Backstory to Deductive Thought

The example of Bohr's atomic work illustrates the innovative use of deduction applied to the subtle area of the foundations of physics. However, deductive logic as a fully systematic discipline can be traced to the ancient Greeks, beginning with Aristotle's (384-322 BCE) syllogistics and Chrysippus's (ca. 279-ca. 206 BCE) system of propositional logic but also included other categories of argument, demonstration and explanation [547] [548]. Greek thought was expansive and characterized by a relentless use of the power of logical thought, even if this led to paradox and contradiction [340, p. 54]. Although the senses may not be perfect, they also had a role as useful guides if employed with judgment. Aristotle's predecessors had already been assessing the criteria for proof and the rules of inference. Among the fundamental questions of most interest were: (1) the underlying material substance of the world including the origins of the atomic world-view, (2) whether or not and how change was possible, and most importantly for the future development of science, (3) the problem of knowledge (*epistemology*) and understanding the rules of reasoning, argumentation, and assessment of theories. The Greek inquiries into knowledge initiated the path that eventually led after much struggle to the methods of modern science.

The earliest scientific theories were formulated by the pre-Socratics, the Greek natural philosophers from the 6th and 5th centuries BCE who were among the first to explain phenomena in terms of naturalistic causes. These were not theories of physics in the modern sense of systematically constraining them by empirical observation. It has even been suggested that to understand these early Greeks, it is better to think of them not as physicists or scientists or even philosophers, but as poets [304, p. 12]. They were predecessors of modern science in that they pioneered the use of causal explanations in place of the tradition of myths and supernatural forces, even if the explanations were sometimes based on speculation and assumption. Imposing current values on the past, sometimes pejoratively labeled *Whig history* by historians, may not be out of place in judging the status of early physical theories [304]. Their importance becomes more apparent if we also compare them with their predecessors [549] [550]. Development of the sciences had their start at the beginning of the 5th century BCE with the Ionian natural philosophers who lived on the coast of Asia Minor, where the influences of the east and south were strongest. It then spread to the Pythagoreans and Eleatics (Parmenides and his school) of what is now southern Italy. Subsequently, philosophy experienced its peak in Athens with Socrates, Plato, and Aristotle. The 6th century BCE Greeks were the result of colonization of the Mediterranean shore and Aegean islands. In the 5th century BCE, the Greeks maintained contact only with the Persian empire. It was a time of questioning of the relation of man to the universe and the individual to society. In the 4th century BCE came the flourishing of Greek philosophy and science, Plato, and Aristotle. Alexander the Great, educated by Aristotle, set out in 334 BCE to overpower the Persian empire and conquer the world.

As a result, Greek culture spread to all conquered lands and Greece was enriched by contacts with Mesopotamia and Egypt, resulting in the important scientific developments of Hellenism and Alexandria in the 1st and 2nd centuries BCE [340, p. 45]. Aristotle's methods in logic were widely adopted following the translations of Boethius in the 6th century. By the 12th and 13th centuries, translations of the ancient texts became available and were assimilated across Europe. However, the Aristotelian model for scientific investigation had been severely challenged by the end of the 16th century. A competing view, in the form of the atomism of Democritus (ca. 460-ca. 370 BCE) and Epicurus (341-270 BCE), became known through the work of the Roman poet Lucretius (ca. 99-ca. 55 BCE), *On the Nature of Things* [506]. This view of the world as randomly moving indivisible atoms in an infinite void found its way into the 17th century to Galileo Galilei (1564-1642) in Italy, René Descartes (1596-1650) and Pierre Gassendi (1592-1655) in France, Robert Boyle (1627-1691) and Isaac Newton in England. By the end of the century this mechanistic philosophy became dominant although in a predominantly deterministic form. The scientific revolution may have appeared as a sharp transition focused on the 16th and 17th centuries when viewed from the scale of millennia but ways of thinking about the world had accumulated across a much larger scale. However, the disciplines of the deductive reasoning of Aristotle and the atomism of Democritus and Epicurus that trace back to ancient Greece are a vital part of science today and are foundational elements for understanding the measurement problem.

The intellectual transition to science in the time and place of ancient Greece is often attributed to favorable circumstances of geography, economics, religion, and politics [551]. The geography of mountains separating cities and the sea separating islands encouraged the formation of diverse city-states in which there was social freedom and democracy as well as no official religion requiring dogma or rituals to interfere with intellectual pursuits. In addition to these factors, Nicolaides has argued for the possible influence of the Greek language, citing a statement from the mathematical logician and historian Bertrand Russell (1872–1970): "The Greeks, borrowing from the Phoenicians, altered the alphabet to suit their language, and made the important innovation of adding vowels instead of having only consonants. There can be no doubt that the acquisition of this convenient method of writing greatly hastened the rise of Greek civilization." [551, p. 81] This development occurred around the 8th century BCE and spread rapidly. Having a phonetic language, where each sound has its own symbol, facilitated the clear formulation of abstract thoughts and encouraged discussion and refinement. It's a plausible and interesting possibility that the invention and flourishing of deductive reasoning, a necessary tool for understanding fundamental aspects of our world today, can be partly traced to the innovation of the vowel some 3000 years ago.

Aristotle's many treatises cover topics which could be seen as the continuation of a long history of inquiry by his predecessors. The exception is his development of logic, for which Aristotle emphasizes [547, p. 27],

> *When it comes to this subject, it is not the case that part had been worked out in advance and part had not; instead, nothing existed at all.* [Sophistical Refutations 34]

R. Smith, Logic; pp. 27-65, In: The Cambridge Companion to Aristotle, J. Barnes (Editor), Cambridge University Press, 1999.

Aristotle was the first to conceive of a systematic treatment of inference and the *Prior Analytics* [353] is a complete exposition of his theory of syllogistics. There are also treatments of two types of arguments: *demonstration* which produces scientific proofs, the subject of his *Posterior Analytics,* and *dialectical argument* which focuses on debates between persons, the subject of his *Topics*. These are supplemented by *On Interpretation,* on the structure of propositions and their truth-conditions, and *Categories,* on the theory of meaning of the terms within propositions. The syllogism though is claimed to be the correct basis for all arguments; e.g., the universal affirmative "All Bs are Cs, all As are Bs, so all As are Cs" where each of the premises is a necessary truth. He goes on to explore many different variations and alternatives to this template. Aristotle recognizes two types of argument which lead to conclusions in fundamentally different ways, deduction and induction [547, p. 32],

> *A deduction is an argument in which, certain things being supposed, something else different from the things supposed follows of necessity because of their being so.*
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> R. Smith, Logic; pp. 27-65, In: The Cambridge Companion to Aristotle, J. Barnes (Editor), Cambridge University Press, 1999.

Aristotle also recognized induction, which infers a general conclusion from a number of instances. This is a generalization of particulars to the universal, such as:

Socrates has red hair.
Plato has red hair.
Aristotle has red hair.
All humans have red hair.

However, a *single* counterexample can render an inductive argument false; e.g., Empedocles has black hair. By its very nature, inductive reasoning can dramatically fail for problems that cannot be solved using existing theory. Thus, induction would not be a good method to test the theory that all humans have red hair. Additional premises could be added in the attempt to make the inductive argument valid. However, as we continue to add more and more premises, we find that the inductive argument is being reworked into making it deductively valid. The large number of required supplementary premises typically required to make deduction valid illustrates how deduction applied to the physical world is an unruly process requiring boldness and intuition. However, deduction is the method that is appropriate for precisely those problems that demand the use of *exceptions* to the currently known theory for their respective solutions. Aristotle does not give a complete theory of inductive argument and his comments on it are less extensive than on deduction. We can recognize situations where induction can be useful; e.g., drawing conclusions by generalizing what is known [547, p. 32]:

Every A observed so far is B; therefore, every A without qualification is B.

R. Smith, Logic; pp. 27-65, In: The Cambridge Companion to Aristotle, J. Barnes (Editor), Cambridge University Press, 1999.

This is the situation in well-established areas of modern science where the inductive application of theory can be very productive.

Aristotle's work on logic was not by any means confined to the syllogisms and deduction. Throughout his works are extensive discussions on reasoning, language, definition, demonstration, dialectical argument, necessity, and possibility without any dependence on the method of the syllogism. Many of his views on reasoning, argument, and language are relatively independent of it. Sometimes these arguments can be thought of as logic supplemented with contingencies for *accidental occurrences* or qualifications along the lines of "*for the most part*" [548, p. 115]. Aristotle's scientific works can be seen to contain a great variety of informal arguments and a miscellany of more or less incredulous *truths about things* to incorporate into these arguments, without any hint of a worked-out syllogism [548, p. 113]. Commenters on Aristotle frequently attempted to restructure his arguments into syllogistic form. However, taking a system of logic outside of its purified framework and applying it to the world around us is a delicate task. This can be seen from the previous example of Bohr's atomic work and in the detailed discussion of deductive reasoning applied to the scientific approach in Chapter 6. Physical deductive reasoning must be constrained by the previously empirically established *great physical principles*. Resolving problems via deduction with these constraints is a form of *radical conservatism*, conservatively respecting great principles while pushing ideas into radically new directions and logically deducing the unexpected consequences and insights if still constrained by the great principles.

The absence of syllogistic argument throughout so many of Aristotle's scientific works may be a reflection of his attempts to carry out arguments in an era before the development of systematic empirical observation. The times of Aristotle lacked the empirical leverage to produce radical conservatism when applied to physical science. There has been a recent trend comparing physical theories of the pre-Socratics with fundamental results in modern physics; e.g., Thales' notion of sameness with the quest for a theory of everything. Although intriguing, such comparisons can seem strained and perhaps can be the result of revisionist cherry-picking when applied to modern empirical results. However, comparisons are less far-fetched when considering areas such as epistemology. When unencumbered by empirical issues, Aristotle's writings show him to be a deductive reasoner of the highest caliber. As a few examples in the area of epistemology will show, his thoughts appear relevant even for our discussions on quantum mechanics [353]:

All men by nature desire to know. An indication of this is the delight we take in our senses. [Metaphysics I.1]

Further, if we admit in the fullest sense that something exists apart

> *from the concrete thing, whenever something is predicated of the matter, must there, if there is something apart, be something corresponding to each set of individuals, or to some and not to others, or to none? If there is nothing apart from individuals, there will be no object of thought, but all things will be objects of sense, and there will not be knowledge of anything, unless we say that sensation is knowledge.* [Metaphysics III.4]

> *And, in general, if only the sensible exists, there would be nothing if animate things were not; for there would be no faculty of sense. The view that neither the objects of sensation nor the sensations would exist is doubtless true (for they are affections of the perceiver), but that the substrata which cause the sensation should not exist even apart from sensation is impossible. For sensation is surely not the sensation of itself, but there is something beyond the sensation, which must be prior to the sensation; for that which moves is prior in nature to that which is moved, and if they are correlative terms, this is no less the case*. [Metaphysics IV.5]

Had Aristotle lived to see the development of quantum mechanics, perhaps he would have argued that knowledge comes about from sensing or measurement. Aristotle states that sensation is knowledge. Furthermore, Aristotle indicates that something external must cause the sensation, other than the sensory system itself. Next consider Aristotle's thoughts on potentiality and actuality [353]:

> *For the same thing can be potentially at the same time two contraries, but it cannot actually.* [Metaphysics IV.5]

> *Further, one must observe that some causes can be expressed in universal terms, and some cannot. The primary principles of all things are the actual primary "this" and another thing which exists potentiality. The universal causes, then, of which we spoke do not exist.* [Metaphysics XII.5]

It seems reasonable that Aristotle might have associated the wave function as representing potentialities whereas actualities occur due to measurement. A similar comparison has been suggested by Heisenberg [552, pp. 9-10]. Aristotle may have anticipated the requirements of entanglement as shown in his statement:

> *One might suppose especially that the parts of living things and the corresponding parts of the soul are both, i.e. exist both actually and potentially, because they have sources of movement in something in their joints; for which reason some animals live when divided. Yet all the parts must exist only potentially, when they are one and*

continuous by nature. [Metaphysics VII.16]

It is of interest to note that by associating an entangled state as being "one" and the parts or subsystems as existing only potentially, Aristotle's statement appears to parallel the theory of entangled states. This is because no subsystem of an entangled state can be specified in terms of a single pure state (which can be considered to be a single classical state), only via a mixture of pure states which requires more than one pure state for specification, so in this sense the subsystems would *only* exist potentially.

Aristotle's invention and development of logic remained essentially the main formulation of this subject until the mathematical treatments of logic by George Boole (1815-1864) and Augusta de Morgan (1806-1871) in the mid-19th century. This was followed by works on mathematical logic by Gottlob Frege (1848-1925) and Bertrand Russell to develop a set of logical axioms sufficient to contain all of mathematics. In the early 20th century, this culminated in Russell and Alfred North Whitehead's (1861-1947) system of logical axioms for mathematics published as the three volume opus *Principia Mathematica* and David Hilbert's program to prove the consistency of mathematics within axiomatic systems. These ambitions were shattered in 1931 by the publication of the incompleteness theorems of Kurt Gödel (1906-1978) that completely changed the nature and possibilities of logic. Gödel demonstrated the construction of a formula via Principia Mathematica that claims it is unprovable within the same system. This had the consequence that if it were provable it would be false and therefore that there will always be at least one true but unprovable statement in any sufficiently rich logical system. This was followed in 1936 by Alan Turing's (1912-1954) proof that the *halting problem* is undecidable: it is not always possible to decide whether a computational algorithm will complete its task. These works dramatically changed the view of how the nature of proof and truth can be embedded within logic and many repercussions followed. In particular, the mathematician and mathematical-physicist Roger Penrose, born the same year as Gödel's landmark paper, has argued that consciousness necessarily transcends the framework of Gödel's incompleteness theorem and Turing's halting theorem, and cannot be described by an algorithmically deterministic system [553].