HU3101: History and Philosophy of Science

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Question 1. Describe the steps through which nuclear fission was discovered.

Answer. The discovery of nuclear fission is a key milestone in science, sandwiched between the discovery of the phenomenon of radioactivity, and the creation of the nuclear bomb.

1. *Discovery of radioactivity:* X-rays were discovered by Wilhelm Röntgen in 1895. Attempting to produce these from uranium salts, Henri Becquerel ended up discovering an entirely new phenomenon merely a year later – these salts were capable of producing an image on an X-ray plate without any external energy source. Marie and Pierre Curie further investigated this phenomenon, finding the same properties in thorium, polonium, and radium (the latter two being elements they discovered themselves). This was dubbed *radioactivity.*

   Ernest Rutherford classified these new rays into two types – α and β. Later, Paul Villard identified a third, namely γ. By 1909, α particles had been identified as helium nuclei, and β particles as electrons/cathode rays. Meanwhile, Rutherford and Curie both observed that these radioactive elements seemed to undergo decay, releasing a radioactive gas – this was named radon. Rutherford and Frederick Soddy investigated these rates of decay of the radioactive products, and introduced the concept of a 'half-life'. Later, Soddy and Margaret Todd introduced the idea of chemical isotopes – atoms of the same element (chemically and spectroscopically identical) by having different half-lives.

2. *Investigations into the atomic nucleus:* In 1909, Rutherford performed his famous gold-foil experiment, firing α particles at a thin sheet of gold. He deduced the existence of an atomic nucleus: a minuscule region within an atom which carried practically all of its mass, with the remainder being mostly empty space. The Rutherford model thus describes a nucleus containing positively charged protons, circled by negatively charged electrons. In 1913, Niels Bohr introduced the Bohr atomic model, a groundbreaking achievement.

   One problem with these models was that it was difficult to account for the stability of an atom, given the intense electrostatic repulsion between the positively charged protons in the nucleus. Rutherford and Bohr began hypothesising about another kind of nuclear particle, which would compensate for these repulsive forces by exerting an attractive nuclear force of its own. This was supported by a mismatch (by a factor of 2) between the observed atomic masses and the mass contributed by protons alone. In 1932, James Chadwick discovered and identified the neutron, confirming these suspicions.

3. *Nuclear transformations:* Following the discovery of radioactivity, a plethora of experiments were performed in which atoms were bombarded by these new α particles. One notable instance is that of the transmutation of nitrogen into oxygen, performed by Rutherford but actually identified by Patrick Blackett.

   $$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \to {}^{17}_{8}\mathrm{O} + \mathrm{p}^{+}.$$

   James Chadwick's experiments used the following nuclear reaction.

   $$^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \to {}^{12}_{6}\mathrm{C} + \mathrm{n}^{0}.$$

It was noted that the electrically neutral neutron would likely serve as a much better bombarding particle. This idea was used by Enrico Fermi and his team in Rome, with help from Lise Meitner and Otto Hahn in Berlin. By performing neutron bombardment of elements such as aluminium and above, they were able to produce ‘induced radioactivity’, i.e. the element would be converted into a radioactive isotope. Fermi identified three results of this neutron irradiation: release of α particles, release of a proton, or release of γ rays. Finally, the newly created radioactive isotope would undergo β decay, resulting in a transmutation of the element. In this way, Fermi generated what was thought to be new, heavier elements by bombarding uranium with neutrons, winning him the 1938 Nobel Prize in Physics.

4. *Nuclear splitting:* Fermi’s discovery was met with skepticism by Ida Noddack, who pointed out that the neutron bombardment of uranium, a fairly heavy element, could have caused it to split into much lighter elements instead of neighbouring ones. This idea was not followed up upon, since there was currently no theoretical understanding of how a tiny neutron could make this happen.

   By 1938, Meitner was forced to flee from Nazi Germany, and ended up in Sweden. She continued to work with Hahn and Fritz Strassman who were at Berlin. When redoing Fermi’s experiments with uranium, they discovered that the products contained barium, a significantly lighter element than uranium. Thus, it was indeed the case that the bombarding neutrons cracked the uranium nucleus into sizeable chunks.

   Meitner discussed this puzzling result with her nephew Otto Frisch, and during the Christmas holiday, they went for a walk in the snow and made the following insights: using the liquid drop model of the nucleus advocated by Gamow and Bohr, they found a mechanism to explain how the incoming neutron could sufficiently deform the uranium nucleus, resulting in it splitting into two fragments. Now, these newly formed nuclei must repel each other and move away at very high speed; this would require around 200 MeV of energy. Where could this energy come from?

   Meitner calculated on the spot that the masses of the daughter nuclei empirically fall short of the mass of the original uranium nucleus by about one-fifth that of a proton. Enter Einstein’s mass-energy equivalence principle,

   $$E = mc^2.$$

   Plugging in m as the mass discrepancy gives precisely the required 200 MeV of energy. The same was experimentally confirmed by Frisch in January 1939. After speaking with the biologist William Arnold, he named this process *fission*, analogous to cell division. These results were published in *Nature* soon afterwards.

It was noted that this nuclear reaction resulted in the release of neutrons as well, which themselves can bombard other nuclei; this would lead to a *chain reaction.* The relevant nuclear equation describing the fission of uranium-235 (one possibility) is as follows.

$$\mathrm{n}^0 + {}^{235}_{92}\mathrm{U} \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + 3\,\mathrm{n}^0.$$

There are two major paths of development after this: using such an uncontrolled chain reaction and its tremendous release of energy to create an atomic bomb, and harnessing a controlled chain reaction to create a power plant. The former was actively pursued during the Second World War, notably in the Manhattan Project. Two atomic bombs were dropped on the cities of Hiroshima and Nagasaki in 1945. The first nuclear reactor producing electricity began operating in 1951.

Question 2. Describe the four kinds of proof admitted in Indian philosophy, indicating the merits and demerits of each as valid scientific reasoning.

Answer. We focus on the Nyaya school of thought, which recognizes four *pramanas*, i.e. means of knowledge.

1. *Pratyaksha (perception):* This is perhaps the most important of the four; it is interesting to note that this is the *only* method accepted by the Charavaka school of thought.

   Here, perception is divided into *laukika* (ordinary) and *alaukika* (extraordinary). Ordinary perception is simply the use of one's sense organs (sight, touch, taste, smell). Extraordinary perception includes *pratibha* (intuition), *samanyalaksanapratyaksa* (induction), and *jnanalaksanapratyaksa* (retrograde analysis).

   In order for an observation to qualify as being valid, it must satisfy *indriyarthasannikarsa* (direct experience), *avyapadesya* (be non-verbal), *avyabhicara* (be unchanging), and *ayavasayatmaka* (be definite). Essentially, one must perceive an object directly, without relying on someone else. This observation must have some sort of stability, and must be free of doubt.

2. *Aumana (inference):* This is the use of previously known knowledge to derive new knowledge, by a combination of induction and deduction. A statement of inference will contain three parts – minor, major, and middle. The *paksha* or minor is the subject of inference, i.e. the thing we are trying to make an inference about. The *sadhya* or major is the object of inference, i.e. the property of the subject which we are trying to establish. These are to be connected by the *hetu* or reason/middle term, which is some general, true statement about the subject. Of course, the strength of such an argument is determined by the *hetu*, which must be free of contradiction. The Nyaya darshan also identifies possible fallacies in the *hetu*, as follows.

   (a) *Asiddha:* The *hetu* is simply false/unproven. It may be the case that the subject is itself non-existent (*ashrayasiddha*), which makes whatever follows meaningless. Another possibility is that the *hetu* is not present in the subject at all (*svarupasiddha*), or it is conditionally present (*vyapyatvasiddha*).

   (b) *Savyabhichara:* The *hetu* is not properly connected with the subject. For instance, the *hetu* may be too general (*sadharana*), too specific (*asadharana*), or non-exclusive (*anupasamhari*).

   (c) *Satpratipaksa:* The *hetu* is contradicted by a different *hetu*.

   (d) *Badhita:* The *hetu* is contradicted by a superseding proof, such as perception.

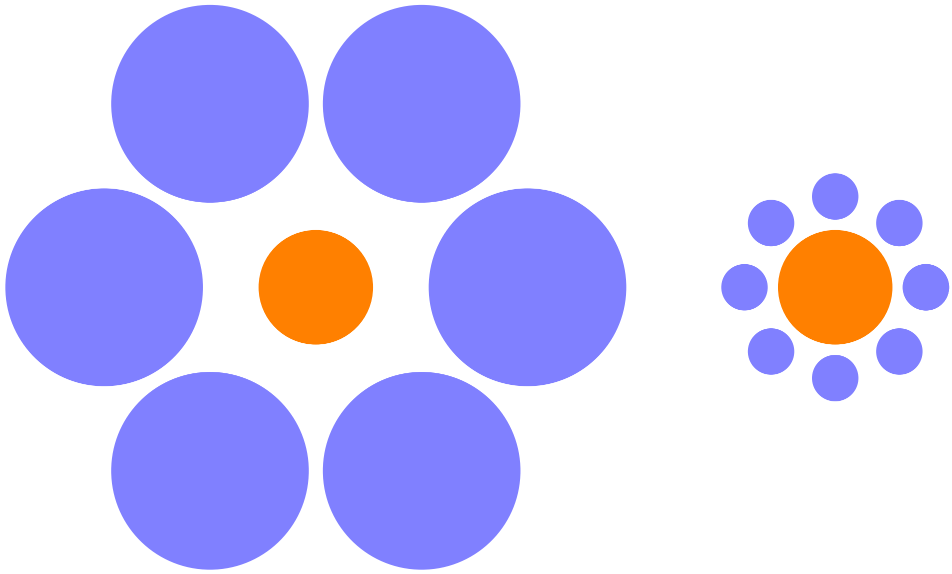
   (e) *Viruddha:* The *hetu* proves the opposite statement.

3. *Upamana (analogy):* This is the use of analogy/comparison with existing knowledge. More precisely, it is the knowledge of the relation between a name, and the object denoted by that name. This is often useful when talking about descriptions: comparing some object with a known one makes it easier to identify.

4. *Sabda (testimony):* This is the use of the word/testimony of others, presumably experts. It can be argued that one person cannot derive everything they need (using the previous means of knowledge) practically; this would require far too much time and energy. Thus, one has to rely on previously acquired knowledge, communicated by the spoken word or writing. *Sabda* has to come from a trustworthy source; divine revelation, or other people. The former is said to be infallible, the latter is not.

We note the absence of the pramanas *Arthapatti* (derivation from circumstances) and *Anupalabdi* (knowing a negative), which are sometimes accepted by other schools.

In the context of modern scientific reasoning, we can reaffirm *pratyaksha* as the most important source of knowledge. Science is almost entirely concerned with the observable/perceivable world, and when assessing a particular hypothesis or theory, raw observational data trumps everything else. Of course with advancements in technology, we have recognized that the human senses are not enough; thus, we use instruments to make up for these deficiencies, say a telescope or a microscope for better vision. This is also recognition that our senses can be unreliable, sometimes consistently so (optical illusions are a great way of demonstrating the unreliability of visual perception) which makes the use of these external tools even more important. The image below shows the Ebbinghaus illusion: the two orange circles are in actually identical. While this is difficult to directly perceive, we are perfectly happy to accept this fact once the circles are measured using a scale, such is our trust in these instruments.



Similar arguments show that *pratibha* or intuition is not a reliable method of reasoning; science today has brought many counter-intuitive results to light, an extreme example being quantum mechanics. Finally, it is not enough to focus on one's own perception, since modern scientific knowledge is based on repeatable, reproducible, testable results. Something perceived by a single individual amounts to anecdotal evidence; only when it has been tested by other independent individuals or bodies does it enter scientific knowledge (this seems to carry an element of *sabda* or authority). These points are meant to highlight the untrustworthiness of perception when applied naïvely under certain circumstances.

As we have seen, the use of *anumana* or inference is heavily dependent on the *hetu* or reason; thus, there has to be a great deal of confidence in this reason, which is typically a general principle applicable to the subject. Thus, the main problem becomes justifying the *hetu*, which ultimately comes down to the problem of induction (how can we guarantee that the reason applies to the subject, based on limited observations). Today, we use Popper's principle of falsifiability to establish this trust (rarely absolute) in the *hetu*. Once this is done, there isn't really any doubt in the validity of the syllogisms that follow. Many objects in modern science, such as subatomic particles, are not directly observable (at least not in same sense as *pratyaksha*), their existence can only be inferred from other observations. Similarly, one could also argue that any observation made by a scientific instrument is not perceived knowledge, but rather inferred knowledge (based on the assumption that the instrument does indeed work, and accurately reflects reality).

Upamana seems to be an essential part of discovery, specifically communicating that discovery to the rest of the world. When a novel phenomenon is first encountered, the job of the discoverer is to document it so that others can independently verify these findings. In this process, one has no choice but to use analogy; after all, the unknown has to be described by something already known for the description to make sense – this is fundamental to human communication, which is based upon common experience. In modern science, this need only apply to the qualitative aspects of a description; the quantitative parts are specified using measurements. In the same way, *upamana* is essential to scientific communication in general, as well as the learning process. Outside of this, *upamana* does not play any role in science; it cannot be used to generate new knowledge.

Like *upamana*, *sabda* or testimony is tied with scientific communication. A person today cannot independently verify (by *pratyaksha* or *anumana*) the vast amount of knowledge required to lead a normal life, there is simply too much. Thus, we rely on experts in various fields to communicate what they know to us. An important distinction between *sabda* and its modern counterpart is that science is rooted in observations of nature, not divine revelation. Thus, in order for a piece of knowledge communicated by *sabda* to be considered scientific, it must be possible to trace it back to a conventional source (something arising from the scientific method). Thus, *sabda* is never the source (nor proof) of scientific knowledge, merely a tool of dissemination; *sabda* used as an 'argument from authority' without adequate evidence backing it is out of the question. In the presence of contradictory *sabda*, there is no way for a casual listener (who presumably has no other way of gaining that knowledge) to judge with absolute certainty which is correct. Here, an element of trust creeps in, and it becomes necessary to talk about 'scientific consensus'. Consensus among experts in a field can be taken as a heuristic, used to determine a level of trust.