counting) numbers ℕ, the integers ℤ (i.e. positive and negative natural numbers), the rational fractions ℚ (i.e. fractions which can be expressed as the division of two integers), and the real number ℝ (numbers which cannot be expressed as the division of two integers). These ae represented mathematically in the table below.

$\mathbb{N} = \{1, 2, 3, 4, 5, \ldots\}$	$\mathbb{Z} = \{\ldots, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, \ldots\}$	$\mathbb{Q} = \left\{\frac{x}{y} : x, y \in \mathbb{Z}\right\}$

$\mathbb{R} = \{x: x \text{ is a Dedekind cut}\}$ or $\mathbb{R} = \{x: x \text{ is an equivalence class of Cauchy sequences}\}$	$\mathbb{C} = \left\{x + iy: x, y \in \mathbb{R}, i = \sqrt{-1}\right\}$

Definition

The term "paradigm" is due to Thomas Kuhn, and comes from his book *The structure of scientific revolutions*. The short definition of a paradigm is that of the *whole worldview* one has about nature and how to study it scientifically. A paradigm is a set of beliefs (facts, assumptions, expectations, etc.) that are so fundamental to someone's world view of nature that they do not think to question them. "This is how the world is". So, everything makes sense in the context of the "worldview" of current science.

For example

- the Pythagoreans and their conception of numbers to describe social affairs;
- the Pythagoreans and their conception of numbers as only integers;
- Ancient people and the geocentric model of planetary motion versus the renaissance people and the heliocentric model of the solar system;
- the ancient Greeks and virtually all mathematicians up to the 18th century with their conception that mathematics was only geometry;
- The concept of heat as being an inherent part of an object (things are either inherently hot or cold) instead of seeing heat as transfer of energy,

etc. This worldview totally dominates our thinking about a natural phenomenon, what methods we use to study that phenomenon, what experiments we conduct and therefore what data we collect. For example,

- If we think that the Earth is flat we won't sail a ship to the edge of the world because we fear we might fall of the edge and into space;
- If we believe the planets move in circular orbits (say, because circles are seen as the perfect curve and therefore planets must move in perfect paths) then when people notice anomalies in the position of the planets they won't think to find a different path, such as an ellipse, which explains the anomalies. Instead they will try to add circular motion within circular motion (the epicycles of the Ptolemaic system) because "planets must move in circular orbits"

- Phlogiston: In the 18th century people believed that substances contained a fire-like element which was released during burning. This element was called *phlogiston*. So keeping the substance cool made phlogiston less volatile, hence it was not released. Smothering the substance would keep hold in phlogiston. For example, if you placed a burning candle in an enclosed jar the candle would extinguish because the enclosed air would become saturated with phlogiston so there would be no more space in the jar for any more phlogiston to be released. This would effectively smother the flame. Today we know that the candle would stop burning not because the flame is smothered but because the oxygen in the jar, which acts as fuel for burning, would have run out.

  Another effect described by phlogiston was the rusting of metals. This was supposed to be an example of phlogiston slowly escaping the metal, thus leaving a residue which was lighter than the original unrusted metal. But there were problems with this theory since it was known that after heating metals these metals would be heavier not lighter. To reconcile this fact with other aspects of the theory, phlogiston was theorised to also have negative weight (such an idea can be demonstrated today: a balloon filled with hydrogen will weigh less than an empty balloon implying hydrogen adds a "negative weight" to the balloon! However, we now know that this "negative weight" is due to another aspect of nature called *buoyancy*)

  Again, today we know that rusting occurs because of the interaction of oxygen with the metal. Here the metal *absorbs* oxygen (rather than releasing anything), and that the rusted metal weighs *more* than the original metal because the metal has taken on oxygen (instead of having lost weight because of anything being released).

  Because of the successes that phlogiston had over the years in explaining certain phenomena the theory of phlogiston lasted for over 100 years, with people trying to explain away anomalies resulting from experimental results. So well entrenched was the theory, that when Joseph Priestley discovered oxygen in 1774 he called it 'dephlogisticated air', believing that the mercuric oxide that he heated with sunlight had adsorbed phlogiston, removing it from the surrounding air.

All of this then influences how we perceive the physical world and therefore the theories we develop about the physical world.

So, paradigms are such that the worldview of a discipline remains constant over many years, decades or even centuries before going through radical shifts when a current theory can no longer

- explain the anomalies and errors of the theory

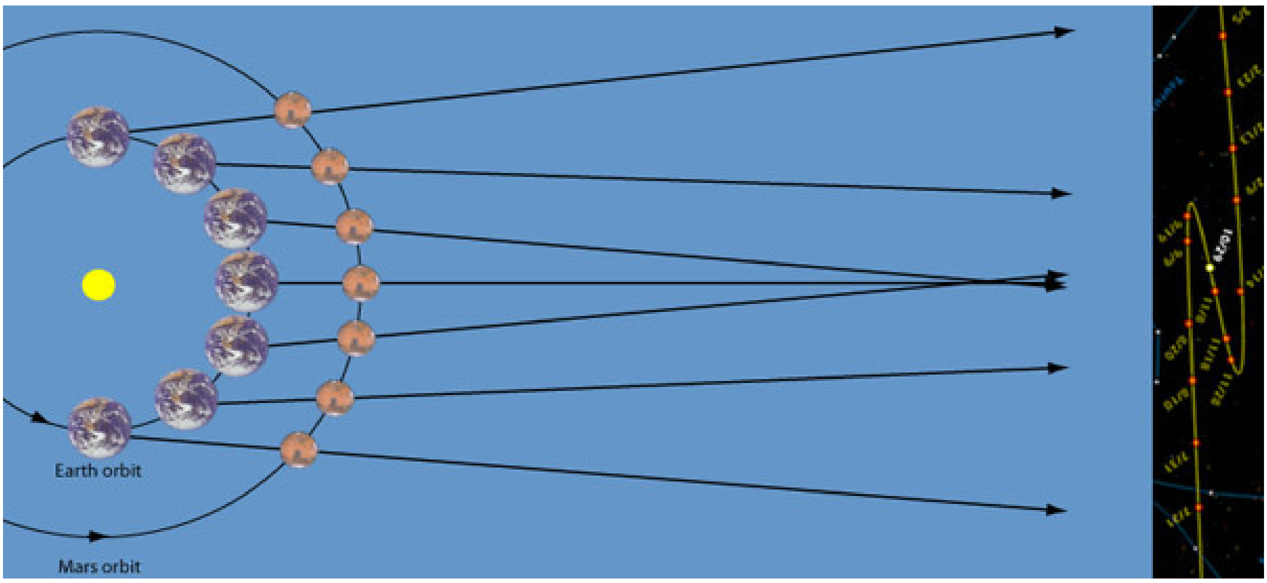
and

- sustain itself under the pressure of ever more anomalies and errors

For example,

- The Ptolemaic geocentric model of the planets (which lasted for 1000 years) could not explain the retrograde motion of Mars. This is the phenomenon whereby Mars seems to move backwards in the sky for a couple of months every two years before returning to its original course.

This was only explained by having a heliocentric planetary system, as illustrated below.



- classical Newtonian mechanics could not explain something called the precession of the perihelion of Mercury. Normally, planets revolve around the Sun in elliptical orbits. The planet changes position as it moves in its orbit around the Sun, but the whole orbit (i.e. the path of the ellipse) is always in the same position. But for Mercury it was seen that its orbit kept changing. In other words, not only is Mercury orbiting around the Sun, but Mercury's orbit is also orbiting the Sun, as illustrated in the diagram below. This change in the position of Mercury's path/orbit is called precession. This could be seen to be so because the point at which Mercury is closest to the Sun (Mercury's perihelion) kept changing. Newton's theory of gravity could explain with great accuracy the position of all the known planets except that of Mercury.

  The precession of Mercury's perihelion was first recognised in 1859 by Urbain LeVerrier. His re-analysis of available timed observations of movement of Mercury over the Sun's disk from 1697 to 1848 showed that the actual rate of the precession disagreed from that predicted from Newton's theory by 38 arcseconds per century (later re-estimated at 43″ by Simon Newcomb in 1882). So, all but 43 arcseconds of Mercury's motion could be explained by Newton's theory.

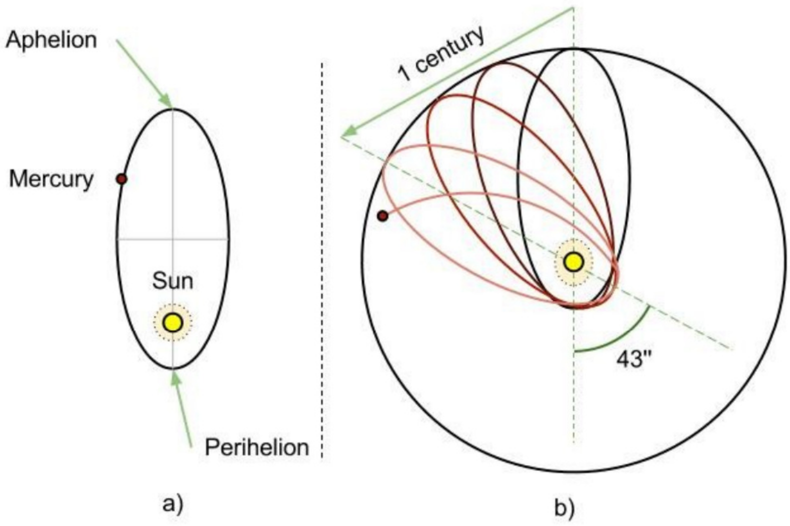


Fig. 3- In a) Mercury describes a "Newtonian" closed orbit, which means that after a period the planet returns to the same point. Therefore in b) Mercury follows a relativistic orbit where the perihelion shifts during each period. This movement is only about 43"/century.

LeVerrier suggested that another hypothetical planet might exist to account for Mercury's behaviour. The previously successful search for Neptune based on its perturbations of the orbit of Uranus led astronomers to place some faith in this possible explanation, and the hypothetical planet was even named Vulcan. Finally, in 1908, W. W. Campbell, Director of the Lick Observatory, after the comprehensive photographic observations by Lick astronomer, Charles D. Perrine, at three solar eclipse expeditions, stated, "In my opinion, Dr. Perrine's work at the three eclipses of 1901, 1905, and 1908 brings the observational side of the famous intramercurial-planet problem definitely to a close". In other words, there was no planet Vulcan.

The shifting orbit of Mercury was finally explained by Einstein's general theory of relativity. In general relativity, this remaining precession, or change of orientation of the elliptical orbit, is explained by gravitation being mediated by the curvature of spacetime. Einstein showed that general relativity agrees closely with the observed amount of perihelion shift. This was a powerful factor motivating the adoption of general relativity.

Both examples above illustrate the scientific revolutions which were confirmed by experiments. Such revolution occurs when the new paradigm better explains anomalous observations and offers a model which better explains the phenomena.

But there are advantages to paradigms (otherwise it would be very difficult to progress). The advantages of accepting a paradigm are that if we accept

- the theory of evolution by natural selection is accurate we can debate precisely what type of fossils we should expect to find in which regions of the world at what times in history;
- that the theory of plate tectonics is accurate we can debate with what frequency we should expect to see earthquakes in which region of the world, and what intensity they may be.

etc.

Exercises

1) What is the overall accepted "worldview" of your discipline? What are the core beliefs/theories accepted by your discipline?

2) What are the current aspects of your discipline that are debated? Which aspects are not open to debate because they are considered foolish or preposterous? Is this an indication of scientific prejudice? Look at any controversial ideas in your discipline: multiple (and possibly conflicting) perspectives on a theory/idea.

The following is a succinct description of the idea of scientific paradigms. It comes from https://en.wikipedia.org/wiki/Paradigm_shift :

> In his 1962 book *The Structure of Scientific Revolutions*, Kuhn explains the development of paradigm shifts in science into four stages:
>
> - **Normal science –** In this stage, which Kuhn sees as most prominent in science, a dominant paradigm is active. This paradigm is characterized by a set of theories and ideas that define what is possible and rational to do, giving scientists a clear set of tools to approach certain problems. Some examples of dominant paradigms that Kuhn gives are: Newtonian physics, caloric theory, and the theory of electromagnetism. Insofar as paradigms are useful, they expand both the scope and the tools with which scientists do research. Kuhn stresses that, rather than being monolithic, the paradigms that define normal science can be particular to different people. A chemist and a physicist might operate with different paradigms of what a helium atom is. Under normal science, scientists encounter anomalies that cannot be explained by the universally accepted paradigm within which scientific progress has thereto been made.
> - **Extraordinary research –** When enough significant anomalies have accrued against a current paradigm, the scientific discipline is thrown into a state of crisis. To address the crisis, scientists push the boundaries of normal science in what Kuhn calls "extraordinary research", which is characterized by its exploratory nature. Without the structures of the dominant paradigm to depend on, scientists engaging in extraordinary research must produce new theories, thought experiments, and experiments to explain the anomalies. Kuhn sees the practice of this stage – "the proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and to debate over fundamentals" – as even more important to science than paradigm shifts.

- **Adoption of a new paradigm –** Eventually a new paradigm is formed, which gains its own new followers. For Kuhn, this stage entails both resistance to the new paradigm, and reasons for why individual scientists adopt it. According to Max Planck, "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." Because scientists are committed to the dominant paradigm, and paradigm shifts involve gestalt-like changes, Kuhn stresses that paradigms are difficult to change. However, paradigms can gain influence by explaining or predicting phenomena much better than before (i.e., Bohr's model of the atom) or by being more subjectively pleasing. During this phase, proponents for competing paradigms address what Kuhn considers the core of a paradigm debate: whether a given paradigm will be a good guide for *future* problems – things that neither the proposed paradigm nor the dominant paradigm are capable of solving currently.
- **Aftermath of the scientific revolution –** In the long run, the new paradigm becomes institutionalized as the dominant one. Textbooks are written, obscuring the revolutionary process.

Exercises

1) What paradigms can you identify in your discipline? You only need to think on broad terms such as that illustrated in example 5. No details needed (unless you want to). What ways of thinking about the world did your discipline have in the past which is longer used today? For example, it might help you to set up a table as below

Discipline	Old paradigm	New paradigm
Astronomy	Geocentric system with circular orbits and fixed stars	Solar system with elliptic orbits and moving stars
Physics	Gravity is a force which acts invisibly at a distance	Gravity is curved spacetime
Mathematics	Mathematics is geometry	Mathematics is number and arithmetic

Physics	The atom is indivisible	The atom has many particles which themselves have many particles.
Heat	Heat is an inherent quality of a substance.	Heat is energy transfer between two substances
Thermodynamics	???	???
Aerodynamics	???	???
Hydrostatics	???	???
Chemistry	???	???
Data science	???	???

The entries in the table above are just examples. Feel free to use your own topics and disciplines.

2) Answer the "Questions to consider" on p1 of these notes.

3) *Optional:* There is a history to the conception of heat and the conception of force. The phenomena of heat and force were not understood in the past as they are today. What is the current conception/paradigm of these phenomena, and what was it in the past. You will need to look into the history science or physics for this (see for example Max Jammer's two books: *The conception of heat* and *The concept of force*).

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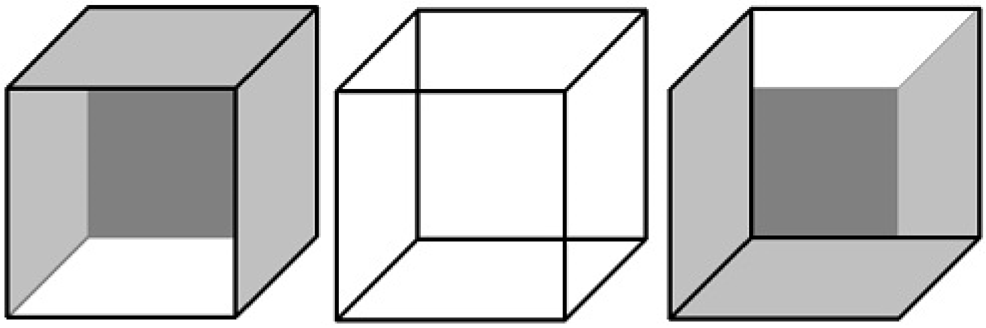
Suggested answer to the visual illusion exercise on p2

There are two ways to look at each diagram. In diagram (a) we can either see the cube as pointing up to the right or down to the left. In diagram (b) we can either see a young woman or an old woman. In diagram (c) we can either see a vase or two people facing at each other.



Spend some time looking at these diagrams. Notice that you have to shift your perception in order to see the alternative version of each diagram.

- Pay attention to the subtle shift in perception you need to go through in order to change from one view of the image to the other view of the image.
- If you stay looking at one particular version of a diagram are you aware of the other version? In other words, for each diagram, can you see both versions at the same time?

These examples are designed to show what I might call a visual paradigm shift. It is a shift in perception or worldview of how you see or perceive the image.