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OPINION

Science, method and critical thinking

Antoine Danchin

School of Biomedical Sciences, Li KaShing Faculty of Medicine, Hong Kong University, Pokfulam, Hong Kong, China

Correspondence
Antoine Danchin, School of Biomedical Sciences, Li KaShing Faculty of Medicine, Hong Kong University, 21 Sassoon Road, Pokfulam, Hong Kong, China.
Email: antoine.danchin@normalesup.org; adanchin@hku.hk

Abstract

Science is founded on a method based on critical thinking. A prerequisite for this is not only a sufficient command of language but also the comprehension of the basic concepts underlying our understanding of reality. This constraint implies an awareness of the fact that the truth of the World is not directly accessible to us, but can only be glimpsed through the construction of models designed to anticipate its behaviour. Because the relationship between models and reality rests on the interpretation of founding postulates and instantiations of their predictions (and is therefore deeply rooted in language and culture), there can be no demarcation between science and non-science. However, critical thinking is essential to ensure that the link between models and reality is gradually made more adequate to reality, based on what has already been established, thus guaranteeing that science progresses on this basis and excluding any form of relativism.

Before illustrating the key requirements for critical thinking, one point must be made clear from the outset: thinking involves using language, and the depth of thought is directly related to the 'active' vocabulary (Magyar, 1942) used by the thinker. A recent study of young students in France showed that a significant percentage of the population had a very limited vocabulary. This unfortunate situation is shared by many countries (Fournier & Rakocevic, 2023). This omnipresent fact, which precludes any attempt to improve critical thinking in the general population, is very visible in a great many texts published on social networks. This is the more concerning because science uses a vocabulary that lies well beyond that available to most people. For example, a word such as 'metabolism' is generally not understood. As a consequence, it is essential to agree on a minimal vocabulary before teaching paths to critical thinking. This may look trivial, but this is an essential prerequisite. Typically, words such as analysis and synthesis must be understood (and the idea of what a 'concept' is not widely shared). It must also be remembered that the way the scientific vocabulary kept creating neologisms in the most creative times of science was based on using the Ancient Greek language, and for a good reason: a considerable advantage of that unsaid rule is that this makes scientific objects and concepts prominent for scientists from all over the world, while precluding implicit domination by any country over the others when science is at stake (Iliopoulos et al., 2019). Unfortunately, and this demonstrates how the domination of an ignorant subset of the research community gains ground, this rule is now seldom followed. This also highlights the lack of extensive scientific background of the majority of researchers: the creation of new words now follows the rule of the self-assertive. Interestingly, the very observation that a neologism in a scientific paper does not follow the traditional rule provides us with a critical way to identify either ignorance of the scientific background of the work or the presence in the text of hidden agendas that have nothing to do with science.

In practice, the initiation of the process of critical thinking ought to begin with a step similar to the 'due diligence' required by investors when they study whether they will invest, or not, in a start-up company. The first expected action should be 'verify', 'verify', 'verify'… any statement which is used as a basis for the reasoning that follows. This asks not only for understanding what is said or written (hence the importance of language), but also for checking the origins of the statement, not only by investigating who is involved but also by checking that the historical context is well known.

Of course, nobody has complete knowledge of everything, not even anything in fact, which means that at some point people have to accept that they will base their reasoning on some kind of 'belief'. This inevitable imperative forces future scientists asking a question about reality to resort to a set of assertions called 'postulates' in conventional science, that is, beliefs *temporarily* accepted without further discussion but understood as such. The way in which postulates are formulated is therefore key to their subsequent role in science. Similarly, the fact that they are temporary is essential to understanding their role. A fundamental feature of critical thinking is to be able to identify these postulates and then remember that they are provisional in nature. When needed this enables anyone to return to the origins of reasoning and then decide whether it is reasonable to retain the postulates or modify or even abandon them.

Here is an example illustrated with the famous greenhouse effect that allows our planet not to be a snowball (Arrhenius, 1896). Note that understanding this phenomenon requires a fair amount of basic physics, as well as a trait that is often forgotten: common sense. There is no doubt that carbon dioxide is a greenhouse gas (this is based on well-established physics, which, nevertheless must be accepted as a postulate by the majority, as they would not be able to demonstrate that). However, a straightforward question arises, which is almost never asked in its proper details. There are many gases in the atmosphere, and the obvious preliminary question should be to ask what they all are, and each of their relative contribution to greenhouse effect. This is partially understood by a fraction of the general public as asking for the contribution of methane, and sometimes N_2O and ozone. However, this is far from enough, because the gas which contributes the most to the greenhouse effect on our planet is … water vapour (about 60% of the total effect: https://www.acs.org/climatescience/climatesciencenarratives/its-water-vapor-not-the-co2.html)! This fact is seldom highlighted. Yet it is extremely important because water is such a strange molecule. Around 300 K water can evolve rapidly to form a liquid, a gas, or a solid (ice). The transitions between these different states (with only the gas having a greenhouse effect, while water droplets in clouds have generally a cooling effect) make that water is unable to directly control the Earth's temperature. Worse, in fact, these phase transitions will amplify the fluctuations around a given temperature, generally in a feedforward way. We know very well the situation in deserts, where the night temperature is very low, with a very high temperature during the day. In fact, this explains why 'global warming' (i.e. shifting upwards the average temperature of the planet) is also parallel with an amplification of weather extremes. It is quite remarkable that the role of water, which is well established, does not belong to popular knowledge. Standard 'due diligence' would have made this knowledge widely shared.

Another straightforward example of the need to have a clear knowledge of the thought of our predecessors is illustrated in the following. When we see expressions such as 'paradigm change', 'change of paradigm', 'paradigm shift' or 'shift of paradigm' (12,424 articles listed in PubMed as of June 26, 2023), we should be aware that the subject of interest of these articles has nothing to do with a paradigm shift, simply because such a change in paradigm is extremely rare, being distributed over centuries, at best (Kuhn, 1962). Worse, the use of the word implies that the authors of the works have most probably never read Thomas Kuhn's work, and are merely using a fashionable hearsay. As a consequence, critical thinking should lead authentic scientists to put aside all these works before further developing their investigation (Figure 1).

This being understood, we can now explore the general way science proceeds. This has been previously discussed at a conference meant to explain the scientific method to an audience of Chinese philosophers, anthropologists and scientists and held at Sun Yat Sen (Zhong Shan) University in Canton (Guangzhou) in 1991. This discussion is expanded in *The Delphic Boat* (Danchin, 2002). For a variety of reasons, it would be useful to anticipate the future of our world. This raises an unlimited number of questions and the aim of the scientific method is to try and answer those. The way in which questions emerge is a subject in itself. This is not addressed here, but this should also be the subject of critical thinking (Yanai & Lercher, 2019).

The basis for scientific investigation accepts that, while the truth of the world exists in itself ('relativism' is foreign to scientific knowledge, as science keeps building up its progresses on previous knowledge, even when changing its paradigms), we can only access it through the mediation of a representation. This has been extensively debated at the time, 2500 years ago, when science and philosophy designed the common endeavour meant to generate knowledge (Frank, 1952). It was then apparent that we cannot escape this omnipresent limitation of human rationality, as Xenophanes of Colophon explicitly stated at the time [discussed in Popper, 1968]. This limitation comes from an inevitable constraint: contrary to what many keep saying, *data do not speak*. Reality must be interpreted within the frame of a particular representation that critical thinking aims at making visible. A sentence that we all forget to reject, such as 'results show…' is meaningless: results are *interpreted as meaning* this or that.

Accepting this limitation is a difficult attribute of scientific judgement. Yet the quality of thought progresses

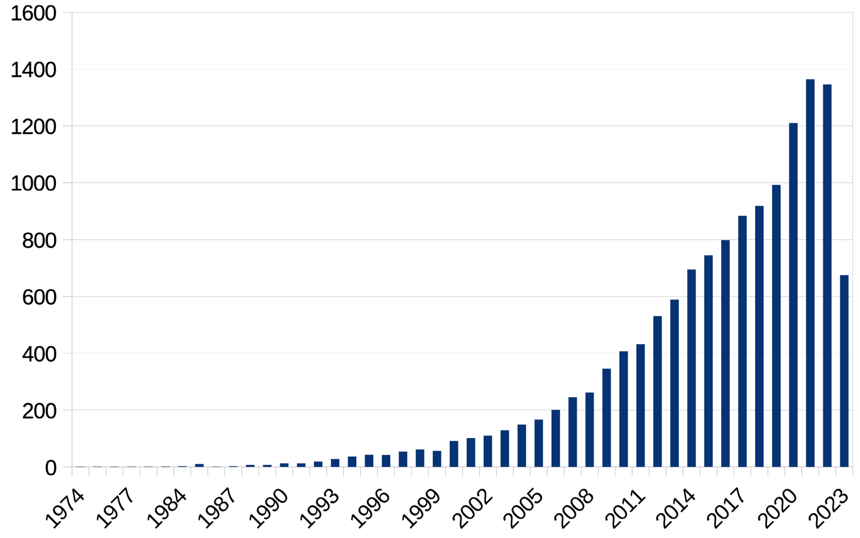

FIGURE 1 Number of articles identified in the PubMed database with the keywords 'paradigm change' or 'change of paradigm' or 'paradigm shift' or 'shift of paradigm'. A very low number of articles, generally reporting information consistent with the Kuhnian view of scientific revolutions is published before 1993. Between 1993 and 2000 a looser view of the term paradigm begins to be used in a metaphoric way. Since then the word has become fashionable while losing entirely its original meaning, while carrying over lack of epistemological knowledge. This example of common behaviour illustrates the decadence of contemporary science.

as the understanding of this constraint becomes more effective: to answer our questions we have to build models of the world, and be satisfied with this perspective. It is through our knowledge of the world's models that we are able to explore and act upon it. We can even become the creators of new behaviours of reality, including new artefacts such as a laser beam, a physics-based device that is unlikely to exist in the universe except in places where agents with an ability similar to ours would exist. Indeed, to create models is to introduce a distance, a mediation through some kind of symbolic coding (via the construction of a model), between ourselves and the world. It is worth pointing out that this feature highlights how science builds its strength from its very radical weakness, which is to know that it is incapable, in principle, of attaining truth. Furthermore and fortunately, we do not have to begin with a *tabula rasa*. Science keeps progressing. The ideas and the models we have received from our fathers form the basis of our first representation of the world. The critical question we all face, then, is: how well these models match up with reality? how do they fare in answering our questions?

Many, over time, think they achieve ultimate understanding of reality (or force others to think so) and abide by the knowledge reached at the time, precluding any progress. A few persist in asking questions about what remains enigmatic in the way things behave. Until fairly recently (and this can still be seen in the fashion for 'organic' things, or the idea, similar to that of the animating 'phlogiston' of the Middle Ages, that things spontaneously organize themselves in certain elusive circumstances usually represented by fancy mathematical models), things were thought to combine four elements: fire, air, water, and earth, in a variety of proportions and combinations. In China, wood, a fifth element that had some link to life was added to the list. Later on, the world was assumed to result from the combination of 10 categories (Danchin, 2009). It took time to develop a physic of reality involving space, time, mass, and energy. What this means is still far from fully understood. How, in our times when the successes of the applications of science are so prominent, is it still possible to question the generally accepted knowledge, to progress in the construction of a new representation of reality?

This is where critical thinking comes in. The first step must be to try and simplify the problem, to abstract from the blurred set of inherited ideas a few foundational concepts that will not immediately be called into question, at least as a preliminary stage of investigation. We begin by isolating a phenomenon whose apparent clarity contrasts with its environment. A key point in the process is to be aware of the fact that the links between correlation and causation are not trivial (Altman & Krzywinski, 2015). The confusion between both properties results probably in the major anti-science behaviour that prevents the development of knowledge. In our time, a better understanding of what causality is is essential to understand the present development of Artificial Intelligence (Schölkopf et al., 2021) as this is directly linked to the process of rational decision (Simon, 1996).

Subsequently, a set of undisputed rules, phenomenological criteria and postulates is associated with the phenomenon. It constitutes temporarily the founding dogma of the theory, made up of the phenomenon of interest, the postulates, the model and the conditions and results of its application to reality. This epistemological attitude can legitimately be described as 'dogmatic' and it remains unchanged for a long time in the progression of scientific knowledge. This is well illustrated by the fact that the word 'dogma', a religious word par excellence, is often misused when referring to a scientific theory. Many still refer, for example, to the expression 'the central dogma of molecular biology' to describe the rules for rewriting the genetic program from DNA to RNA and then proteins (Crick, 1970). Of course, critical thinking understands that this is no dogma, and variations on the theme are omnipresent, as seen for instance in the role of the enzyme reverse transcriptase which allows RNA to be rewritten into a DNA sequence.

Yet, whereas isolating postulates is an important step, it does not permit one to give explanations or predictions. To go further, one must therefore initiate a constructive process. The essential step there will be the constitution of a model (or in weaker instances, a simulation) of the phenomenon (Figure 2).

To this aim, the postulates will be interpreted in the form of entities (concrete or abstract) or of relationships between entities, which will be further manipulated by an independent set of processes. The perfect stage, generally considered as the ultimate one, associates the manipulation of abstract entities, interpreting postulates into axioms and definitions, manipulable according to the rules of logic. In the construction of a model, one assists therefore first to a process of *abstraction*, which allows one to go from the postulates to the axioms. Quite often, however, one will not be able to axiomatize the postulates. It will only be possible to represent them using analogies involving the founding elements of another phenomenon, better known and considered as analogous. One could also change the scales of a phenomenon (this is the case when one uses mock-ups as models). In these families of approaches, the model is considered as a simulation. For example, it will be possible to simulate an electromagnetic phenomenon using a hydrodynamic phenomenon [for a general example in physics (Vives & Ricou, 1985)]. In recent times the simulation is generally performed numerically, using (super)computers [e.g. the mesoscopic scale typical for cells (Huber & McCammon, 2019)]. While all these approaches have important implications in terms of diagnostic, for example, they are generally purely phenomenological and descriptive. This is understood by critical thinking, despite the general tendency to mistake the mimic for what it represents. Recent artificial intelligence approaches that use 'neuronal networks' are not, at least for the time being, models of the brain.

However useful and effective, the simulation of a phenomenon is clearly an admission of failure. A simulation represents behaviour that conforms to reality, but does not explain it. Yet science aims to do more than simply represent a phenomenon; it aims to anticipate what will happen in the near and distant future. To get closer to the truth, we need to understand and explain, that is, reduce the representation to simpler elementary principles (and as few as possible) in order to escape the omnipresent anecdotes that parasitize our vision of the future. In the case of the study of genomes, for example, this will lead us to question their origin and evolution. It will also require us to understand the formal nature of the control processes (of which feedback, e.g. is one) that they encode. As soon as possible, therefore, we would like to translate the postulates that enabled the model's construction into well-formed

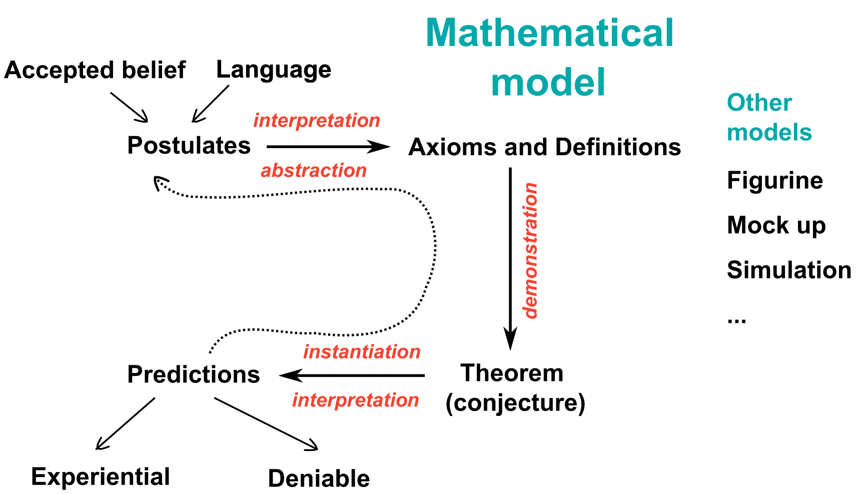

FIGURE 2 The Critical Generative Method. Science is based on the premises that while we can look for the truth of reality, this is in principle impossible. The only way out is to build up models of reality ('realistic models') and find ways to compare their outcome to the behaviour of reality [see an explicit example for genome sequences in Hénaut et al., 1996]. The ultimate model is mathematical model, but this is rarely possible to achieve. Other models are based on simulations, that is, models that mimic the behaviour of reality without trying to propose an explanation of that behaviour. A primitive attempt of this endeavour is illustrated when people use figurines that they manipulate hoping that this will anticipate the behaviour of their environment (e.g. 'voodoo'). This is also frequent in borderline science (Friedman & Brown, 2018).

statements that will constitute the axioms and definitions of an explanatory model. At a later stage, the axioms and definitions will be linked together to create a demonstration leading to a theorem or, more often than not, a simple conjecture.

When based on mathematics, the model is made up of its axioms and definitions, and the demonstrations and theorems it conveys. It is an entirely autonomous entity, which can only be justified by its own rules. To be valid, it must necessarily be true according to the rules of mathematical logic. So here we have an essential truth criterion, but one that can say nothing about the truth of the phenomenon. A key feature of critical thinking is the understanding that the truth of the model is not the truth of the phenomenon. The amalgam of these two truths, common in magical thinking, often results in the model (identified as a portion of the world) being given a sacred value, and changes the role of the scientist to that of a priest.

Having started from the phenomenon of interest to build the model, we now need to return from the model to the real world. A process symmetrical to that which provided the basis for the model, an instantiation of the conclusions summarized in the theorem, is now required. This can take the form of predictions, observations or experiments, for which at least two types can be broadly identified. These predictions are either existential (the object, process, or relations predicted by the instantiation of the theorem must be discovered), or phenomenological, and therefore subject to verification and deniability. An experimental set-up will have to be constructed to explore what has been predicted by the instantiations of the model theorems and to support or falsify the predictions. In the case of hypotheses based on genes, for example, this will lead to synthetic biology constructs experiments (Danchin & Huang, 2023), where genes are replaced by counterparts, even made of atoms that differ from the canonical ones.

The reaction of reality, either to simple (passive) observation or to the observation of phenomena triggered by the experiments, will validate the model and measure the degree of adequacy between the model and the reality. This follows a constructive path when the model's shortcomings are identified, and when are discovered the predicted new objects that must now be included in further models of reality. This process imposes the falsification of certain instantiated conclusions that have been falsified as a major driving force for the progression of the model in line with reality. This part of the thought process is essential to escape infinite regression in a series of confirmation experiments, one after the other, ad infinitum. Identifying this type of situation, based on the understanding that the behaviour of the model is not reality but an interpretation of reality, is essential to promote critical thinking.

It must also be stressed that, of course, the weight of the proof of the model's adequacy to reality belongs to the authors of the model. It would be both contrary to the simplest rules of logic (the proof of non-existence is only possible for finite sets), and also totally inefficient, as well as sterile, to produce an unfalsifiable model. This is indeed a critical way to identify the many pretenders who plague science. They are easy to recognize since they identify themselves precisely by the fact that they ask the others: 'repeat my experiments again and show me that they are wrong!'. Unfortunately, this old conjuring trick is still well spread, especially in a world dominated by mass media looking for scoops, not for truth.

When certain predictions of the model are not verified, critical thinking forces us to study its relationship with reality, and we must proceed in reverse, following the path that led to these inadequate predictions (Figure 2). In this reverse process, we go backwards until we reach the postulates on which the model was built, at which point we modify, refine and, if necessary, change them. The explanatory power of the model will increase each time we can *reduce the number of postulates* on which it is built. This is another way of developing critical thinking skills: the more factors there are underlying an explanation, the less reliable the model. As an example in molecular biology, the selective model used by Monod and coworkers to account for allostery (Monod et al., 1965) used far fewer adjustable parameters than Koshland's induced-fit model (Koshland, 1959).

In real-life situations, this reverse path is long and difficult to build. The model's resistance to change is quickly organized, if only because, lacking critical thinking, its creators cannot help thinking that, in fact, the model manifests, rather than represents, the truth of the world. It is only natural, then, to think that the lack of predictive power is primarily due not to the model's inadequacy, but to the inappropriate way in which its broad conclusions have been instantiated. This corresponds, in effect, to a stage where formal terms have been interpreted in terms of real behaviour, which involves a great deal of fine-tuning. Because it is inherently difficult to identify the inadequacy of the model or its links with the phenomenon of interest, it is often the case that a model persists, sometimes for a very long time, despite numerous signs of imperfection.

During this critical process, the very nature of the model is questioned, and its construction, the meaning it represents, is clarified and refined under the constraint of contradictions. The very terms of the instantiations of predictions, or of the abstraction of founding postulates, are made finer and finer. This is why this dogmatic stage plays such an essential role: a model that was too inadequate would have been quickly discarded, and would not have been able to generate and advance knowledge, whereas a succession of improvements leads to an ever finer understanding, and hence better representation of the phenomenon of interest.

Then comes a time when the very axioms on which the model is based are called into question, and when the most recent abstractions made from the initial postulates lead to them being called into question. This is of course very rare and difficult, and is the source of those genuine scientific revolutions, those paradigm shifts (to use Thomas Kuhn's word), from which new models are born, develop and die, based on assumptions that differ profoundly from those of their predecessors. This manifests an ultimate, but extremely rare, success of critical thinking.

A final comment. Karl Popper in his *Logik der Forschung* (*The Logic of Scientific Discovery*) tried to show that there was a demarcation separating science from non-science (Keuth and Popper, 1934). This resulted from the implementation of a refutation process that he named falsification that was sufficient to tell the observer that a model was failing. However, as displayed in Figure 2, *refutation does not work directly on the model of interest, but on the interpretation of its predictions*. This means that while science is associated with a method, its implementation in practice is variable, and its borders fuzzy. In fact, trying to match models with reality allows us to progress by producing better adequacy with reality (Putnam, 1991). Nevertheless, because the separation between models and reality rests on *interpretations* (processes rooted in culture and language), establishing an explicit demarcation is impossible. This intrinsic difficulty, which is associated with a property that we could name 'context associated with a research programme' (Lakatos, 1976, 1978), shows that the demarcation between science and non-science is dominated by a particular currency of reality, which we have to consider under the name *information*, using the word with all its common (and accordingly fuzzy) connotations, and which operates in addition to the standard categories, mass, energy, space and time.

The first attempts to solve contradictions between model predictions and observed phenomena do *not* immediately discard the model, as Popper would have it. The common practice is for the authors of a model to re-interpret the instantiation process that has coupled the theorem to reality. Typically: 'exceptions make the rule', or 'this is not exactly what we meant, we need to focus more on this or that feature', etc. This polishing step is essential, it allows the frontiers of the model and its associated phenomena to be defined as accurately as possible. It marks the moment when technically arid efforts such as defining a proper nomenclature, a database data schema, etc., have a central role. In contrast to the hopes of Popper, who sought for a principle telling us whether a particular creation of knowledge can be named Science, using refutation as principle, there is no ultimate demarcation between science and non-science. Then comes a time when, despite all efforts to reconcile predictions and phenomena, the inadequacy between the model and reality becomes insoluble. Assuming no mistake in the demonstration (within the model), this contradiction implies that we need to reconsider the axioms and definitions upon which the model has been constructed. This is the time when critical thinking becomes imperative.

AUTHOR CONTRIBUTIONS

Antoine Danchin: Conceptualization (lead); writing – original draft (lead); writing – review and editing (lead).

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The general outline of the Critical Generative Method presented at Zhong Shan University in Guangzhou, China in 1991, and discussed over the years in the Stanislas Noria seminar (https://www.normalesup.org/~adanchin/causeries/causeries-en.html) has previously been published in Danchin (2009) and in a variety of texts. Because scientific knowledge results from accumulation of knowledge painstakingly created by the generations that preceded us, the present text purposely makes reference to work which is seldom cited at a moment when scientists become amnesiac and tend to reinvent the wheel.

CONFLICT OF INTEREST STATEMENT

This work belongs to efforts pertaining to epistemological thinking and does not imply any conflict of interest.

ORCID

Antoine Danchin https://orcid.org/0000-0002-6350-5001

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