INTRODUCTION

Philosophy of science and the theory of knowledge (epistemology) are important branches of philosophy. However, philosophy has over the centuries lost its dominant role it enjoyed in antiquity and became in Medieval Ages the maid of theology (ancilla theologiae) and after the rise of natural sciences and its...
In the following, I will illustrate the importance of hypothesis building for the history of science and the development of knowledge and illustrate it with two famous concepts, the parallel axiom in mathematics and the five elements hypothesis in physics.

Euclidean geometry

The prominent role of hypotheses in the development of science becomes already clear in the first science book of the Western civilization: Euclid's *The Elements* written about 300 BC starts with a set of statements called Definitions, Postulates and Common Notions that lay out the foundation of geometry (Euclid, c.323-c.283). This axiomatic approach is very modern as exemplified by the fact that Euclid's book remained for long time after the Bible the most read book in the Western hemisphere and a backbone of school teaching in mathematics. Euclid's twenty-three definitions start with sentences such as "1. A point is that which has no part; 2. A line is breadthless length; 3. The extremities of a line are points;" and continues with the definition of angles ("8. A plane angle is the inclination to one another of two lines in a plane which meet one another and do not lie in a straight line") and that of circles, triangles and quadrilateral figures. For the history of science, the 23rd definition of parallels is particularly interesting: "Parallel straight lines are straight lines which, being in the same plane and being produced indefinitely in both directions, do not meet one another in either direction". This is the famous parallel axiom. It is clear that the parallel axiom cannot be the result of experimental observations, but must be a concept created in the mind. Euclid ends with five Common Notions ("1. Things which are equal to the same thing are also equal to one another, to 5. The whole is greater than the part") and that the establishment of a contradiction-free system for a branch of mathematics based on a set of axioms from which theorems were deduced was revolutionary modern. Hilbert (1899) formulated a sound modern formulation for Euclidian geometry. Hilbert's axiom system contains the notions "point, line and plane" and the concepts of "betweenness, containment and congruence" leading to five axioms, namely the axioms of Incidence ("Verknüpfung"), of Order ("Anordnung"), of Congruence, of Continuity ("Stetigkeit") and of Parallels.

Origin of axioms

Philosophers gave various explanations for the origin of the Euclidean hypotheses or axioms. Plato considered geometrical figures as related to ideas (the true things behind the world of appearances). Aristoteles considered geometric figures as abstractions of physical bodies. Descartes perceived geometric figures as inborn ideas from extended bodies (res extensa), while Pascal thought that the axioms of Euclidian geometry were derived from intuition. Kant reasoned that Euclidian geometry represented a priori perceptions of space. Newton considered geometry as part of general mechanics linked to theories of measurement. Hilbert argued that the axioms of mathematical geometry are neither the result of contemplation ("Anschauung") nor of psychological source. For him, axioms were formal propositions ("formale Aussageformen") characterized by consistency ("Widerspruchsfreiheit", i.e. absence of contradiction) (Mittelstrass, 1980a).

Definitions

Axioms were also differently defined by philosophers. In *Topics*, Aristoteles calls axioms the assumptions taken
up by one partner of a dialogue to initiate a dialectic discussion. Plato states that an axiom needs to be an acceptable or credible proposition, which cannot be justified by reference to other statements. Yet, a justification is not necessary because an axiom is an evident statement. In modern definition, axioms are methodical first sentences in the foundation of a deductive science (Mittelstrass, 1980a). In Posterior Analytics, Aristotle defines postulates as positions which are at least initially not accepted by the dialogue partners while hypotheses are accepted for the sake of reasoning. In Euclid’s book, postulates are construction methods that assure the existence of the geometric objects. Today postulates and axioms are used as synonyms while the 18th-century philosophy made differences: Lambert defined axioms as descriptive sentences and postulates as prescriptive sentences. According to Kant, mathematical postulates create (synthesize) concepts (Mittelstrass, 1980b). Definitions then fix the use of signs; they can be semantic definitions that explain the proper meaning of a sign in common language use (in a dictionary style) or they can be syntactic definitions that regulate the use of these signs in formal operations. Nominal definitions explain the words, while real definitions explain the meaning or the nature of the defined object. Definitions are thus essential for the development of a language of science, assuring communication and mutual understanding (Mittelstrass, 1980c). Finally, hypotheses are also frequently defined as consistent conjectures that are compatible with the available knowledge. The truth of the hypothesis is only supposed in order to explain true observations and facts. Consequences of this hypothetical assumptions should explain the observed facts. Normally, descriptive hypotheses precede explanatory hypotheses in the development of scientific thought. Sometimes only tentative concepts are introduced as working hypotheses to test whether they have an explanatory capacity for the observations (Mittelstrass, 1980d).

Meanings

The Euclidean geometry is constructed along a logical “if-then” concept. The “if-clause” formulates at the beginning the supposition, the “then clause” formulates the consequences from these axioms which provides a system of geometric theorems or insights. The conclusions do not follow directly from the hypothesis; this would otherwise represent self-evident immediate conclusions. The “if-then” concept in geometry is not used as in other branches of science where the consequences deduced from the axioms are checked against reality whether they are true, in order to confirm the validity of the hypothesis. The task in mathematics is: what can be logically deduced from a given set of axioms to build a contradiction-free system of geometry. Whether this applies to the real world is in contrast to the situation in natural sciences another question and absolutely secondary to mathematics (Syntopicon, 1992).

Pascal’s rules for hypotheses

In his Scientific Treatises on Geometric Demonstrations, Pascal (1623-1662b) formulates “Five rules are absolutely necessary and we cannot dispense with them without an essential defect and frequently even error. Do not leave undefined any terms at all obscure or ambiguous. Use in definitions of terms only words perfectly well known or already explained. Do not fail to ask that each of the necessary principles be granted, however clear and evident it may be. Ask only that perfectly self-evident things be granted as axioms. Prove all propositions, using for their proof only axioms that are perfectly self-evident or propositions already demonstrated or granted. Never get caught in the ambiguity of terms by failing to substitute in thought the definitions which restrict or define them. One should accept as true only those things whose contradiction appears to be false. We may then boldly affirm the original statement, however incomprehensible it is.”

Kant’s rules on hypotheses

Kant (1724-1804) wrote that the analysis described in his book The Critique of Pure Reason “has now taught us that all its efforts to extend the bounds of knowledge by means of pure speculation, are utterly fruitless. So much the wider field lies open to hypothesis; as where we cannot know with certainty, we are at liberty to make guesses and to form suppositions. Imagination may be allowed, under the strict surveillance of reason, to invent suppositions; but these must be based on something that is perfectly certain and that is the possibility of the object. Such a supposition is termed a hypothesis. We cannot imagine or invent any object or any property of an object not given in experience and employ it in a hypothesis; otherwise we should be basing our chain of reasoning upon mere chimerical fancies and not upon conception of things. Thus, we have no right to assume of new powers, not existing in nature and consequently we cannot assume that there is any other kind of community among substances than that observable in experience, any kind of presence than that in space and any kind of duration than that in time. The conditions of possible experience are for reason the only conditions of the possibility of things. Otherwise, such conceptions, although not self-contradictory, are without object and without application. Transcendental hypotheses are therefore inadmissible, and we cannot use the liberty of employing in the absence of physical, hyperphysical
groundswells of explanation because such hypotheses do not advance reason, but rather stop it in its progress. When the explanation of natural phenomena happens to be difficult, we have constantly at hand a transcendental ground of explanation, which lifts us above the necessity of investigating nature. The next requisite for the admissibility of a hypothesis is its sufficiency. That is it must determine a priori the consequences which are given in experience and which are supposed to follow from the hypothesis itself." Kant stresses another aspect when dealing with hypotheses: “It is our duty to try to discover new objections, to put weapons in the hands of our opponent, and to grant him the most favorable position. We have nothing to fear from these concessions; on the contrary, we may rather hope that we shall thus make ourselves master of a possession which no one will ever venture to dispute.”

For Kant’s analytical and synthetical judgements and Difference between philosophy and mathematics (Kant, Whitehead), see Appendices S1 and S2, respectively.

**Poincaré on hypotheses**

The mathematician-philosopher Poincaré (1854–1912a) explored the foundation of mathematics and physics in his book *Science and Hypothesis*. In the preface to the book, he summarizes common thinking of scientists at the end of the 19th century. “To the superficial observer scientific truth is unassailable, the logic of science is infallible, and if scientific men sometimes make mistakes, it is because they have not understood the rules of the game. Mathematical truths are derived from a few self-evident propositions, by a chain of flawless reasoning, they are imposed not only by us, but on Nature itself. This is for the minds of most people the origin of certainty in science.” Poincaré then continues “but upon more mature reflection the position held by hypothesis was seen; it was recognized that it is as necessary to the experimenter as it is to the mathematician. And then the doubt arose if all these constructions are built on solid foundations.” However, “to doubt everything or to believe everything are two equally convenient solutions: both dispense with the necessity of reflection. Instead, we should examine with the utmost care the role of hypothesis; we shall then recognize not only that it is necessary, but that in most cases it is legitimate. We shall also see that there are several kinds of hypotheses; that some are verifiable and when once confirmed by experiment become truths of great fertility; that others may be useful to us in fixing our ideas; and finally that others are hypotheses only in appearance, and reduce to definitions or to conventions in disguise.” Poincaré argues that “we must seek mathematical thought where it has remained pure—i.e. in arithmetic, in the proofs of the most elementary theorems. The process is proof by recurrence. We first show that a theorem is true for $n = 1$; we then show that if it is true for $n−1$ it is true for $n$; and we conclude that it is true for all integers. The essential characteristic of reasoning by recurrence is that it contains, condensed in a single formula, an infinite number of syllogisms.” Syllogism is logical argument that applies deductive reasoning to arrive at a conclusion. Poincaré notes “that here is a striking analogy with the usual process of induction. But an essential difference exists. Induction applied to the physical sciences is always uncertain because it is based on the belief in a general order of the universe, an order which is external to us. Mathematical induction—i.e. proof by recurrence—is on the contrary, necessarily imposed on us, because it is only the affirmation of a property of the mind itself. No doubt mathematical recurrent reasoning and physical inductive reasoning are based on different foundations, but they move in parallel lines and in the same direction—namely, from the particular to the general.”

**Non-Euclidian geometry: from Gauss to Lobatschewsky**

Mathematics is an abstract science that intrinsically does not request that the structures described reflect a physical reality. Paradoxically, mathematics is the language of physics since the founder of experimental physics Galilei used Euclidian geometry when exploring the laws of the free fall. In his 1623 treatise The Assayer, Galilei (1564–1642a) famously formulated that the book of Nature is written in the language of mathematics, thus establishing a link between formal concepts in mathematics and the structure of the physical world. Euclid’s parallel axiom played historically a prominent role for the connection between mathematical concepts and physical realities. Mathematicians had doubted that the parallel axiom was needed and tried to prove it. In Euclidian geometry, there is a connection between the parallel axiom and the sum of the angles in a triangle being two right angles. It is therefore revealing that the famous mathematician C.F. Gauss investigated in the early 19th century experimentally whether this Euclidian theorem applies in nature. He approached this problem by measuring the sum of angles in a real triangle by using geodetic angle measurements of three geographical elevations in the vicinity of Göttingen where he was teaching mathematics. He reportedly measured a sum of the angles in this triangle that differed from 180°. Gauss had at the same time also developed statistical methods to evaluate the accuracy of measurements. Apparently, the difference of his measured angles was still within the interval of Gaussian error propagation. He did not publish the reasoning and the results for this experiment because he
feared the outcry of colleagues about this unorthodox, even heretical approach to mathematical reasoning (Carnap, 1891-1970a). However, soon afterwards non-Euclidian geometries were developed. In the words of Poincaré, “Lobatschewsky assumes at the outset that several parallels may be drawn through a point to a given straight line, and he retains all the other axioms of Euclid. From these hypotheses he deduces a series of theorems between which it is impossible to find any contradiction, and he constructs a geometry as impeccable in its logic as Euclidian geometry. The theorems are very different, however, from those to which we are accustomed, and at first will be found a little disconcerting. For instance, the sum of the angles of a triangle is always less than two right angles, and the difference between that sum and two right angles is proportional to the area of the triangle. Lobatschewsky's propositions have no relation to those of Euclid, but are none the less logically interconnected.” Poincaré continues “most mathematicians regard Lobatschewsky's geometry as a mere logical curiosity. Some of them have, however, gone further. If several geometries are possible, they say, is it certain that our geometry is true? Experiments no doubt teaches us that the sum of the angles of a triangle is equal to two right angles, but this is because the triangles we deal with are too small” (Poincaré, 1854-1912a)—hence the importance of Gauss' geodetic triangulation experiment. Gauss was aware that his three hills experiment was too small and thought on measurements on triangles formed with stars.

**Poincaré vs. Einstein**

Lobatschewsky's hyperbolic geometry did not remain the only non-Euclidian geometry. Riemann developed a geometry without the parallel axiom, while the other Euclidian axioms were maintained with the exception of that of Order (Anordnung). Poincaré notes “so there is a kind of opposition between the geometries. For instance the sum of the angles in a triangle is equal to two right angles in Lobatschewsky's, and greater than two right angles in that of Riemann. The number of parallel lines that can be drawn through a given point to a given line is one in Euclid's geometry, none in Riemann's, and an infinite number in the geometry of Lobatschewsky. Let us add that Riemann's space isfinite, although unbounded.” As further distinction, the ratio of the circumference to the diameter of a circle is equal to π in Euclid’s, greater than π in Lobatschewsky’s, and smaller than π in Riemann’s geometry. A further difference between these geometries concerns the degree of curvature (Krümmungsmass k) which is 0 for a Euclidian surface, smaller than 0 for a Lobatschewsky and greater than 0 for a Riemann surface. The difference in curvature can be roughly compared with plane, concave and convex surfaces. The inner geometric structure of a Riemann plane resembles the surface structure of a Euclidean sphere and a Lobatschewsky plane resembles that of a Euclidean pseudosphere (a negatively curved geometry of a saddle). What geometry is true? Poincaré asked “Ought we then, to conclude that the axioms of geometry are experimental truths?” and continues “If geometry were an experimental science, it would not be an exact science. The geometric axioms are therefore neither synthetic a priori intuitions as affirmed by Kant nor experimental facts. They are conventions. Our choice among all possible conventions is guided by experimental facts; but it remains free and is only limited by the necessity of avoiding contradictions. In other words, the axioms of geometry are only definitions in disguise. What then are we to think of the question: Is Euclidean geometry true? It has no meaning. One geometry cannot be more true than another, it can only be more convenient. Now, Euclidean geometry is, and will remain, the most convenient, 1st because it is the simplest and 2nd because it sufficiently agrees with the properties of natural bodies” (Poincaré, 1854-1912a).

Poincaré's book was published in 1903 and only a few years later Einstein published his general theory of relativity (1916) where he used a non-Euclidean, Riemann geometry and where he demonstrated a structure of space that deviated from Euclidean geometry in the vicinity of strong gravitational fields. And in 1919, astronomical observations during a solar eclipse showed that light rays from a distant star were indeed “bent” when passing next to the sun. These physical observations challenged the view of Poincaré, and we should now address some aspects of hypotheses in physics (Carnap, 1891-1970b).

**HYPOTHESES IN PHYSICS**

**The long life of the five elements hypothesis**

Physical sciences—not to speak of biological sciences—were less developed in antiquity than mathematics which is already demonstrated by the primitive ideas on the elements constituting physical bodies. Plato and Aristotle spoke of the four elements which they took over from Thales (water), Anaximenes (air) and Parmenides (fire and earth) and add a fifth element (quinta essentia, our quintessence), namely ether. Ether is imagined a heavenly element belonging to the supralunar world. In Plato's dialogue *Timaios* (Plato, c.424-c.348 BC a), the five elements were associated with regular polyhedra in geometry and became known as Platonic bodies: tetrahedron (fire), octahedron (air), cube (earth), icosahedron (water) and dodecahedron (ether). In regular polyhedra, faces are congruent (identical in shape and
size), all angles and all edges are congruent, and the same number of faces meet at each vertex. The number of elements is limited to five because in Euclidian space there are exactly five regular polyhedral. There is in Plato's writing even a kind of geometrical chemistry. Since two octahedra (air) plus one tetrahedron (fire) can be combined into one icosahedron (water), these "liquid" elements can combine while this is not the case for combinations with the cube (earth). The 12 faces of the dodecahedron were compared with the 12 zodiac signs (Mittelstrass, 1980e). This geometry-based hypothesis of physics had a long life. As late as 1612, Kepler in his Mysterium cosmographicum tried to fit the Platonic bodies into the planetary shells of his solar system model. The ether theory even survived into the scientific discussion of the 19th-century physics and the idea of a mathematical structure of the universe dominated by symmetry operations even fertilized 20th-century ideas about symmetry concepts in the physics of elementary particles.

Huygens on sound waves in air

The ether hypothesis figures prominently in the 1690 Treatise on Light from Huygens (1617-1670). He first reports on the transmission of sound by air when writing “this may be proved by shutting up a sounding body in a glass vessel from which the air is withdrawn and care was taken to place the sounding body on cotton that it cannot communicate its tremor to the glass vessel which encloses it. After having exhausted all the air, one hears no sound from the metal though it is struck.” Huygens comes up with some foresight when suspecting “the air is of such a nature that it can be compressed and reduced to a much smaller space than that it normally occupies. Air is made up of small bodies which float about and which are agitated very rapidly. So that the spreading of sound is the effort which these little bodies make in collisions with one another, to regain freedom when they are a little more squeezed together in the circuit of these waves than elsewhere.”

Huygens on light waves in ether

“That is not the same air but another kind of matter in which light spreads; since if the air is removed from the vessel the light does not cease to traverse it as before. The extreme velocity of light cannot admit such a propagation of motion” as sound waves. To achieve the propagation of light, Huygens invokes ether “as a substance approaching to perfect hardness and possessing springiness as prompt as we choose. One may conceive light to spread successively by spherical waves. The propagation consists nowise in the transport of those particles but merely in a small agitation which they cannot help communicate to those surrounding.” The hypothesis of an ether in outer space fills libraries of physical discussions, but all experimental approaches led to contradictions with respect to postulated properties of this hypothetical material for example when optical experiments showed that light waves display transversal and not longitudinal oscillations.

The demise of ether

Mechanical models for the transmission of light or gravitation waves requiring ether were finally put to rest by the theory of relativity from Einstein (Mittelstrass, 1980f). This theory posits that the speed of light in an empty space is constant and does not depend on movements of the source of light or that of an observer as requested by the ether hypothesis. The theory of relativity also provides an answer how the force of gravitation is transmitted from one mass to another across an essentially empty space. In the non-Euclidian formulation of the theory of relativity (Einstein used the Riemann geometry), there is no gravitation force in the sense of mechanical or electromagnetic forces. The gravitation force is in this formulation simply replaced by a geometric structure (space curvature near high and dense masses) of a four-dimensional space–time system (Carnap, 1891-1970c; Einstein & Imfeld, 1956). Gravitation waves and gravitation lens effects have indeed been experimental demonstrated by astrophysicists (Dorfmüller et al., 1998).

For Aristotle’s on physical hypotheses, see Appendix S3.

PHILOSOPHICAL THOUGHTS ON HYPOTHESES

In the following, the opinions of a number of famous scientists and philosophers on hypotheses are quoted to provide a historical overview on the subject.

Copernicus’ hypothesis: a calculus which fits observations

In his book Revolutions of Heavenly Spheres Copernicus (1473–1543) reasoned in the preface about hypotheses in physics. “Since the newness of the hypotheses of this work -which sets the earth in motion and puts an immovable sun at the center of the universe- has already received a great deal of publicity, I have no doubt that certain of the savants have taken great offense.” He defended his heliocentric thesis by stating “For it is the job of the astronomer to use pains-taking and skilled observations in gathering together the history of the celestial movements- and then – since he
cannot by any line of reasoning reach the true causes of these movements: to think up or construct whatever causes or hypotheses he pleases such that, by the assumption of these causes, those same movements can be calculated from the principles of geometry for the past and the future too. This artist is markedly outstanding in both of these respects: for it is not necessary that these hypotheses should be true, or even probable; but it is enough if they provide a calculus which fits the observations. This preface written in 1543 sounds in its arguments very modern physics. However, historians of science have discovered that it was probably written by a theologian friend of Copernicus to defend the book against the criticism by the church.

Bacon's intermediate hypotheses

In his book *Novum Organum*, Francis Bacon (1561–1626) claims for hypotheses and scientific reasoning “that they augur well for the sciences, when the ascent shall proceed by a true scale and successive steps, without interruption or breach, from particulars to the lesser axioms, thence to the intermediates and lastly to the most general.” He then notes “that the lowest axioms differ but little from bare experiments, the highest and most general are notional, abstract, and of no real weight. The intermediate are true, solid, full of life, and up to them depend the business and fortune of mankind.” He warns that “we must not then add wings, but rather lead and ballast to the understanding, to prevent its jumping and flying, which has not yet been done; but whenever this takes place we may entertain greater hopes of the sciences.” With respect to methodology, Bacon claims that “we must invent a different form of induction. The induction which proceeds by simple enumeration is puerile, leads to uncertain conclusions, …deciding generally from too small a number of facts. Sciences should separate nature by proper rejections and exclusions and then conclude for the affirmative, after collecting a sufficient number of negatives.”

Gilbert and Descartes for plausible hypotheses

William Gilbert introduced in his book *On the Loadstone* (Gilbert, 1544–1603) the argument of plausibility into physical hypothesis building. “From these arguments, therefore, we infer not with mere probability, but with certainty, the diurnal rotation of the earth; for nature ever acts with fewer than with many means; and because it is more accordant to reason that the one small body, the earth, should make a daily revolution than the whole universe should be whirled around it.”

Descartes (1596-1650) reflected on the sources of understanding in his book *Rules for Direction* and distinguished what “comes about by impulse, by conjecture, or by deduction. Impulse can assign no reason for their belief and when determined by fanciful disposition, it is almost always a source of error.” When speaking about the working of conjectures he quotes thoughts of Aristotle: “water which is at a greater distance from the center of the globe than earth is likewise less dense substance, and likewise the air which is above the water, is still rarer. Hence, we hazard the guess that above the air nothing exists but a very pure ether which is much rarer than air itself. Moreover nothing that we construct in this way really deceives, if we merely judge it to be probable and never affirm it to be true; in fact it makes us better instructed. Deduction is thus left to us as the only means of putting things together so as to be sure of their truth. Yet in it, too, there may be many defects.”

Care in formulating hypotheses

Locke (1632-1704) in his treatise *Concerning Human Understanding* admits that “we may make use of any probable hypotheses whatsoever. Hypotheses if they are well made are at least great helps to the memory and often direct us to new discoveries. However, we should not take up any one too hastily.” Also, practising scientists argued against careless use of hypotheses and proposed remedies. Lavoisier (1743-1794) in the preface to his *Element of Chemistry* warned about beaten-track hypotheses. “Instead of applying observation to the things we wished to know, we have chosen rather to imagine them. Advancing from one ill-founded supposition to another, we have at last bewildered ourselves amidst a multitude of errors. These errors becoming prejudices, are adopted as principles and we thus bewilder ourselves more and more. We abuse words which we do not understand. There is but one remedy: this is to forget all that we have learned, to trace back our ideas to their sources and as Bacon says to frame the human understanding anew.”

Faraday (1791–1867) in a *Speculation Touching Electric Conduction and the Nature of Matter* highlighted the fundamental difference between hypotheses and facts when noting “that he has most power of penetrating the secrets of nature, and guessing by hypothesis at her mode of working, will also be most careful for his own safe progress and that of others, to distinguish that knowledge which consists of assumption, by which I mean theory and hypothesis, from that which is the knowledge of facts and laws; never raising the former to the dignity or authority of the latter.”
Explocatory power justifies hypotheses

Darwin (1809–1882a) defended the conclusions and hypothesis of his book *The Origin of Species* “that species have been modified in a long course of descent. This has been affected chiefly through the natural selection of numerous, slight, favorable variations.” He uses a *post hoc* argument for this hypothesis: “It can hardly be supposed that a false theory would explain, to so satisfactory a manner as does the theory of natural selection, the several large classes of facts” described in his book.

The natural selection of hypotheses

In the concluding chapter of *The Descent of Man* Darwin (1809–1882b) admits “that many of the views which have been advanced in this book are highly speculative and some no doubt will prove erroneous.” However, he distinguished that “false facts are highly injurious to the progress of science for they often endure long; but false views do little harm for everyone takes a salutory pleasure in proving their falseness; and when this is done, one path to error is closed and the road to truth is often at the same time opened.”

The American philosopher William James (1842–1907) concurred with Darwin's view when he wrote in his *Principles of Psychology* “every scientific conception is in the first instance a spontaneous variation in someone’s brain. For one that proves useful and applicable there are a thousand that perish through their worthlessness. The scientific conceptions must prove their worth by being verified. This test, however, is the cause of their preservation, not of their production.”

The American philosopher J. Dewey (1859–1952) in his treatise *Experience and Education* notes that “the experimental method of science attaches more importance not less to ideas than do other methods. There is no such thing as experiment in the scientific sense unless action is directed by some leading idea. The fact that the ideas employed are hypotheses, not final truths, is the reason why ideas are more jealously guarded and tested in science than anywhere else. As fixed truths they must be accepted and that is the end of the matter. But as hypotheses, they must be continuously tested and revised, a requirement that demands they be accurately formulated. Ideas or hypotheses are tested by the consequences which they produce when they are acted upon. The method of intelligence manifested in the experimental method demands keeping track of ideas, activities, and observed consequences. Keeping track is a matter of reflective review.”

The reductionist principle

James (1842-1907) pushed this idea further when saying “Scientific thought goes by selection. We break the solid plenitude of fact into separate essences, conceive generally what only exists particularly, and by our classifications leave nothing in its natural neighborhood. The reality exists as a plenum. All its part are contemporaneous, but we can neither experience nor think this plenum. What we experience is a chaos of fragmentary impressions, what we think is an abstract system of hypothetical data and laws. We must decompose each chaos into single facts. We must learn to see in the chaotic antecedent a multitude of distinct antecedents, in the chaotic consequent a multitude of distinct consequents.” From these considerations James concluded “even those experiences which are used to prove a scientific truth are for the most part artificial experiences of the laboratory gained after the truth itself has been conjectured. Instead of experiences engendering the inner relations, the inner relations are what engender the experience here.”

Following curiosity

Freud (1856–1939) considered curiosity and imagination as driving forces of hypothesis building which need to be confronted as quickly as possible with observations. In *Beyond the Pleasure Principle*, Freud wrote “One may surely give oneself up to a line of thought to be confronted as quickly as possible with observation. In *Beyond the Pleasure Principle*, Freud wrote “One may surely give oneself up to a line of thought and follow it up as far as it leads, simply out of scientific curiosity. These innovations were direct translations of observation into theory, subject to no greater sources of error than is inevitable in anything of the kind. At all events there is no way of working out this idea except by combining facts with pure imagination and thereby departing far from observation.” This can quickly go astray when trusting intuition. Freud recommends “that one may inexorably reject theories that are contradicted by the very first steps in the analysis of observation and be aware that those one holds have only a tentative validity.”

Feed-forward aspects of hypotheses

The geneticist Waddington (1905–1975) in his essay *The Nature of Life* states that “a scientific theory cannot remain a mere structure within the world of logic, but must have implications for action and that in two rather different ways. It must involve the consequence that if you do so and so, such and such result will follow. That is to say it must give, or at least offer, the possibility of controlling the process. Secondly, its value is quite largely dependent on its power of suggesting
the next step in scientific advance. Any complete piece of scientific work starts with an activity essentially the same as that of an artist. It starts by asking a relevant question. The first step may be a new awareness of some facet of the world that no one else had previously thought worth attending to. Or some new imaginative idea which depends on a sensitive receptiveness to the oddity of nature essentially similar to that of the artist. In his logical analysis and manipulative experimentation, the scientist is behaving arrogantly towards nature, trying to force her into his categories of thought or to trick her into doing what he wants. But finally he has to be humble. He has to take his intuition, his logical theory and his manipulative skill to the bar of Nature and see whether she answers yes or no; and he has to abide by the result. Science is often quite ready to tolerate some logical inadequacy in a theory—or even a flat logical contradiction like that between the particle and wave theories of matter—so long as it finds itself in the possession of a hypothesis which offers both the possibility of control and a guide to worthwhile avenues of exploration.”

**Poincaré: the dialogue between experiment and hypothesis**

Poincaré (1854–1912b) also dealt with physics in *Science and Hypothesis*. “Experiment is the sole source of truth. It alone can teach us certainty. Cannot we be content with experiment alone? What place is left for mathematical physics? The man of science must work with method. Science is built up of facts, as a house is built of stones, but an accumulation of facts is no more a science than a heap of stones is a house. It is often said that experiments should be made without preconceived concepts. That is impossible. Without the hypothesis, no conclusion could have been drawn; nothing extraordinary would have been seen; and only one fact the more would have been catalogued, without deducing from it the remotest consequence.” Poincaré compares science to a library. Experimental physics alone can enrich the library with new books, but mathematical theoretical physics draw up the catalogue to find the books and to reveal gaps which have to be closed by the purchase of new books.

**Poincaré: false, true, fruitful and dangerous hypotheses**

Poincaré continues “we all know that there are good and bad experiments. The latter accumulate in vain. Whether there are hundred or thousand, one single piece of work will be sufficient to sweep them into oblivion. Bacon invented the term of an *experimentum crucis* for such experiments. What then is a good experiment? It is that which teaches us something more than an isolated fact. It is that which enables us to predict and to generalize. Experiments only gives us a certain number of isolated points. They must be connected by a continuous line and that is true generalization. Every generalization is a hypothesis. It should be as soon as possible submitted to verification. If it cannot stand the test, it must be abandoned without any hesitation. The physicist who has just given up one of his hypotheses should rejoice, for he found an unexpected opportunity of discovery. The hypothesis took into account all the known factors which seem capable of intervention in the phenomenon. If it is not verified, it is because there is something unexpected. Has the hypothesis thus rejected been sterile? Far from it. It has rendered more service than a true hypothesis.” Poincaré notes that “with a true hypothesis only one fact the more would have been catalogued, without deducing from it the remotest consequence. It may be said that the wrong hypothesis has rendered more service than a true hypothesis.” However, Poincaré warns that “some hypotheses are dangerous – first and foremost those which are tacit and unconscious. And since we make them without knowing them, we cannot get rid of them.” Poincaré notes that here mathematical physics is of help because by its precision one is compelled to formulate *all* the hypotheses, revealing also the tacit ones.

**Arguments for the reductionist principle**

Poincaré also warned against multiplying hypotheses indefinitely: “If we construct a theory upon multiple hypotheses, and if experiment condemns it, which of the premisses must be changed?” Poincaré also recommended to “resolve the complex phenomenon given directly by experiment into a very large number of elementary phenomena. First, with respect to time. Instead of embracing in its entirety the progressive development of a phenomenon, we simply try to connect each moment with the one immediately preceding. Next, we try to decompose the phenomenon in space. We must try to deduce the elementary phenomenon localized in a very small region of space.” Poincaré suggested that the physicist should “be guided by the instinct of simplicity, and that is why in physical science generalization so readily takes the mathematical form to state the problem in the form of an equation.” This argument goes back to Galilei (1564–1642b) who wrote in *The Two Sciences* “when I observe a stone initially at rest falling from an elevated position and continually acquiring new increments of speed, why should I not believe that such increases take place in a manner which is exceedingly simple and rather obvious to everybody? If now we examine the matter carefully we find no addition or increment more simple than that which repeats itself always in the same manner. It seems we shall not
be far wrong if we put the increment of speed as proportional to the increment of time.” With a bit of geometrical reasoning, Galilei deduced that the distance travelled by a freely falling body varies as the square of the time. However, Galilei was not naïve and continued “I grant that these conclusions proved in the abstract will be different when applied in the concrete” and considers disturbances cause by friction and air resistance that complicate the initially conceived simplicity.

Four sequential steps of discovery...

Some philosophers of science attributed a fundamental importance to observations for the acquisition of experience in science. The process starts with accidental observations (Aristotle), going to systematic observations (Bacon), leading to quantitative rules obtained with exact measurements (Newton and Kant) and culminating in observations under artificially created conditions in experiments (Galilei) (Mittelstrass, 1980g).

...rejected by Popper and Kant

In fact, Newton wrote that he had developed his theory of gravitation from experience followed by induction. K. Popper (1902-1994) in his book Conjectures and Refutations did not agree with this logical flow “experience leading to theory” and that for several reasons. This scheme is according to Popper intuitively false because observations are always inexact, while theory makes absolute exact assertions. It is also historically false because Copernicus and Kepler were not led to their theories by experimental observations but by geometry and number theories of Plato and Pythagoras for which they searched verifications in observational data. Kepler, for example, tried to prove the concept of circular planetary movement influenced by Greek theory of the circle being a perfect geometric figure and only when he could not demonstrate this with observational data, he tried elliptical movements. Popper noted that it was Kant who realized that even physical experiments are not prior to theories when quoting Kant’s preface to the Critique of Pure Reason: “When Galilei let his globes run down an inclined plane with a gravity which he has chosen himself, then a light dawned on all natural philosophers. They learnt that our reason can only understand what it creates according to its own design; that we must compel Nature to answer our questions, rather than cling to Nature’s apron strings and allow her to guide us. For purely accidental observations, made without any plan having been thought out in advance, cannot be connected by a law- which is what reason is searching for.” From that reasoning Popper concluded that “we ourselves must confront nature with hypotheses and demand a reply to our questions; and that lacking such hypotheses, we can only make haphazard observations which follow no plan and which can therefore never lead to a natural law. Everyday experience, too, goes far beyond all observations. Everyday experience must interpret observations for without theoretical interpretation, observations remain blind and uninformative. Everyday experience constantly operates with abstract ideas, such as that of cause and effect, and so it cannot be derived from observation.” Popper agreed with Kant who said “Our intellect does not draw its laws from nature…but imposes them on nature”. Popper modifies this statement to “Our intellect does not draw its laws from nature, but tries- with varying degrees of success – to impose upon nature laws which it freely invents. Theories are seen to be free creations of our mind, the result of almost poetic intuition. While theories cannot be logically derived from observations, they can, however, clash with observations. This fact makes it possible to infer from observations that a theory is false. The possibility of refuting theories by observations is the basis of all empirical tests. All empirical tests are therefore attempted refutations.”

OUTLOOK: HYPOTHESES IN BIOLOGY

Is biology special?

Waddington notes that “living organisms are much more complicated than the non-living things. Biology has therefore developed more slowly than sciences such as physics and chemistry and has tended to rely on them for many of its basic ideas. These older physical sciences have provided biology with many firm foundations which have been of the greatest value to it, but throughout most of its history biology has found itself faced with the dilemma as to how far its reliance on physics and chemistry should be pushed” both with respect to its experimental methods and its theoretical foundations. Vitalism is indeed such a theory maintaining that organisms cannot be explained solely by physicochemical laws claiming specific biological forces active in organisms. However, efforts to prove the existence of such vital forces have failed and today most biologists consider vitalism a superseded theory.

Biology as a branch of science is as old as physics. If one takes Aristotle as a reference, he has written more on biology than on physics. Sophisticated animal experiments were already conducted in the antiquity by Galen (Brüssow, 2022). Alertus Magnus displayed biological research interest during the medieval time. Knowledge on plants provided the basis of medical drugs in early modern times. What explains biology's decreasing influence compared with the rapid development of physics by Galilei and Newton? One reason is the possibility to use mathematical equations
to describe physical phenomena which was not possible for biological phenomena. Physics has from the beginning displayed a trend to few fundamental underlying principles. This is not the case for biology. With the discovery of new continents, biologists were fascinated by the diversity of life. Diversity was the conducting line of biological thinking. This changed only when taxonomists and comparative anatomists revealed recurring pattern in this stunning biological variety and when Darwin provided a theoretical concept to understand variation as a driving force in biology. Even when genetics and molecular biology allowed to understand biology from a few universally shared properties, such as a universal genetic code, biology differed in fundamental aspects from physics and chemistry. First, biology is so far restricted to the planet earth while the laws of physics and chemistry apply in principle to the entire universe. Second, biology is to a great extent a historical discipline; many biological processes cannot be understood from present-day observations because they are the result of historical developments in evolution. Hence, the importance of Dobzhansky's dictum that nothing makes sense in biology except in the light of evolution. The great diversity of life forms, the complexity of processes occurring in cells and their integration in higher organisms and the importance of a historical past for the understanding of extant organisms, all that has delayed the successful application of mathematical methods in biology or the construction of theoretical frameworks in biology. Theoretical biology by far did not achieve a comparable role as theoretical physics which is on equal foot with experimental physics. Many biologists are even rather sceptical towards a theoretical biology and see progress in the development of ever more sophisticated experimental methods instead in theoretical concepts expressed by new hypotheses.

Knowledge from data without hypothesis?

Philosophers distinguish rational knowledge (cognitio ex principiis) from knowledge from data (cognitio ex data). Kant associates these two branches with natural sciences and natural history, respectively. The latter with descriptions of natural objects as prominently done with systematic classification of animals and plants or, where it is really history, when describing events in the evolution of life forms on earth. Cognitio ex data thus played a much more prominent role in biology than in physics and explains why the compilation of data and in extremis the collection of museum specimen characterizes biological research. To account for this difference, philosophers of the logical empiricism developed a two-level concept of science languages consisting of a language of observations (Beobachtungssprache) and a language of theories (Theoriesprache) which are linked by certain rules of correspondence (Korrespondenzregeln) (Carnap, 1891–1970d). If one looks into leading biological research journals, it becomes clear that biology has a sophisticated language of observation and a much less developed language of theories.

OUTLOOK

Do we need more philosophical thinking in biology or at least a more vigorous theoretical biology? The breathtaking speed of progress in experimental biology seems to indicate that biology can well develop without much theoretical or philosophical thinking. At the same time, one could argue that some fields in biology might need more theoretical rigour. Microbiologists might think on microbiome research—one of the breakthrough developments of microbiology research in recent years. The field teems with fascinating, but ill-defined terms (our second genome; holobionts; gut–brain axis; dysbiosis, symbionts; probiotics; health benefits) that call for stricter definitions. One might also argue that biologists should at least consider the criticism of Goethe (1749–1832), a poet who was also an active scientist. In Faust, the devil ironically teaches biology to a young student.

"Wer will was Lebendigs erkennen und beschreiben,
Sucht erst den Geist herauszutreiben,
Dann hat er die Teile in seiner Hand,
Fehlt, leider! nur das geistige Band."

(To docket living things past any doubt.
You cancel first the living spirit out:
The parts lie in the hollow of your hand,
You only lack the living thing you banned).

We probably need both in biology: more data and more theory and hypotheses.

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SUPPORTING INFORMATION
Additional supporting information can be found online in the Supporting Information section at the end of this article.

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