HU3101: History and Philosophy of Science

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Question 1. What are the most enduring contributions of Aristotle in science?

Answer. Aristotle was one of the great thinkers of the Ancient Greek civilization. In the context of science, he is mostly known for ideas which were later disproved by future scientists (say Galileo, who showed that objects in free-fall do so at the same rate, regardless of mass). However, his methodology and ways about thinking about problems in science were important stepping stones.

Following are some areas of science where his contributions stand out.

1. *Natural science:* At the heart of Aristotle's natural philosophy were the four classical elements: air, earth, fire, water. To this, he added a fifth: aether, which constitutes the heavenly bodies. Each of these elements is associated with a quality.

   (a) *Air* is hot and wet.
   (b) *Earth* is cold and dry.
   (c) *Fire* is hot and dry.
   (d) *Water* is cold and wet.
   (e) *Aether* is weightless and unchangeable.

   The first four form the terrestrial, 'corruptible' sphere in the universe: the Earth at its center. Here, the elements can change from one form to another, since they share certain properties. For instance, water can change into air (vapour) by heating, or into earth by drying.

   Surrounding it are the concentric, celestial, crystal spheres, on which the Moon, Sun, the planets, and finally the firmament of the stars are embedded. These are in constant circular motion at a constant rate, as it is the aether's tendency to remain in motion.

2. *Physics:* Aristotle uses the formulation of the elements to explain the motion of objects, which he divides into two types: natural and unnatural. Natural motion is that which happens of its own accord, without being forced in any (apparent) way. Recall how he explained the natural motion of the heavenly bodies by invoking the tendency of aether to be in circular motion. Similarly, he said that earth and water tend to move downwards, while air and fire move upwards. In this way, the natural motion of objects is related to the ratios of the four elements comprising it. Thus, objects of earth and water move down towards the center of the Earth (indeed, the universe), explaining 'gravity'. In addition to natural motion, these elements have related natural places: earth and water at the center of the universe, air above water (bubbles rise in water), and fire higher still (but not as high as the Moon's celestial sphere). The natural motion of these elements is thus their attempts at reaching their natural place; they have a certain potential to do so, which when actualised is seen as motion.

   Aristotle said that if a heavier object and an otherwise identical lighter object are dropped, the heavier one would wall faster. In other words, the speed of free-fall is directly proportional to the object's weight, inversely to the surrounding medium. When coming to natural motion unnatural motion, Aristotle said that a heavier object takes more force to move; the greater the force, the faster the motion. Furthermore, an object's natural state is one of rest, so upon removing the applied force, the motion will cease. Put together, Aristotle says that an object in a vacuum would fall arbitrarily/infinitely fast, and thus argues that such a vacuum is impossible (things such as air would move into this vacuum and fill it up).

Today, we know that these formulations are incorrect; objects in free-fall move together regardless of weight, and the apparent 'natural state of rest' is the work of friction (which Aristotle was unaware of). It seems simple enough to disprove these via experimentation, yet it took well over a millennium to actually do so (Galileo and Newton stand out in the context of mechanics). This is partly because of Aristotle's methodology of arriving at these principles via common experience and reason alone, without emphasis on rigorously verifying these results via experiments in the modern sense.

3. *Teleology:* Related to the idea of motion, Aristotle talks about his *four causes*: why do things happen/change? The answers to such questions have these four aspects.

   (a) *Material cause:* The physical matter comprising an object.
   (b) *Formal cause:* The shape/arrangement/appearance of an object.
   (c) *Efficient cause:* An (external) agent which interacts with an object.
   (d) *Final cause:* The purpose an object exists to serve, often called *telos*.

   To illustrate this, consider a table: its existence is determined by wood (material), the actual shape of the table (form), the carpenter who built it with his tools (agent), and its role as something to dine on top of (purpose).

4. *Biology:* Aristotle's chief contribution is his systematic approach to classification of life-forms, which earned him the title of "father of zoology" – this is perhaps his most enduring contribution to science. He made observations for two years in the island of Lesbos, and accumulated massive amounts of data in *History of Animals*, *Generation of Animals*, *Movement of Animals*, and *Parts of Animals*. He also took into account observations made by others, such as fishermen and sailors. He also carried out dissections in order to carefully study the structure of animals. Some of his anatomical observations (for instance the hectococtyl arm of cephalopods) were not fully believed/appreciated until very recently (the 19th century in this instance). Armed with this data, he broadly classified animals into those with blood (vertebrates) and those without (invertebrates). These were further divided into categories such as Man (an indivisble form), birds (of which he distinguished around 500 species), Cetaceans, Fish (egg-laying and non-egg-laying), Crustaceans, Insects, etc. These fifteen or so categories were each given qualities (hot/cold/wet/dry), a type of 'soul', and arranged in a hierarchy with Man at the top and Plants and Minerals at the bottom.

   Aristotle identified five major biological processes, essential to the functioning of an organism.

   (a) *Metabolism:* The intake of food (matter), which is used to by the organism to live/grow/reproduce.
   (b) *Temperature regulation:* How the blood is heated and cooled by metabolism and the outside air, with the process driven by the heart and lungs.
   (c) *Information processing:* The ability of an organism to sense its surroundings, process it, and act accordingly.
   (d) *Inheritance:* The transmission of the parents' characteristics to their offspring.
   (e) *Embryonic development:* The formation and development of an embryo.

Together, these form a system called a 'soul' (this is purely biological in nature). A vegetative soul such as in plants is associated with reproduction/growth, a sensitive sould such as in animals with sensation/movement. Humans also have a rational soul, associated with thought.

Aristotle also observed many simple patterns in his data. For instance, smaller animals like mice have significantly shorter lifespans, shorter gestation periods, and larger brood sizes compared to larger ones like elephants (we know that these quantities vary logarithmically). We highlight again that while Aristotle did not go out of his way to carry out motivated experiments, his system of gathering lots of data and finding correlations was quite fruitful, and may even be called scientific in some sense (this is often the first stage in scientific enquiry, i.e. looking at patterns).

Question 3. Despite the glorious achievements of science in the 19th century, the century ended with a theoretical pessimism. Why?

Answer. The 19th century was indeed a glorious time for science and technology, with world-changing advancements in all fields: physics, chemistry, biology, and engineering to name a few. First, we explore some of these below.

1. *Classical mechanics:* Newton's Laws proved to be an incredible achievement in physics, and these principles were tested and used extensively; as Newton's predictions continued to be proved right time and again, this inspired great confidence in these theories. Two important reformulations of Newtonian mechanics were Lagrangian mechanics (earlier in 1788) and Hamiltonian mechanics (in 1833).

   Here, we wish to emphasize that with the success of classical mechanics, the general opinion in this era was that Newton was right beyond a shadow of a doubt. This air of confidence (at least in the field of physics) is what defined this century.

2. *Electromagnetism:* The connection between electrical and magnetic phenomena was first observed by Oersted: a moving electrical current (say in a wire) can deflect the needle of a magnetic compass. This was followed by Faraday's great and numerous experiments (often public demonstrations which were incredibly popular), by which he discovered the reverse principle of electromagnetic induction: a moving magnet can induce a flow of current. His assistant James Clerk Maxwell went on to formalize these ideas mathematically, and in doing so united electricity, magnetism – as well as optics! His theory indicated the possibility of self-propagating electromagnetic waves (oscillations of electric and magnetic fields), and he calculated that these waves move at a speed which was very close to the (then known) speed of light. Thus, he proposed that light itself is nothing more than an electromagnetic wave. Maxwell's equations are known as one of the most beautiful in physics.

$$\epsilon_0 \nabla \cdot \mathbf{E} = \rho \qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \epsilon_0 c^2 \nabla \times \mathbf{B} = \mathbf{j} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

3. *Thermodynamics:* Sadie Carnot, known today as the 'father of thermodynamics', published *Reflections on the Motive Power of Fire* in 1824, where he talks about heat, energy, and engine efficiency. Instead of looking at a steam engine with all its complication, he studies an abstract 'heat engine'. With this idealized picture, he showed that the most efficient engine possible is the Carnot cycle: its efficiency is a function only of the temperatures of the source and sink of heat, and is always strictly less than one. This work was

later extended by Clapeyron, and entered the body of work later contributed by other greats in the field.

The fact that heat is not a 'fluid' as advocated by the caloric theory, but is instead produced by motion was demonstrated by James Joule. He calculated a relation between a unit of heat, and a unit of mechanical energy: this *mechanical equivalent of heat* says that 1 cal $\approx$ 4.15 joule (in modern units). Later, Helmholtz wrote on the conservation of energy in his 1847 paper, examining various phenomena in mechanics, heat, light, electricity, magnetism in the context of this energy.

Lord Kelvin (William Thomson) was also a key contributor in this field. For instance, he developed the absolute temperature scale which bears his name, he studied and improved the work of Carnot and Clausius, and collaborated with Joule (the Joule-Thomson effect is well a known phenomenon). He also contemplated the second law of thermodynamics, and spoke of the heat death of the universe. Later, Ludwig Boltzmann, Willard Gibbs, and Maxwell developed the field of statistical mechanics, which offered another interpretation of entropy.

4. *Periodic Table of Elements:* With new element after element being discovered in the field of chemistry, there were many attempts at classifying them. Notable is Newlands' law of octaves, where he used the fact that when elements are arranged in order of increasing atomic mass, several properties repeat in groups of eight. Dmitri Mendeleev devised the first truly useful periodic table of elements, which in a slightly modified form is used even today. One of its merits was its predictive power: Mendeleev saw that in order to abide by the rules of his table (periodic properties down a group, increasing atomic weight across a period), he would have to leave gaps. He declared that these gaps represented new elements which had not been discovered yet, and made stunningly accurate predictions of their properties, which were confirmed within the end of the century. This revolutionized the study of chemistry.

5. *Theory of Evolution:* The introduction of the Theory of Evolution by Natural Selection by Charles Darwin and Alfred Wallace was revolutionary in the field of biology: Darwin's *On the Origin of Species* of 1859 was an incredibly popular book. The theory speaks of how individuals in a species can accumulate small, inheritable changes over long periods of time; those changes that are favourable to the survival and reproduction of the individual survive while unfavourable ones do not. Thus, the characteristics of a species gradually change over time. Furthermore, different groups of individuals from the same species may undergo a different route of changes (perhaps they end up developing in different geographic locations) until they are sufficiently distinct to be regarded as different species. This is how multiple species can originate from common ones. A corollary of Darwin's theory was that mankind and today's primates descended from a common ancestor. These ideas were greatly opposed by Christian fundamentalists, as their religion seems to imply that all modern species were present at the time of Creation, unchanged over time. Today, we know that the theory of evolution is indispensable to biology, appearing in some form or another as a guiding principle in every corner.

6. *Engineering:* The 19th century say many technological and engineering innovations; we mention just a few, closely related to our discussion on physics. Siemens used the steam engine coupled to a dynamo for power generation. Reversing this principle and improving it, Ferraris and Tesla create their own induction motors. Parsons built the first practical large steam turbines for generating electricity.

By the end of the century, there seemed to be a general feeling that all the basic principles of nature had been discovered: first Newton's classical mechanics, then thermodynamics and electromagnetism in physics, the periodic table in chemistry, and the theory of evolution in biology. In the words of one writer, the work of science was at an end, with

> ...only a few turrets and pinnacles to be added, a few roof bosses to be carved.[1]

Quite a few scientists believed that all that remained for science to do was to make better and better measurements.

In physics at least, there were three major unresolved problems.

1. The nature of the all pervading luminiferous ether, the medium for the propagation of light.
2. The ultraviolet catastrophe, a failure of the Rayleigh-Jean law.
3. The anomalous precession of Mercury, a discrepancy of 42 arcseconds per century.

The first was shown by Michelson and Morley (the former strongly shared the sentiment that all natural phenomena trace back to this ether) to be non-existent. The second demanded the power of quantum mechanics; the third demanded the power of general relativity. Both of these are defining theories of modern physics.

Even in biology, the fundamental mechanism behind inheritance – the role of the DNA molecule – was yet to be discovered and understood (DNA itself had been isolated by Miescher in 1869, but its purpose had not been determined). Another problem was that evolution of species necessitated immense amounts of time; so do various geological processes such as mountain building or the passage of glaciers. There was an abundance of palaeontological evidence supporting the idea that the Earth was much older than previously thought; yet eminent scientists such as Lord Kelvin estimated its age at no more than 80 million years, with his final prediction at 20 million years. This is because there was no known process/source of energy that could keep the Sun burning for more longer that (the source of the Sun's energy was thought to be gravitational collapse). This changed with the discovery of radiation by Becquerel and Rutherford, then the subsequent discovery of nuclear fusion. It is interesting to note that the size of the Earth had been measured by Eratosthenes around 200 BC; the weight of the Earth had been properly measured by Cavendish around 1800 AD; the age of the Earth was only accurately determined by Clair Patterson to be around 4.5 billion years (using radiometric dating of meteorites) in 1956.

[1] See Bill Bryson's *A Short History of Nearly Everything.*