Analogy and Originality in the Context of Scientific Enquiry

Alexander M. Korsunsky

Abstract— **In this paper I attempt to address the concepts of analogy and originality, and their role in the advancement of knowledge via scientific enquiry. I argue that the use of analogy can be seen as a core part of the scientific method, and that the study of research practice shows that vast majority of projects rely on analogy for their success. Originality, on the other hand, emerges much less frequently and is associated with a step change in understanding. What constitutes originality then? How can one identify what is truly original, as opposed to derivative, or built on analogy? A tentative definition of what constitutes an original step in the process of learning and discovery is proposed. Some illustrative examples are introduced in order to substantiate the argument in favour of the proposed definition.**

Index Terms—**Originality, analogy, enquiry, discovery.**

I. INTRODUCTION

We are witnessing an unprecedented explosion in the quantity of published research. The volume can be quantified by the number of records entering abstracting and indexing databases year upon year. More and more new journals are being founded; competition for visibility, citations, impact factor grows stiffer. As always, the pyramidal structure of success means that one finds there is less and less room, the higher one climbs to the top. Ever more efficient ways of accessing and handling data mean that the users can cope with this maelstrom of information with the help of navigation aids performing a sort of GPS function, helping the lost traveller find the route to a particular address, topic, method, solution.

But what about the quality? Attempts are being made to introduce measures that would help us distinguish truly original contributions from more routine applications of the existing, well-established principles and methods. Publications that exert significant influence on the work of other researchers are more frequently referred to, so they float up in lists of citations. We rely on this kind of "free market of ideas" to sort itself out, in a way that some economists adhere with almost religious fervour to their belief that free economic markets have the ability to right themselves of any evil imagined and unimaginable by humans. However, the present rapidly developing global economic crisis seems to have put paid to such simplistic views of the problem: the emerging consensus seems to suggest that the world must accept the necessity of some degree of direction, intervention, restriction and coordination.

Returning to the world of scientific research, we may ask ourselves the question: is popularity the same as originality? If we projected this question onto the landscape of mass culture, the answer would be obvious: most certainly not! Someone truly original in their thinking, behaviour, life outlook would not be able to sustain celebrity status for very long; the admirers must see a clear and recognisable reflection of themselves in their idol to worship it. Many popular television programmes or stage shows are demonstrably successful, but can hardly be called original (although one must not underestimate the skill and insight required in order to turn even someone else's original idea into a successful product).

Might one then suspect that similarly, some of the most widely cited papers in science are in fact not the most original, but those that succeed in translating the original ideas into a form that can be readily digested by the mass (scientific) consumer?

It seems, therefore, that popularity, or citation count, may not be readily used as a measure of originality. Is it possible to identify, at least qualitatively, what constitutes originality in research?

In the present paper I wish to address the dichotomy between analogy and originality. The latter term is, in fact, so difficult to define that I would like to leave this task till the end. The former term, on the other hand, is something that we are all pretty familiar with, and many might even consider themselves reasonably expert. Whenever some aspects or relationships characteristic for a particular phenomenon, object, or process can also be detected in another phenomenon, or in a somewhat different context, one may talk about an analogy existing between the two. If the analogy is good, then these aspects must be fundamental and crucial for the very phenomena considered; otherwise one might find that the significance of such analogy is obscured and overridden by other, more substantial effects.

A good analogy is therefore almost necessarily scientific and analytical. Einstein once said, famously: "Everything should be made as simple as possible, but not simpler." He could have been referring to creating analogies; or he could have been talking about the nature of scientific enquiry and the task of creating scientific models.

Analogy is central to the scientific method. Identifying the key features of a particular phenomenon, establishing relationships between parameters, describing these

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Manuscript received December 17, 2008. The author acknowledges discussions with colleagues and friends.

Alexander M. Korsunsky is Professor of Engineering Science in the Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK, and Fellow of Trinity College, Oxford, OX1 3BH, UK. (phone: +44(1865) 273043; fax: +44(1865)372010; e-mail: alexander.korsunsky@ eng.ox.ac.uk).

relationships in a mathematical form that falls into one of the patterns contained in the great library of models – these are the key steps in any research project. In other words, the job of carrying out a research study in most cases involves the process of identifying an analogy between the present object of study, on the one hand, and something that has been studied before, on the other.

There is an old joke about the difference between approaches employed by an engineer and a mathematician: they are each given a kettle and a tap, and asked to boil some water to make tea. Naturally, both do the same: pour some water into the kettle, put in on the heat, and boil the water to make tea. The next task they are given is subtly different: the kettle already contains the water. The engineer says: “Aha, I already have the water in there. I recognise this step from my previous exercise. Now all I need to do is put the kettle on the stove,” – and so he does. The mathematician sees water inside the kettle, pours it out into the sink, and declares: “Now I’ve reduced the problem to the one that I already know how to solve.” The two approaches are starkly different! However, the key component in both of them is the ability to recognise an analogy between the present problem and the one already seen before.

Suppose we extend the applicability of our term “analogy” to include such situations. Then one might soon be forgiven for thinking that in most cases all that the scientists and researchers do is seek analogies – and they would be right! Finding the similarity between a present problem and the ones that we are already familiar with is a huge step towards solving it. By learning about the experiences of other researchers of finding analogies between problems we expand our library of useable analogies, and make ourselves better equipped to tackle a larger range of problems. Practice shows that one can travel a very long way using this principle alone.

What about originality, then? Is it not, by definition, the antithesis of analogy? If something is analogous to something else (let’s assume we are talking about scientific models here), then, naturally, it is no longer entirely original. But we have seen that the very nature of scientific enquiry often pre-supposes a search for similarity, a way of “projecting” a new phenomenon into the space of existing modelling frameworks. So is there anything truly original in the world?

This is the point at which we encounter real problems. Of course, one could simply declare the term “original” inappropriate and outlawed; but then one would be left only to adjudicate between better or less appealing analogies; analogies drawn between concepts that have closer or more remote contextual connections. So let’s postpone discarding the term “original” for the time being, and look for ways of identifying originality.

When global considerations fail, it is sometimes useful to begin analysis by considering specific examples. The selection of such examples discussed below may necessarily appear to be highly subjective. Yet, it seems sufficient insofar it serves the purpose of illustrating the point I am trying to make. The role of analogy and originality is discussed in the context of the work of Leonardo da Vinci, Dmitrii Ivanovich Mendeleev and Albert Einstein. Then we come down from those giddy heights to consider today’s mundane research practice, in an attempt to address the question whether some lessons can be learned, and applied in the context of daily scientific research.

II. Leonardo Da Vinci

Leonardo’s contribution to the world culture and knowledge, and his enduring presence are monumental in both art and science. What is perhaps particularly fascinating in his work is his ability to cross easily and naturally the now well-established boundary between natural sciences and humanities. This aspect of Leonardo’s genius must have proved irresistible to Professor Martin Kemp (a world authority on Leonardo and my colleague at Trinity College in Oxford) who has devoted much of his time not only to the study and popularisation of Leonardo’s legacy [1], but also to the re-enactment of da Vinci’s projects and designs. Martin Kemp’s lectures on the Leonardo leave one deeply moved and stimulate reflection on many topics, the originality of Leonardo’s perception of the world being one of them.

In the context of our discussion of particular interest is Leonardo’s ability and readiness to draw analogies between concepts and objects far removed from each other, in order to achieve breakthroughs in understanding. By transplanting the analogy into a totally different context Leonardo is able to discover aspects of a particular phenomenon that are otherwise extremely difficult to elucidate. Figure 1 illustrates Leonardo’s studies of the arm. These investigations may have influenced Leonardo’s designs for a flying machine.

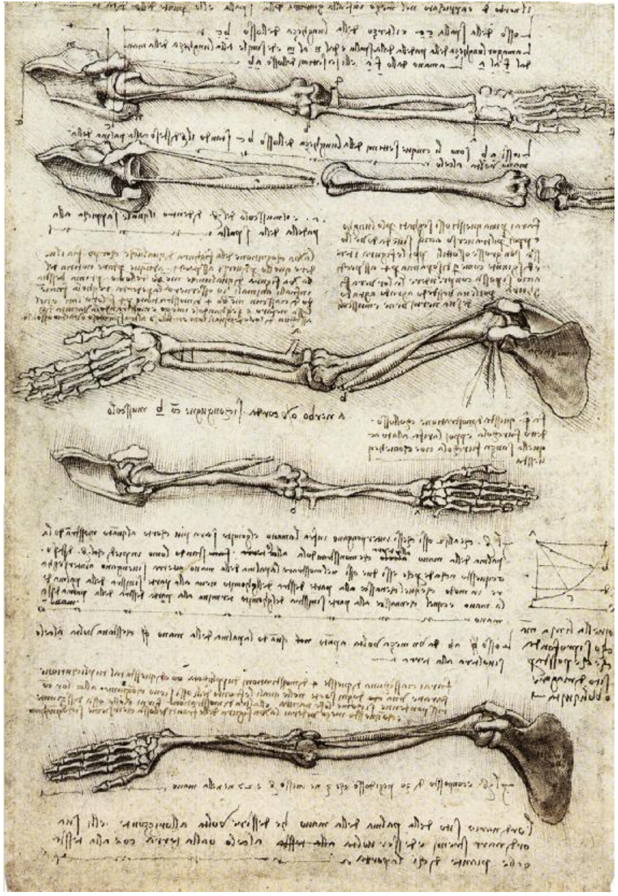


Figure 1. Leonardo’s studies of the arm showing the movements by the biceps.

Around 1508 Leonardo became particularly interested by the aortic valve in the human heart. His approach was highly scientific, in that he studied the structure of the heart and the flow in it, and executed numerous drawings. He made wax casts and glass models of the aorta, and left notes of experiments with flowing water with grass seeds used to track the flow of blood through the valves. Leonardo identified the triangular shape of the open valve, and concluded that the flow must be slowed down by the contact with the sides, and must therefore be the greatest at the centre, where the effect of friction was the least. The velocity gradients appearing in the outflow must then result in the creation of three distinct vortices causing an increase in pressure and closing the valve, as illustrated in his diagrams (Figure 2). Leonardo's drawings also show that he was fascinated by the analogy between such disparate (but visually similar) phenomena as stream lines and the patterns formed by braided hair. It is Leonardo's ability both to identify analogies and also to extend their use beyond the obvious original scope that makes his work and conclusions so highly original. For the purposes of our discussion we note that it is the act of transposing an analogy into a fundamentally different context that seems to bring with it the seed of originality.

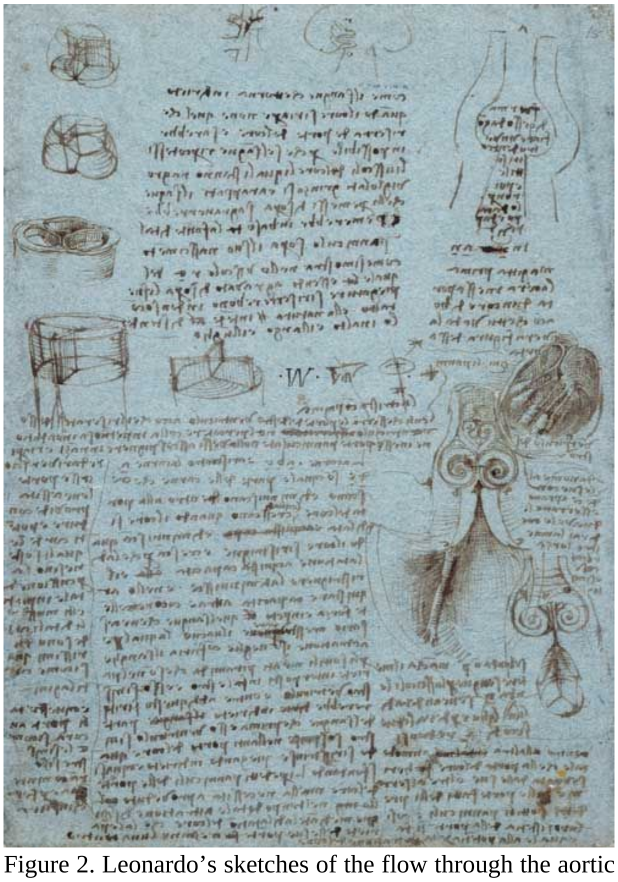


Figure 2. Leonardo's sketches of the flow through the aortic valve (Royal Collection, Her Majesty Queen Elizabeth II).

III. MENDELEEV'S PERIODIC TABLE OF ELEMENTS

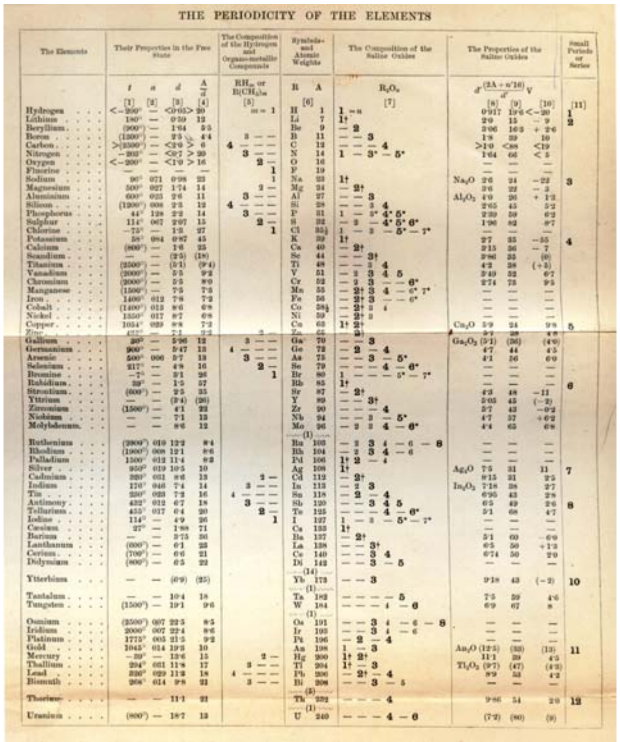
Dmitri Ivanovich Mendeleev (1834-1907) is a prominent figure in Russian and world science. In 1865 he finished his doctoral dissertation entitled "On the Combinations of Water with Alcohol", a subject to which he returned in 1890-ies when his work served as the basis for the Russian (and Polish) standard for vodka. Although Mendeleev recommended the "perfect" mixture of 38% by volume, the 40% ABV standard was adopted to simplify the computation of taxes (based on spirit content) by the Russian imperial authorities. As Director of the Russian Imperial Bureau of Weights and Measures, Mendeleev was involved in formulating and maintaining many other standards, and is credited with introducing the metric system in Russia. He also investigated the composition of oil fields, and was involved in the founding of the first oil refinery in Russia.

However, Mendeleev's most enduring and prominent contribution to the world of knowledge is undoubtedly his discovery of the periodic table of the chemical elements. Although to a modern student of physics and chemistry listing the elements in the order of atomic number (charge of the nucleus) might seem the most natural thing to do, this was not the case in 1860-s. Mendeleev proposed his law of periodicity of the properties of the elements in 1869, long before the structure of the atom was understood, and the connection was established between the nucleus charge and the number of electrons orbiting it, and hence the chemical and structural properties of the corresponding substances. The basis for Mendeleev's argument was that, if the elements were listed in the order of their atomic weights, as they were known then, then a certain periodicity of property variation was observed. That in itself was a useful and correct observation, but, as we know full well now, this was a manifestation of a deeper and more fundamental relationship between the atomic charge and chemical properties. Mendeleev seemed to have been looking, perhaps unknowingly, for this deeper, more fundamental underlying regularity.

The story has it that in order to help his attempts to find the correct arrangement of the elements, Mendeleev made up cards with short descriptions of each substance, and for days and months kept trying to arrange them on his desk in a way that he would find intellectually satisfying. One day, having failed again at this task, he fell asleep, only to wake up *knowing* the correct arrangement! Mendeleev's periodic table was the result.

There have been arguments about the originality of Mendeleev's discovery. Around the same time, albeit unknown to Mendeleev other scientists had been working on similar tabular arrangements of the elements [2]. Although John Newlands published his Law of Octaves in 1865, his arrangement did not have empty spaces for undiscovered elements, and also required placing two elements in one box. Lothar Meyer published a work in 1864 that described 28 elements, but, similarly to Newlands he did not have the idea of using such a table in order to predict the existence and properties of new elements.

Mendeleev's original and deciding breakthrough was the successful prediction of the existence and properties of several then unknown elements. He postulated the necessity of the elements that he called *ekasilicon* (germanium), *ekaaluminium* (gallium) and *ekaboron* (scandium) [3]. It is this capacity of Mendeleev's approach not only to find a representation of known facts, but also to predict those that were not know, that played the decisive role in giving him priority in this discovery.



THE PERIODICITY OF THE ELEMENTS

Figure 3. A page from the 1891 English edition of Mendeleev's *Principles of Chemistry* textbook.

Mendeleev's deduction is particularly interesting since, in order to make the elements conform to his imagined pattern, occasionally he had to swap the positions of elements (like tellurium and iodine) despite their atomic weights – even though this property served as the principal basis for establishing the sequence!

The key advancement achieved by Mendeleev was thus not the identification of similarities or analogies, but the placement of emphasis on the *periodicity of properties* as the basis for rational understanding of the nature of the element series. It seems therefore that it is this selective change of relative significance, the *re-assignment of principal importance* and of what is consequential, that constitutes a key aspect of originality.

IV. ALBERT EINSTEIN'S "ANNUS MIRABILIS"

Few scientists and even lay people, if asked, would disagree or doubt that Einstein was one of the most original scientific minds of the 20-th century. Albert Einstein and the story of how the special relativity theory was created will provide us with an interesting case study.

In the year 1905 often referred to as the "annus mirabilis" by science historians, Einstein published four seminal papers in the journal *Annalen der Physik* [4]-[7]. These papers did nothing less than lay down some of the foundations of modern physics. They dealt with such disparate topics as the photoelectric effect, Brownian motion, the energy-mass equivalence, and the electro-dynamics of moving bodies.

The latter paper was devoted to what later became known as the special theory of relativity, and had a most profound impact on modern physics, but also other sciences branches of knowledge, including philosophy, politics, etc.

Einstein's construction begins with the definition of simultaneity. By conducting thought experiments involving two observers A and B, Einstein arrives at the necessity of introducing separate (relative) time A and time B, and at the unavoidability of considering the transmission of information, or signal, between observers. In the course of such analysis the self-evident nature of simultaneity disappears. Further progress would now be impossible without introducing an alternative fixed reference. Einstein chooses to postulate that the speed of light in vacuum to be a universal constant [6]:

> "Wir setzen … der Erfahrung gemäß fest, daß die große … (die Lichtgeschwindigkeit im leeren Raume) eine universelle Konstante sei."

Having identified and defined the fundamental building blocks of his theory, the author goes on to consider the relativity of time and length with respect to moving systems; and to introduce the transformations of coordinates and time, as well as the addition theorem for velocities. Einstein then goes on to consider the implications of this approach for the transformation of the Maxwell-Hertz equations with respect to moving systems.

The fact that Einstein's paper does not contain any references at the end, nor in the footnotes, suggests that he, too, may have wanted to imply that his approach was original. However, the results enumerated above are expressed mathematically through Lorentz formulas that were published in the previous year [8], and are likely to have been known to Einstein. So what was the principal original content of Einstein's theory?

The key step in Einstein's reasoning was the shift of emphasis. A clear analogy exists between the Galilean transformation that applies to slowly moving bodies, on the one hand, and the transformation equations that apply to small particles moving at speeds comparable with the speed of light, on the other. Einstein's original contribution was in realising that this analogy cannot be stretched any further without selecting another axiom to serve as the principal foundation of the new theory.

V. EPISTEMOLOGICAL PERSPECTIVE

It appears from the examples presented above that, despite analogy being an omnipresent and universal tool in scientific enquiry, original thinking and original results are invariably associated with the re-positioning of emphasis in terms of primary and secondary, source and consequence, cause and effect.

A connection can be readily found linking the present subject of discussion, namely, the tension between the analogous and the original, and the work of Karl Popper [9] and Thomas Kuhn [10].

Popper devotes a lot of attention to the study of the process of scientific discovery, and identifies it with the following sequence:

$$PS_1 \to TT_1 \to EE_1 \to PS_2 \qquad (1)$$

where the abbreviations stand for "problem situation", "tentative theory" and "error elimination", respectively. The above expression builds on Popper's idea about *falsifiability* of scientific theories by comparison with experimental results that allows better theories to survive in a manner not dissimilar to Darwinian evolution.

The key point being made presently is, however, that many tentative theories falling under TT_1 may in fact differ qualitatively within themsleves, by either being built on an analogy (and some very successful theories indeed are), or involving a change of emphasis and re-definition of key axiomatic foundations.

Thomas Kuhn in his book on the structure of scientific revolutions [10] describes the "paradigm shift" that is responsible for a revolutionary change of fundamentals within a given science. Indeed, the conclusion to which we arrived through the consideration of examples sounds similar, in that we identify the shift of emphasis as the key original step in the development on ideas and concepts.

It is worth noting, however, that the present discussion is not aimed specifically at revolutionary ideas that overturn, or disrupt, the entire edifice of knowledge in a particular field of human endeavour, as in the case of Thomas Kuhn's paradigm shift. Our conclusion about the change of emphasis applies even to smaller, micro-scale issues of originality. While the significance of an original thought may be limited in its scope, the principle of what constitutes original thinking seems to remain unchanged.

In order to consider the validity of this conclusion, it is interesting to attempt its application to a smaller scale example of scientific theory or analytical approach. This is the subject of the following section.

VI. EXAMPLE: THE HARDNESS OF COATED SYSTEMS

Having established a tentative definition of what constitutes an original forward step in the process of scientific research, it seems natural to attempt to delineate the range of applicability of such consideration. For this purpose we seek to apply the same reasoning to some much more recent and far more modest research results. This might allow us to falsify the conclusions.

In 1998 the present author collaborated with a number of colleagues on a paper entitled "On the hardness of coated systems" [11]. The paper introduced a novel model for the description of the dependence of apparent (composite) indentation hardness of coated systems on the applied load or, alternatively, on the depth of indentation. The approach developed in that paper has proved attractive and useful, as signified by the paper attracting over 150 citations in the ten years since its publication.

As mentioned in the introduction, however, high citation count does not guarantee originality, and so cannot serve as a criterion. As an exercise, nevertheless, it is interesting to consider the development of that model presented in the paper in somewhat finer detail, in order to attempt and discover whether some shift of emphasis was present in the derivation that may in fact be considered an original step.

The model development relies on the so-called *work-of-indentation* analysis. This approach was necessitated by the fact that detailed analysis of stresses and strains in indentation experiments can be tremendously complicated and dependent on the material behaviour. Energy dissipation, on the other hand, is likely to follow simpler scaling laws that may allow simplified description. However, even if our attention is focused on dissipated energy, how may that help determine the load dependence of hardness?

The key aspect of the novel approach lied in the re-definition of conventional hardness in terms of energy, rather than load and projected area of the indent. Indeed, in the classical case of homogeneous plastically deformable substrate the load-displacement relationship is given by

$$P = \frac{H\delta^2}{\kappa}, \tag{2}$$

where P is the indentation load, δ is the indenter tip displacement into the sample, H is the hardness, and κ is a dimensionless parameter depending on the indenter tip geometry. The total work done by the indentation system is then given by

$$W_{tot} = \int_0^d P dx = \frac{H\,\delta^3}{3\kappa}. \tag{3}$$

If the above equation is now used in order to *re-define* the very concept of hardness, then the following expression emerges:

$$H = \frac{3\kappa W_{tot}}{\delta^3}. \tag{4}$$

The difficulty in obtaining a generic mathematical description of the apparent composite hardness of a coated system lies in the fact that precise determination of the load-displacement relationship in equation (2) for complex samples is extremely laborious, particularly in cases when material response involves through-thickness and/or interfacial fracture of the coating and/or substrate.

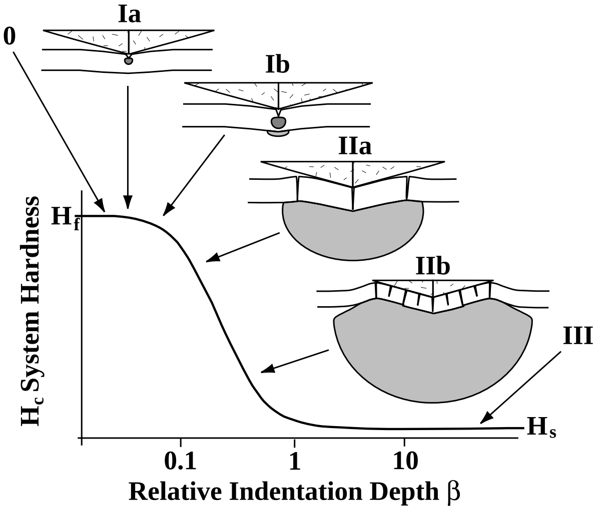


Figure 4. Variation of the response mechanisms and the partition of deformation between the substrate and the film during indentation of a coated system.

However, the considerations of the expenditure of energy that appears in equation (3) allow estimations of the contributions from different parts of the composite system and from different mechanisms to be estimated more readily. Furthermore, whereas the partitioning of load and displacement (or even supporting area) between the coating and substrate cannot be readily determined, this is more easily done for energy that is a scalar additive quantity. These considerations can be used for a variety of indentation responses and throughout the indentation process illustrated in Figure 4.

The above considerations, in combination with the analysis of the dependence of different energy contributions on the coating thickness, allow the following expression for the composite hardness to be arrived at:

$$H_c = H_s + \frac{H_f - H_s}{1 + k(\delta / t)^2}. \qquad (5)$$

Here *t* is the coating thickness, and H_s and H_f denote the substrate and film hardness, respectively. Parameter *k* can be adjusted in order to achieve the closest agreement with the experimental results.

The proposed model has been validated extensively against experimental data [11] collected from nanoindentation tests conducted on hard coatings (such as TiN, NbN and other hard ceramic coatings) on more ductile substrates (such as tool steels). Figure 5 illustrates the experimental data (markers) for TiN and NbN coatings of different thickness. The model description is indicated by continuous curves corresponding to the expression in equation (5). A satisfactory description was obtained for a variety of coated systems, confirming the flexibility and versatility of the proposed work-of-indentation composite hardness model.

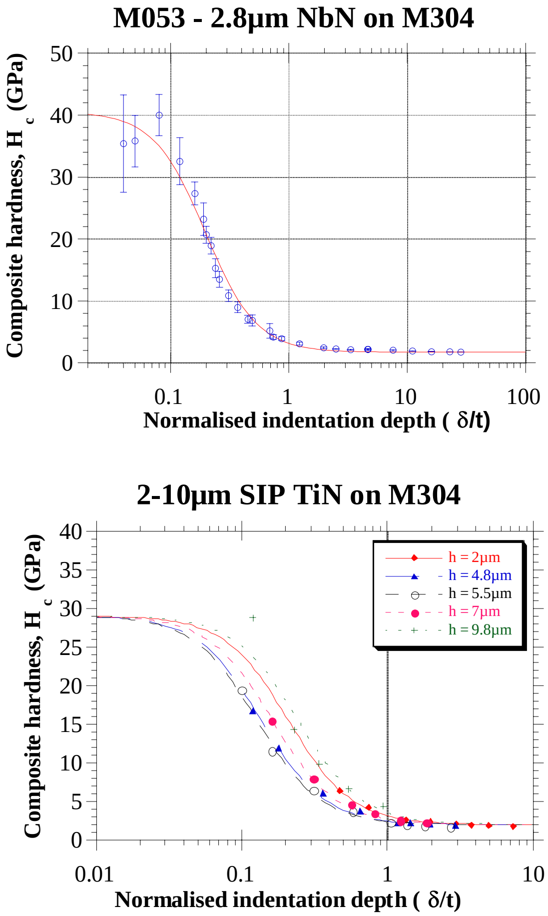


Figure 5. Indentation hardness (markers) and work-of-indentation model fit (continuous curves) for a NbN coating (upper plot) and TiN coatings with thicknesses in the range 2-10μm on M304 tool steel (lower plot).

To conclude this section it is worth to note that the change of emphasis consisting of the re-definition of hardness was in this case instrumental in the development of a successful new modeling approach.

CONCLUSION

Analogy and originality co-exist in the context of scientific enquiry. Analogy is indispensable as a tool for the construction of scientific models, and is necessary for understanding phenomena by means of establishing their similarities with other, better known processes and systems. However, application of analogy alone confines the results to incremental advances.

Originality lies in the departure from the existing understanding that is associated with finding analogies. It appears that originality consists in the new placement of emphasis that changes the nature of understanding.

In order to substantiate this hypothesis, several well-known examples are considered (these are naturally chosen to support the proposed viewpoint).

An attempt is made to consider the relationship between the presently advanced point of view and the works of Karl Popper, who devoted a lot of attention to the analysis of the scientific method; and of Thomas Kuhn, who introduced and studied paradigm shifts and revolutionary theories.

An attempt is also made to apply these considerations to recent results and author’s research experience, in order to seek small scale examples of the effect of shifting emphasis.

ACKNOWLEDGMENT

The author wishes to thank colleagues at Trinity College, Oxford, for providing a convivial and stimulating environment for interdisciplinary thought. Special thanks are due to Mike Inwood for lunchtime discussions about philosophy and life; and also to Katerina Reed-Tsocha for the organisation of Friday evening seminars on the history and philosophy of art.

REFERENCES

[1] M. Kemp, *Leonardo da Vinci: The Marvellous Works of Nature and Man*, Cambridge, Mass: Harvard University Press, 1981.
[2] P. Strathern, *Mendeleyev's Dream: The Quest For the Elements*, New York: St. Martins Press, 2001.
[3] D.I. Mendeleev, *Principles of Chemistry*. New York: Collier, 1901.
[4] A. Einstein, "Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen", Annalen der Physik, 17:549-560. (1905)
[5] A. Einstein, "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt", Annalen der Physik, 17:132-148 (1905)
[6] A. Einstein, "Zur Elektrodynamik bewegter Körper", Annalen der Physik. 17:891-921. (1905)
[7] A.Einstein, "Ist die Trägheit eines Körpers von seinem Energiegehalt abhängig?", Annalen der Physik, 18:639-641. (1905)
[8] H.A. Lorentz, “Electromagnetic phenomena in a system moving with any velocity less than that of light”, Proc. Acad. Science Amsterdam IV, 1904, pp. 669–678.
[9] K.R. Popper, *Objective Knowledge: An Evolutionary Approach*, New York: Oxford University Press, 1972.
[10] T.S. Kuhn, *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1962.
[11] A.M. Korsunsky, M. R. McGurk, S.J. Bull, T.F. Page “On the hardness of coated systems.” Surface & Coatings Technology (1998) 99: 171-183.