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Opinion

How to be a better scientist: Lessons from scientific philosophy, the historical development of science, and past errors within exercise physiology

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ABSTRACT

What is science? While a simple question, the answer is complex. Science is a process involving human behaviour, and due to the human influence, science is often not pursued correctly. In fact, one can argue that we still do not know what the "correct" pursuit of science should entail. This is because science remains a work in progress, differs for different questions, and we often are not aware of the mistakes made until years, or decades, later. Such mistakes are common, regardless of the discipline. Within exercise physiology, mistakes have been frequent and led to eventual corrections; the replacement of the post-exercise rate of oxygen consumption (VO_2) debt concept with that of excess post-exercise VO_2; the invalidation of the cellular production of lactic acid; improvements to maximal heart rate estimation; and on-going debate over the Central Governor Model. Improved training and education in the historical development of science and the contributions from scientific philosophy are important in providing an understanding of science, and more importantly, how to pursue "better" vs. "inferior" forms of science. The writings of Popper and Kuhn are core to enhanced understanding of how to improve the quality of science pursued. Unfortunately, quality education and training in the historical and philosophical development of science remain poor in most countries. Until inadequate educational training is overcome, there is sustained risk for the pursuit of science to remain inadequate, which in turn has a potential widespread detriment to humanity and the planet we live on.

Introduction

In 1984, Gaesser and Brooks published a commentary[1] on the need to correct the continued use of the early 20th-century construct of a metabolic connection between a deficit in exercise induced oxygen consumption (VO_2 deficit) and the repayment of this deficit by a post-exercise VO_2 debt. Such data and its interpretation were apparent in the original research of Hill and Lupton[2–5] (see p.142-152, Fig. 1, p. 147, Fig. 2, p. 149 of the 1923 reference). Gaesser and Brooks[1] presented the evidence and rationale against the 'debt' terminology of the post-exercise VO_2 side of this construct, informed from an added 60 years of improved research inquiry, knowledge, and instrumentation. As such, the original VO_2 debt hypothesis was over-simplistic, developed without first proposing a theory to be further tested, and was too rapidly assumed to be correct. Presumably, such original assumptions were based on misconstrued understandings of cellular energy metabolism during exercise and the immediate post-exercise (recovery) period, in addition to a lack of consideration of multifaceted (complex) regulation across multiple physiological systems.

The VO_2 debt construct is not the only example of a needed correction to inadequately constructed scientific research and data interpretation within the academic disciplines of basic and applied physiology. In 2002, Robergs and Landwehr[7] revealed the incorrect acceptance and applications of the '220-age' maximal heart rate prediction equation used in the exercise and clinical sciences. Such acceptance of this equation continued to occur despite prior evidence spanning more than 30 years for the lack of empirical evidence regarding the validity of the equation,[8] and the disregard of alternate, more accurate and research-validated prediction equations.[9,10]

In 1923, Hill and Lupton also proposed that during intense exercise skeletal muscle produced lactic acid, and this acid production was the

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Abbreviations

VO_2	rate of oxygen consumption
VO_2 deficit	a deficit in exercise induced oxygen consumption
VO_2 debt	the post-exercise repayment of the VO2 debt measured as an elevated VO2
H^+	hydrogen ion, also referred to as a proton
CGM	Central Governor Model

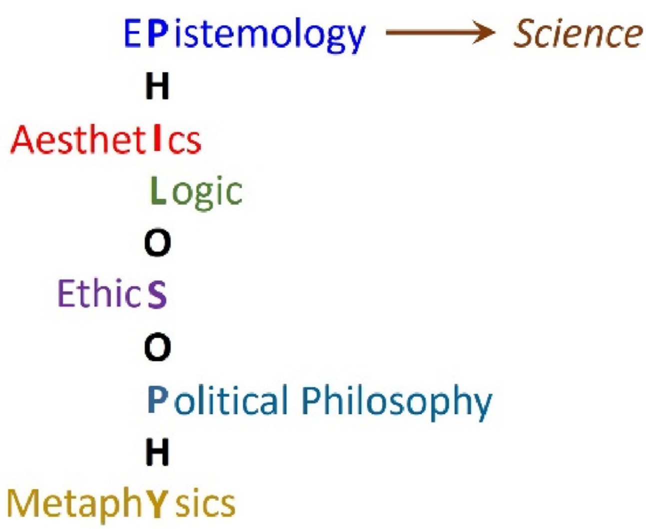

Fig. 1. The multiple components (branches) of philosophy. As explained in the text, science was developed from the philosophical branch of epistemology.

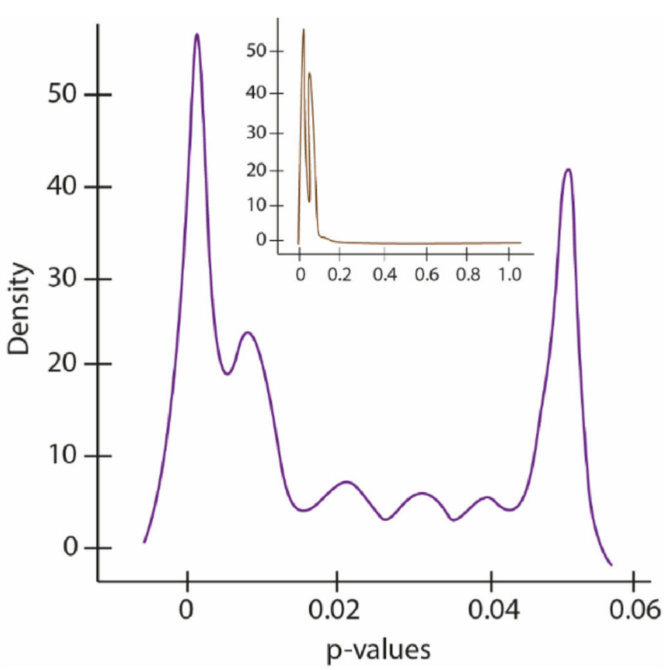

Fig. 2. A reproduction of the *p*-curve data from Kagereki et al.[6] (Fig. 2, p.4)]. The *p*-curve is a frequency distribution (spectral density) of a data set of *p*-values.

cause of proton (H^+) release which in turn induced the cellular and systemic acidosis of intense exercise.[2–5] Such a construct was rapidly accepted within biochemistry, physiology, and medicine, where the latter clinical disciplines interpreted lactic acid production from numerous tissues and organs as an explanation for the systemic acidosis of numerous disease processes and acute infections; lactic acidosis.[11] Within exercise physiology, skeletal muscle lactic acid production was interpreted to be the cause of exercise-induced metabolic acidosis, metabolic perturbations, and contractile failure.[12] Such acceptance continued until 2004 when evidence was compiled across organic chemistry, cellular biochemistry, and computational acid-base chemistry documenting the impossibility for cells to produce lactic acid, or for that matter any metabolic acid, and that cellular lactate production consumes, not produces a proton.[13] Another causal explanation must exist to explain cellular and systemic metabolic acidosis.

Since the 1920's an awareness has existed of the possible presence and/or role of a neural regulatory system, or 'governor' that constrained tolerance of continued intense exercise (e.g., contributed to voluntary termination of exercise) based on the assumption that this would prevent tissue and/or organ damage.[2–5] In 1997 Tim Noakes formalized this original interpretation into the Central Governor Model (CGM), and there has been sustained debate on the validity and relevance of this model and related interpretations of the exercise physiology of intense exercise to the current time.[14] Despite this on-going conjecture over the CGM, recently the CGM was proclaimed to be evidence of a new paradigm shift within exercise physiology.[15] Nevertheless, the CGM was never expressed as a theory that directs other researchers to critically challenge this concept, and the latest arguments opposing the CGM have been based on applications of core principles within scientific philosophy that reveal flaws in the development of the model and subsequent intent and design of most of the ensuing research that has been interpreted to support it.[16,17]

In his classic work, culminating in an appraisal of the historical development of the physical sciences to the 1960s, Kuhn[18] explained the time dependence of routine scientific practice within a discipline. Such time progression eventually leads to a crisis and subsequent period of discovery that finally fuels a major paradigm shift. Such a paradigm shift involves a dramatic change (improvement) in scientific achievement for a specific topic within a discipline. This work will be discussed in more detail later, but for now, it is logical to ask the question of whether this pattern of progress in science (a relatively lengthy dormant period followed by crisis and paradigm shift) is normal and therefore to be expected, or is it evidence of a broader series of multifaceted, systemic problems with the human endeavour in the pursuit of science?

Problem

As documented above, there are forces at play during the pursuit of science that encourages premature acceptance of incorrect research methodologies, assumptions, and data interpretations. This premature acceptance is not unique to exercise physiology, and concerns about the integrity of science across all disciplines have been expressed in investigations of scientific research, peer review, and decisions on manuscript acceptance or rejection for many decades.[19–25]

As exemplified by the latest criticisms of the CGM, core features of scientific philosophy play important roles in providing the evidence and rationale for 'ideal' vs. 'less than ideal' scientific practice. Pompeu[17] attempted to explain such features of scientific philosophy within his appraisal of the CGM and provided terms such as '*ad infinitum* regression' '*modus ponens* inference' and 'verisimilitude'. Such content was highly philosophical, and despite clear efforts to provide examples within exercise physiology for why these terms are relevant, the reality is that most scientists are poorly educated on aspects of scientific philosophy. As such, the concern exists that the overall content was likely to cause more confusion and/or dislike of philosophical arguments of topics within the scientific method; afterall, the pursuit of science is based on the clarity of empirical observation (objectivity) not philosophical thought (subjectivity). Nevertheless, as will be detailed in this manuscript, an awareness of scientific philosophy is incredibly important to understanding the historical development of science, and more importantly, what features of scientific practice make science, science.

Consequently, the purposes of this opinion statement are to, a) provide explanations for why knowledge in scientific philosophy can reinforce core principles of quality scientific conduct, b) identify that sustained problems exist in the human pursuit of the scientific method, c) propose explanations of this scientific dysfunction, informed from an understanding of scientific philosophy, and d) give examples within university academic teaching and research settings where the deficit of this knowledge can impart critical damage to society.

The beginnings: what is science?

Before there can be progress in deciphering the differences between the 'good' vs. 'bad' pursuit of science, one needs to understand what science is. To do this, a brief historical account of how science developed is given. The word 'science' is derived from the Latin word, 'Scientia'; which in turn means knowledge. Knowledge has always been a core component of philosophy, and indeed, one of the so-called branches of philosophy that is pertinent to knowledge is epistemology; the study of the nature of knowledge (Fig. 1). One example of the epistemological thought process is the philosophical problem of how to know if a belief is true or justified and therefore able to be classified as knowledge. In other words, knowledge pertains to understandings that are most likely to be true. Aristotle (384-322 B.C.) is widely acclaimed to be one of the early philosophers (he was educated by Plato (423-347 B.C.), who was educated by Socrates (470-399 B.C.), to be responsible for the process which eventually, some 2,000 years later, developed into the contemporary scientific method.[26,27] For example, in Aristotle's Nicomachean Ethics, Crisp[28] translated Aristotle to imply that a rational approach is followed in solving philosophical problems, with this approach consisting of four stages (p. ix);

1) Decide on the topic of inquiry.
2) Seek different views on the topic from wise people.
3) Identify any puzzles (problems) that exist.
4) Resolve the problems to the best of one's ability

While this expression of Aristotle revealed a structured thought process that somewhat embodies what we now know to include components within the pursuit of science, there is an omission of the most important item in establishing the likely truth linked to a problem or question; that of empirical observation through structured testing. Thus, from very early in human history, even before the development of science, thanks to philosophical thinking one point has become clear; for societies and human behaviour to flourish, decisions and behaviours needed to be nested in factual truth and not perceptions or beliefs of truth such as often espoused through religion, idolatry, dictatorship, etc. Before the progressive development of what we now know as modern science, quality philosophical thinking was the only approach to be taken to direct one towards 'the truth'. Such challenge against false truths developed slowly, and was eventually, some 1,800 years later, most evident in the work of Copernicus (1473–1543) and Gallileo (1564–1642) who are viewed as the first practitioners of the start of the modern scientific revolution due to their dependence on empirical observation to support or refute opinion.[26,27]

As the prior cursory review of the philosophical origins of science revealed, the development of science was a gradual process, and to be continually developed, and refined. As such, science is a structured human behaviour designed to increase the probability that a question, or problem, is resolved or answered correctly. There are many features that influence how well this process is done, and these features will be revealed and explained later in this manuscript. The key feature to be aware of at this time is the challenge of knowing how to structure this process of science to make it function more optimally; to raise the likelihood or probability that a correct answer is obtained. This dilemma of science is where more modern (the last 100 years) scientific philosophy is important, and there is a need to provide considerable content to these developments that occurred throughout the 20th century.

Kuhn and Popper: both their approaches matter

Karl Popper detailed his views on the processes that should be pursued within a scientific method as early as 1934,[29] though such work was constrained in influence to the Western English speaking world until after World War II and the translation of the text from Austrian to English. Nevertheless, Popper rationalized that science would function best if based on a foundation of critical thinking. His arguments were quite profound, for Popper was emphatic in his view that the only way to support a theory or data interpretation was to fail in attempts to disprove the theory; failed disproof is the best proof! Popper referred to this aspect of science as falsification, and other synonymous terms that have also been used for this principle are 'refutation' and 'disproof'[30,31]; proving that a statement or theory is wrong. Popper was also wise in detecting the need to provide a trait from which to separate optimal from less optimal scientific practice. Popper[29] termed this trait the 'criterion of demarcation', which he explained as the ability of a statement to be tested and proven false. In other words, any statement of presumed knowledge made in a scientific context that could not be tested was unscientific and Popper further proposed that such practice was pseudoscience.

Thomas Kuhn first published his classic text on the historical development of the physical sciences in 1970.[18] Kuhn was trained in physics, and due to an interest in the history of science, Kuhn's work was a product of historical inquiry and observation of how the physical sciences were practiced to the mid-20th century. While many scientific philosophers and scientists have heralded Kuhn's work as the most important description of what science is,[26,27] concern exists that this conceptualization is an over-simplistic representation of this work.[31] For example, to argue that you can learn about what science is from how it is practiced is illogical. This construct is analogous to stating that democracy is learned from how politicians within a democracy practice democracy; too often reality is a dysfunctional version of the ideal, and the modern partisan politics of most western democracies are evidence of this. The same is true for the pursuit of science; humans pursue science and for this reason, science is frequently derailed and distant from anything resembling perfection. In this regard, Atkins[32] had a great expression for the human-infused flaws of science, which he referred to as "mud". This term is appriopriate for mud conjures the images we all understand from the life experience of how mud can damage, impair, or otherwise eventually destroy the workings of any complex mechanical system. The pertinent quote from Atkins follows, though as you will read, there is disagreement to the conclusion that is made.

*"The scientific method is a liberal polity and the gut plays an important role in the early stages of comprehension. Scientists have hunches, make intellectual leaps, certainly make mistakes, nick ideas from others, muddle through, and then just occasionally see the light. That is the scientific method, despite the idealizations of the philosophers of science. Their idealization is like a limiting law, identifying the essence of the scientific method stripped of its **human mud**, a human activity practised to the limit of the absence of humans and their frailties." (Atkins[32] p. 9).*

Peter Atkins[32] postulated that science is characterized, and therefore defined, by the errors infused by human flaws. As previously explained, this viewpoint is a Kuhn perspective and one that does harm to science by justifying acceptance and/or tolerance of inferior forms of science. At any rate, the 'mud of humanity' can all too often tarnish human endeavour in science. Some of the components of this 'mud' will be revealed later in this manuscript.

What is the ideal practice of science? This question frames Popper's contributions to the development of how to pursue science. As explained, Popper[29] was convinced that the best practiced science is that which confronts convention. Thus, as previously explained, Popper's view was that the greatest progress in science would be evidenced by failed attempts at falsification. Similarly, for added progress towards new areas of scientific inquiry, there should always initially be the proposal of a new theory, worded in such a way that the theory is easily challenged and if possible proven incorrect, or at least in need of refinement, by added research inquiry from other scientists. As explained in the Introduction, too many examples of knowledge development within basic and applied physiology exist where the formulation of a theory was omitted, and opinion was erroneously taken as empirical proof.

Based on the prior overview, it is now opportune to bring together the approaches of Popper and Kuhn, for the combination of their work provides a more correct interpretation of the more ideal pursuit of science. It is best to return to Kuhn[18] for the start of this challenge. Kuhn's historical account of the development of the physical sciences to the mid- 1960s was previously explained as a transition from an extended period of minimal discovery or innovation, followed by a rapid or turbulent period of improved knowledge acquisition. Kuhn labelled the multiple components for the pursuit of science. The period of minimal discovery was termed ‘normal science’ and was characterized by the scientists of that time to be immersed within a generally accepted view of a topic, which was the conventional ‘paradigm’ of interest that could be applied to different scenarios to refine (not replace) the paradigm. Core to this phase of the pursuit of science is the acceptance of a given approach or interpretation of data. Thus, at one time within exercise physiology constructs existed that were supportive of a ‘VO_2 debt’, a maximal heart rate of 220-age, a ‘lactic acidosis’, and a ‘central governor’ that integrates physiological and psychological cues to limit exercise tolerance and preserve muscle and/or organ structure and function. The premature acceptance of any of these constructs, which would raise their status to paradigms, would cause drastic harm to a discipline area because the recognition as paradigms would thwart further research interest away from critical confrontation, limit the probability of discovering evidence against the construct/theory/paradigm, and result in lost opportunity costs from the gains that could have been made with earlier more accepted and supported falsification of the construct/theory/paradigm.

Regardless, if we stick with Kuhn's[18] observations gained from historical context, normal science eventually transitions into a period of detection of inconsistencies within the paradigm. Kuhn referred to such inconsistency as an ‘anomaly’. Over time, added anomalies are detected and amass to an unavoidable challenge of the prevailing paradigm. It is clear from Kuhn's account that normal science, therefore, has a type of scientific momentum that is difficult to break, and the passage of time and growing extent of critical evidence is necessary to overcome this inertia. Regardless, eventually a ‘crisis’, occurs where the prevailing paradigm is challenged by the development of a new approach to interpret all the evidence gained from the anomalies, culminating in the proposal of a new paradigm.

Kuhn[18] observed through history that anomalies and a developing crisis are not enough to reject a conventional paradigm. Paradigms are only rejected when sufficient evidence is gathered to support the validity of a new construct/theory/paradigm so that the prior is replaced with the new. This feature explains the ‘crisis’ phase, which by Kuhn's definition only becomes real when the accumulation of the evidence from the growing number and severity of the anomalies reveals the need to confront the prevailing paradigm. The time to progress to and resolve the crisis can be lengthy; as much as 30–50 years or more, depending on the discipline and topic in question. Yet the ‘crisis’ is resolved when a sufficiently accepted alternate paradigm is proposed/developed from the now available research evidence that revealed the anomalies. Kuhn labelled the research of this final transition as ‘extraordinary science’, which then pre-empted the proof and development of a ‘paradigm shift’. Kuhn[18] labelled the process spanning ‘anomalies’ to ‘crisis’ to ‘extraordinary science’ to ‘paradigm shift’ as a ‘scientific revolution’.

Kuhn[18] is open to criticism for observing these trends in the historical development of science and not critically challenging them. Indeed, Kuhn's work is constrained by its descriptive account and absence of more advanced contemplation, albeit accompanied by well-assigned words to each phase for the process. Here, a comparison to Popper is not only interesting but essential. In 1970, Lakatos and Musgrave[33] edited the proceedings of the International Colloquium in the Philosophy of Science, held in London, 1965. Kuhn and Popper both spoke at this meeting, and the content of their speeches and resultant manuscripts within this edited text is revealing of their different views of the historical pursuit of science vs. how science should be pursued. Popper[34] was disgusted at the acceptance and labelling of Kuhn's ‘normal science’. For example, to Popper, based on his prior writing about the need for critical confrontation in science, the importance of falsification, and the extension of this trait to the criterion of demarcation between science and pseudoscience, ‘normal science’ was anything but normal. For example, if the so-called ‘normal science’ existed, yet was to be eventually replaced by a totally different, and more correct alternative, then what does that reveal about the quality of the ‘normal science’? Technological advances could rapidly induce a transition into ‘crisis’ ‘extraordinary science’ ‘paradigm shift’ and ‘scientific revolution’. Yet, if prior evidence existed to support a different understanding but was overlooked or intentionally disregarded, then surely that reveals major negative features for the competency of the scientists and the ‘normal science’ they practiced that reinforced a completely incorrect paradigm. Such views are best presented in Popper's[34] own words:

“… the ‘normal’ scientist, as Kuhn describes him, is a person one ought to be sorry for. The ‘normal’ scientist … … has been badly taught. He has been taught in a dogmatic spirit: he is a victim of indoctrination. He has learned a technique which can be applied without asking for the reason why.” (Popper[34] p.52, 53).

It is important to realize that both Popper and Kuhn agreed that such ‘normal’ scientists and the pursuit of ‘normal’ science existed and continues to exist. Popper was annoyed that Kuhn was not critical of this, or able to realize the long-term harm that such questionable scientific pursuit would inflict upon society. Once again, in Popper's[34] own words:

“I admit that this kind of attitude (‘normal’ science) exists … … among people trained as scientists. I can only say that I see a very great danger in it and in the possibility of it becoming normal … ….: a danger to science and, indeed, to our civilization.” (Popper[34] p. 53).

Further evidence of undesirable features of ‘normal’ science

What is important for this opinion piece are the following facts and related questions; 1) Why did it take more than 60 years from the inception of the VO_2 deficit-debt construct for scientists to challenge or refute a current practice, hypothesis, model, or theory? Why did academics and researchers refrain from seeking clarification of the source of the ‘220-age’ maximal heart rate prediction equation for more than 30 years, and in so doing fail to reveal much earlier the poor internal and external validity of this method? 3) Why did it take more than 90 years for the empirical evidence refuting the lactic acidosis construct to become presented and eventually, reluctantly, and gradually recognized as likely to be true? How extensive are the dysfunctions of ‘normal’ science across other disciplines, what are the lost opportunity costs from prior scientific dysfunction and what can be done to prevent the high probability of further errors in science?

In the context of the critical appraisal of the roles of peer review within science regardless of the disciplines, numerous concerns were raised and discussed in the March 1990 issue of the *Journal Of The American Medical Association* (JAMA) resulting from the 1989 conference entitled, “Guarding the guardians: Research on editorial peer review”.[20] This work has been reviewed elsewhere.[25] There are other notable commentaries and research evidence on concerns about past and contemporary scientific practice across numerous disciplines. For example, Fig. 2 presents results from Kagereki et al.[6] from their research of the p-value distribution within the oral health literature spanning 2004 to 2014. The results were processed to reveal a frequency distribution of 44,315 reported p-values that revealed a bi-modal profile with the highest frequencies of reported statistical significance occurring around the 0.05 and 0.001 values and a smaller third peak centred close to $p = 0.01$.

No positive way exists to interpret these results. The lack of p-values above 0.05 was clear evidence of significance bias (also termed publication bias). The magnitude of the frequencies of p-values around the conventional standards of "significance" is disturbing because, in addition to significance bias, the results may also reflect contrived research designs and/or statistics to force results to target these values. The worst-case explanation is that researchers are so aware of the bias of peer-reviewed journals to pursue significance bias that they develop questions, design studies, and analyse their data to produce this desired end-result. The external peer review process adds another layer of disdain to this scenario, as it means that scientists themselves (the peer reviewers and journal editors) may also be a component of this dysfunction, which further prompts one to question the quality of the training scientists receive in their formal and continuing education concerning ethics, the philosophy of science and the traits of the scientific method.

Based on the content thus far, 'normal' science is seen as a pursuit of science infused with a collection of interferences that deviate the scientific efforts away from a more direct path to the truth. Such schemes are presented in Fig. 3a and b, revealing a more ideal approach (Fig. 3a) contrasted to an approach distorted by flaws (the 'mud') of humanity (Fig. 3b) revealed by numerous components that can compromise the scientific integrity of the scientist and pursuit of science; finances, bias across numerous levels (self, peers, journals, funding agencies, employers, society, etc.), ego, power, recognition, institutional pressure, peer pressure, etc. These components, if left unguarded, can take hold and thwart what may have once been sincere efforts to pursue a more ideal scientific process.

Good vs. bad science: it is not binary

In the movie "Steve Jobs" (2015) a poignant scene exists where the actors who played Mark Wozniak and Steve Jobs argue over a balance between business finance and human emotions. Jobs argued that human endeavour in the pursuit of innovation was either quality or insufficient. In contrast, Wozniak argued that you can make a profit while still embodying empathy; as Wazniak expressed it; "*It* (success) *is not binary*". This illustration is a pertinent historical reference of a time during a paradigm shift away from analogue to digital, and for the point of the argument that is referred to in the movie, for how to behave as a leader of others in a complex workplace and broader society. The scene has relevance to the topic of this manuscript because the pursuit of science is a human behaviour immersed within complex layers of function.

Given this information, Popper can be criticized for defining science as either being right (adhering to all components of the pursuit of science that raises the probability of a correct answer) or pseudoscientific (when done in an inferior way that lowers the probability of a correct answer), regardless of intent. Based on the components of Fig. 3, the pursuit of science is not binary; neither right nor wrong. A continuum of progress towards superior scientific endeavour exists, as well as a risk for a gradual regression towards pseudoscience. As we are unsure of what we do not know, and often blind to the consequences of our own biases, it is unlikely that science can ever be pursued perfectly! Such a depiction of the continuum of the pursuit of science is presented in Fig. 4. The challenge for all scientists is to acquire this knowledge and devise an approach to their pursuit of the scientific method that improves their likelihood of being a better scientist (to discover the truth while simultaneously being aware of their limitations).

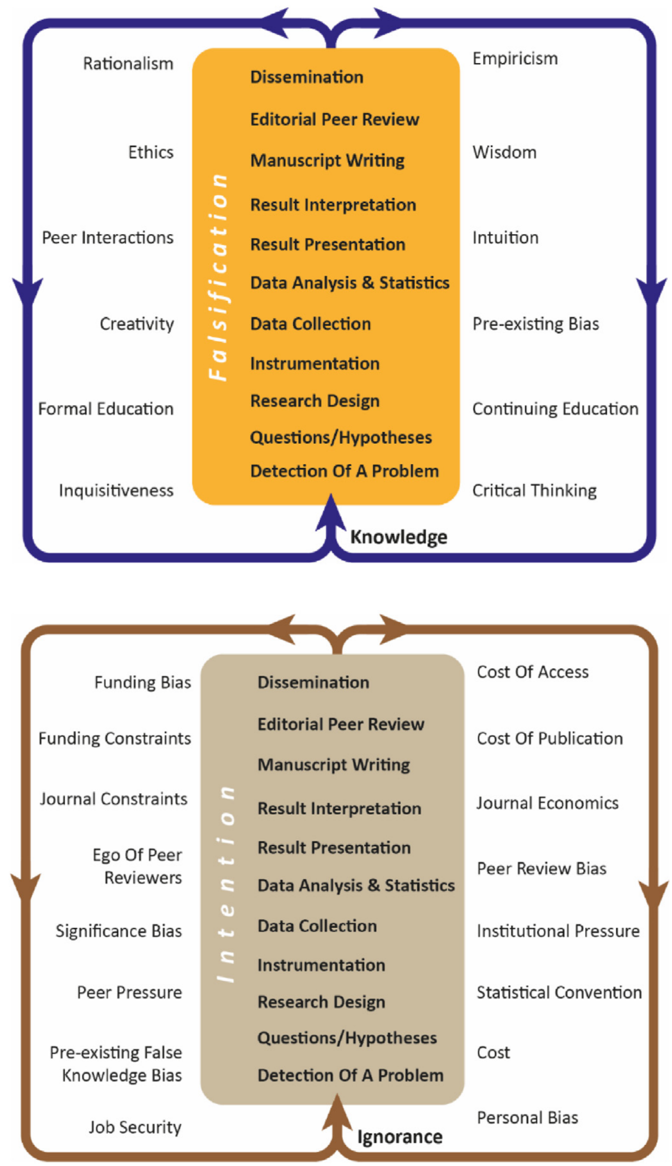

Fig. 3. A summary of two contrasted approaches in the pursuit of science. a) A more ideal approach informed from core features developed from scientific philosophy, with emphasis on the importance of knowledge/education and the core construct of falsification. b) The myriad of competing influences that can individually, and collectively, derail the process of science from the rigors of the scientific method. Such dysfunction changes the framework of the scientific method from falsification to intention, and the process of science becomes driven by forces incompatible with, or lowering the probability for success in, the search for the truth.

How to be a better scientist

To be able to fix a problem, you first need to know you have a problem. In the context of the quality of how humans pursue science, the problem identified is that both scientists and non-scientists alike are mostly (not all) poorly educated in understanding what science is, and how to best perform it (as a scientist) or understand it (as a consumer). This situation is disastrous, for the fuel of scientific endeavour, and democracy, is knowledge. Yes, other components are also important, such as creativity, perseverance, hard work, and a vision to foresee how different is better. But it is the knowledge that allows all the pieces of the pursuit of science to come together in a cohesive whole and provide the opportunity to change the world for the better.

Fig. 4. A simple illustration depicting the continuum of science spanning incorrect (pseudoscientific) to exemplary (extraordinary) forms. Note that the word "routine" has replaced Kuhn's label of "normal" due to the conflict this term has caused within science.

We need to do better in educating and training our students, at all levels of education, about what science is and what can pollute it. This idea applies just as much to high school and university undergraduate students as it does to future Ph.D.-qualified researchers. At one time, to attain a Ph.D. you had to challenge a paradigm and provide evidence to support the challenge. Such qualities linked to falsifiability have arguably disappeared from the training of most Ph.D. academics in contemporary times. Why? While the answer could build into a separate manuscript, the question needs to be asked and many would immediately proclaim that the finances and economics of higher education have compromised quality. These circumstances need to change.

Current scientists need to recognize their own limitations in pursuing science and take the action necessary to constrain these features. Fig. 3 can help with this. A good place to start is to always read (critically) and then cite original research for a method or data interpretation. If all scientists did this, when supported by quality education and an inquisitive mind, the premature acceptance of poor methods as valid, or oversimplistic interpretations as true would have a greater chance to be prevented and 'normal' science would be raised to higher ideals.

There are a couple more added items of importance presented as questions and explanations.

Do I want to pursue 'normal' science, or 'extraordinary' science?

Given that all scientists should be trained to pursue 'extraordinary' science, the core question to ask and establish an answer is; do I want to pursue 'normal' science or 'extraordinary' science? If you are content to ask questions and publish on topics that are easier to navigate through the journal peer review system or align best with your institutional research performance metrics (most are based on numbers of publications and the ranking of the journals published in, though high impact factor journals are likely to be just as supporting of outdated paradigms as any other), then the content of this manuscript will likely not interest you. However, if you are motivated to make a high impact on your disciplines by challenging conventions when there is empirical evidence to support your argument, even though this process is difficult and change is slow, then your approach needs to be applauded. To be able to confront outdated paradigms for any given topic, the added question becomes relevant.

Do I really understand the limitations of the paradigm that I have accepted in the pursuit of the research I do?

This issue is most difficult. We are taught through our higher education (post-graduate training) to focus on a specialization. Most of us are directed by our mentors to work within this topic/paradigm because that is how they were trained, and over time, multiple generations of scientific training, producing multiple generations of scientists, too often result in scientists who predominantly reinforce paradigms rather than confront them. Perhaps we should return to the pursuit and awarding of Master and Ph.D. research degrees based on the quality of the crafting of falsifiable research to either contribute to the proof or disproof of existing or alternate paradigms. For that matter, why don't we infuse this into High School and undergraduate university education? Surely this is where we need to start with the reinvigoration of the teaching of science.

Conclusion

Clearly, the pursuit and commentary of scientific research is consistent in revealing multiple aspects of concern for how science has been and continues to be practiced. As such, the problem is clear; human endeavour to pursue science frequently results in errors in research design, data interpretation and insufficient rigor that result in the premature acceptance of theories, models, methodological approaches, and/or data interpretations, with equal probability for the delayed rejection of contemporary paradigms. Kuhn's efforts to describe the process of science-based on the historical development of science overlooked the dysfunction of the 'human mud'[32] that interferes with the more ideal pursuit of science. Popper may have been too ideal in arguing for a simple demarcation between science and pseudoscience,[29] for the forces that compete with the ideal pursuit of science are numerous, and many can exert their influences subconsciously. Science vs. pseudoscience is not binary; a continuum of deterioration exists in the pursuit of science and the scientist needs to understand the diverse components of the limitations to their own scientific credibility.

Popper once stated that he thought that a scientist pursuing Kuhn's version of 'normal' science was "*badly taught*" and in need of "*feeling sorry for*".[34] When taken further, this perspective also reveals a form of science that is less likely to make an impact, which means it forms a career that is less likely to be relevant for a given discipline, regardless of the number of publications compiled. What impact do you want your scientific career to have? How are you measuring this impact? What are we likely to be doing wrong today, and how can you change that while performing science in a manner that befits Kuhn's label and definition of 'extraordinary'?

Submission Statement

The work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

Authors' contributions

Robert Robergs: Conceived of the need for the manuscript. Read the pertinent prior content on scientific philosophy. Wrote the first draft of the manuscript. Developed all figures.

Olumide Opeyemi: Read the pertinent prior content on scientific philosophy. Edited drafts of the manuscript. Provided feedback and constructive criticisms of content, wording, emphasis, grammar and structure.

Sam Torrens: Read the pertinent prior content on scientific philosophy. Edited drafts of the manuscript. Provided feedback and constructive criticisms of content, wording, emphasis, grammar and structure.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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