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Styles of Scientific Thinking

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ABSTRACT. It is a main contention of this paper that the history of science is not so much a story of the progressive advance in our understanding and discovery of 'the facts of nature', but rather, an account of different ways of 'seeing' things; where 'the things' thus seen are to a considerable extent themselves the result of 'realizational' processes operating in terms of some theory or other. But further, such theories are in turn controlled by some respective methodology which has its history: with the latter itself a record of different views about those elements believed to be essential for any adequate construction of scientific theories. The paper then distinguishes between three views, the 'rationalist', the 'empiricist', and the 'systemic' processing of scientific 'facts'; the last-named view operating under the guidance of certain leading maxims and principles. Finally, the paper formulates a triadic type of methodology whose three components mirror the three views just mentioned: the 'probative', the 'explicative' and the 'systemic' components; which in turn are then shown to generate three corresponding ontologies.

I. PRINCIPLES

The title of my paper, "Styles of Scientific Thinking", is intended to highlight the importance and usefulness of the concept of 'style' in any reflection on the relevance of the historical dimension of science, both in respect of its content and of its methodological framework. To focus on 'style' is intended to draw attention, on the one hand, to certain analogies in connection with the concept of style in the history of art, and on the other, to highlight some central ideas that have become prominent in recent years in the area of the historiography of science.

First, as to art, and its history. The existence of 'style' emphasises the fact that art is never simply representational, but that what matters in both the creation and in our appreciation of works of art is the fact that in them the world is represented, or is 'seen', from certain points of view. Thus, in contemplating the transition from a pre-Giotto to a post-Giotto period, or from Impressionism to Abstract Painting, what is primarily of relevance are the sensitive and formal responses on the part of the artist to his world – the 'method' in terms of which he expresses these responses as well as his own sensibilities. It is not so much the detail of the subject which is being represented on a canvas or in a piece of sculpture that is here of interest, but rather the fact that through such works the artist expresses his own vision of the world; each 'seeing the world' from his own point of view, and in terms of his own set of formal values. Indeed, even speaking of 'a world', seen by the artist in 'his' way, does not quite represent the matter adequately, since the different images each yield for us a number or different worlds; there *is* no *one* world, 'simply given', or 'pre-given': it is the 'how', the 'style', that matters – not 'what is shown or depicted'.

Now until recently it would have been said that such an account of the artistic situation, even if true or adequate, has litle relevance for anyone wanting to characterise the situation in science. Surely, so it would have been objected, what matters in science is 'description'; scientific understanding is a way of rendering the world 'as it really is', both 'on the surface' and in respect of the 'inner structure' of things. However, the general consensus of those who have reflected on the situation in science, during the last 30 years or so at least, is that such an account of scientific creativity is possibly as misleading as when the account of the artistic objective was being conceived as one of rendering the world 'descriptively' by means of the painter's brush or the sculptor's chisel. No one, of course, has had a greater influence in producing a change in attitude towards science and its history as well as methodology – at least, in the popular imagination – than Thomas Kuhn, one or whose sayings in his influential *Structure of Scientific Revolutions* of 1962 precisely echoes the situation as I have just characterised it in our revised attitude to art; namely, that different scientists, through their different 'paradigms', each see the world in their own different way, from their own point of view.[1]

Now in part Kuhn was here echoing (on his own admission) the ideas of a writer who had put forward similar views on the nature of science already 30 years earlier: Ludwig Fleck: with the difference that instead of speaking of 'paradigms', Fleck employs the term 'style': witness the very title of his book: *Genesis and Development of a Scientific Fact: Introduction into the Theory of the Thought Style and Thought Collective* – published in 1935, one year after Popper's Logik der Forschung; which by comparison now seems both pedestrian and old-fashioned.[2] I cannot go here into the details of Fleck's account: instead, I will simply quote a couple of passages which may speak for themselves and which aptly summarise Fleck's general ideas about science and its history:

> In the history of scientific knowledge, no formal relation of logic exists between conceptions and evidence. Evidence conforms to conceptions just as often as conceptions conform to evidence. After all, conceptions are not logical systems, no matter how much they aspire to that status. They are *stylized units* which either develop or atrophy just as they are or merge with their proofs into others. Analogously to social structures, every age has its own dominant conceptions as well as remnants of past ones and rudiments of those of the future. It is one of the most important tasks in comparative-epistemology to find out how conceptions and hazy ideas *pass from one thought style to another*, how they emerge as spontaneously generated pre-ideas, and how they are preserved as enduring, rigid structures owing to a kind of harmony of illusions. (*op. cit.*, pp. 27–28; italics mine)
>
> Observation and experiment are subject to a very popular myth. The knower is seen as a kind of conquerer, ... 'I came, I saw, I conquered.' . . . In more modern, more remote, and still complicated fields, in which it is important first of all to learn to observe and ask questions properly, this situation does not obtain – and perhaps never does originally in any field – until tradition, education, and familiarity have produced *a readiness for stylized (that is, directed and restricted) perception and action*; until an answer becomes largely

> pre-formed in the question, and a decision is confined merely to 'yes' or 'no', or perhaps to a numerical determination; until methods and apparatus automatically carry out the greatest part of our mental work for us. (*op. cit.*, p. 84)

So: different scientific periods, with their different theoretical structures, embody "stylized units" which "direct and restrict perception". The parallel with the artistic, and also the literary, areas of knowledge and action will be obvious; and the usefulness of such an approach in the physics teacher's attempt to establish some significant relationships between his subject and those of the humanities, suggesting that there are considerable areas of agreement between the latter and the former, will not be lost on this audience. The history of science, on such a reading, is no longer a catalogue of errors and misconceptions but instead is indicative of so many different paradigmatic visions or thought-styles; a view of history that need not deny that some of these 'visions' may yield more powerful technical results than others.

This last observation brings us, however, to another set of considerations. The 'paradigm' or 'stylistic' approach is here put forward as a way of viewing scientific theorising. It says that not only our *understanding* of 'the facts' is contingent on theory, but in some sense their very *being*; where 'theory' is to be viewed not merely as an instrument for the systematisation and explanation of the facts, otherwise putatively already pregiven, but where to a greater or lesser extent theory has become a '*constructive*' device, to yield (so to speak) a 'realization' of the 'facts' in the first place. This last point is not new: it is a commonplace of the philosophy of science of the last 50 years that the so-called 'theoretical entities' or 'terms' of a science are a function of some particular theory or other. What is novel is the Quinean generalisation that not only 'theoretical terms' but all those constituents which make up the 'observational level' of a theory are likewise a function of this constructive process of 'theoretical realization'. This is simply a consequence of the Quine–Duhem doctrine about the essential semantic inter-relatedness of the theoretical and observational levels of any science; and I need not enlarge on this here any further.

To sum up so far: The history of science, on the reading just given, is not so much a story of the progressive advance in our understanding and discovery of 'the facts of nature', but instead is an account of different ways of seeing things; where 'the things' thus seen are to a considerable extent the result of the 'realizational' processes operating in terms of some theory or other.

However – to move now to the next stage – in their turn, theories are controlled by some respective methodology; and what is of interest to us here as historians is that the topic of methodology has itself a history likewise; a fact which in its turn gives evidence, not so much of progressive advance towards an optimum method of theorising about nature, but rather, of different ways of construing *what it is like* to get at the nature of things; and where, furthermore, this expression: 'getting at the nature of things' must again be interpreted in the constructive-realizational mode, as before.

I will explain. Methodology has a history. That history is primarily a record of different views about those elements believed to be essential for any adequate construction of scientific theories. Here, a study of the history of the subject reveals three broad tendencies, or types of emphases, not to say styles, in terms of which methodological views have been formulated. It is worthwhile to make these formulations precise, partly because the subject is left a little vague in the writings of the type I mentioned before, e.g. Fleck or Kuhn, and partly because greater precision in our thinking about methodology will help us subsequently to extract the philosophical implications of the whole exercise more adequately.

Of the three kinds of emphases in reflections on the nature of scientific thought one may be termed, roughly, Baconian. It emphasises obervational and experimental evidence, the formation of hypotheses and their processing through various 'methods', which have themselves been formulated in different ways during the history of the subject: induction, hypothetico-deduction; more recently, confirmation, falsification and corroboration, Bayesian statistics, etc. etc. This type of methodology is clearly an expression of the empiricist tradition, associated and contemporaneous with the rise of modern science since the seventeenth century.

There is however also a second strain embedded in the origins of modern science, though going back rather farther into the history of thought: this is associated with the rationalist tradition both of philosophy and of science. A major example of this can be found in Descartes' writings on the foundations of dynamics, which purport to develop the basic laws of this science on largely conceptual considerations, rather than on the basis of empirical observation. Other examples of this trend may be found in some nineteenth century periods; for example, that connected with the origins of conservation principles. Thus, Robert Mayer, one of the 'discoverers' (so-called) of the principle of conservation of energy, bases this on the law of causation in the form: 'cause equals effect'; and E. Meyerson, in his influential philosophical account of the history of modern physics, entitled *Identity and Reality*, has carefully traced the development of a number of modern physical principles to certain purely conceptual argument patterns. Similarly, the celebrated classic by E.A. Burtt, *The Metaphsical Foundations of Modern Physical Science*, has supplied a rich canvas of evidence, demonstrating that modern science in its development owes much to purely conceptual and metaphysical considerations.

A third strand in the development of modern methodological ideas has its origin in the notion of harmony and rational coherence, which forms an essential element in the development of the concept of a scientific theory, viewed as a *system* of hypotheses, displaying a logical consistency with one another as well as with neighbouring theoretical schemes. This central theme of systematic harmony has again deep roots in the history of intellectual thought which stretch back to the Greeks, but surfaces more explicitly in many seventeenth and eighteenth century philosophical writings. Thus, both Leibniz and Berkeley base the idea of a system or an architectonic on the thought of the Creator Himself; a theological version of the metaphysically-grounded idea that nature does actually form an harmonious whole. It is an idea that has inspired many later physical thinkers; I need only mention Einstein whose motivating impulse was basically rooted in the view that different strands in apparently widely-separated areas of physics must be mutually reconcilable in a harmonious unity.

The notion of systemicity is however insufficiently characterised when viewed merely as an expression of the demand for logical coherence. A further, and perhaps more important aspect, is the fact that the process of systematisation operates almost universally under the guidance of certain leading maxims or principles which (not surprisingly) are found to be expressions of the particular style of scientific thinking in question. Thus, in Einstein again, it is the idea of 'symmetry' that formed an important component of his thinking. Even more deeply-engrained is the demand that the multiplicity of effects should be reducible to some underlying identical agency – we need only think of the atomic hypothesis of the Greeks and the seventeenth century, and later; or again, the already-mentioned idea of energy, and the accompanying notion of conservation. Other such 'regulative' ideas are of a more formal type, such as the maxims of simplicity and economy which have played such an important part in the development of physical theory.

Nor is this all. Deeply engrained in the development of physical theory are certain preferred explanation types, as one may term this. Many years ago, K. Lewin wrote an influential paper entitled "The Conflict between Aristotelian and Galilean Modes of Thought in Contemporary Psychology" – a conflict that extends of course beyond the confines of that science. (Indeed, in recent years, this type of conflict has been discerned also in the deelopment of different theoretical approaches to Social Theory.) One expression of the distinction here implied is that between explanation in terms of classes and substances, on the one hand, and between interacting laws, on the other. Another expression is the distinction between teleological and mechanistic approaches in physics or in biological science. A third expression we meet with in the different types of approaches that formed so much of the battlefieid af nineteenth century physics and chemistry, though it stretches right into our own century: I am thinking of the difference between a 'macro-' as against a 'micro-' approach towards physical phenomena, also referred to as the distinction between phenomenological as against atomistic (or surface vs. deep-structure) theory types; illustrated in the famous battles between the school of energetics (Ostwald, Mach) and the adherents of Boltzmann.[3]

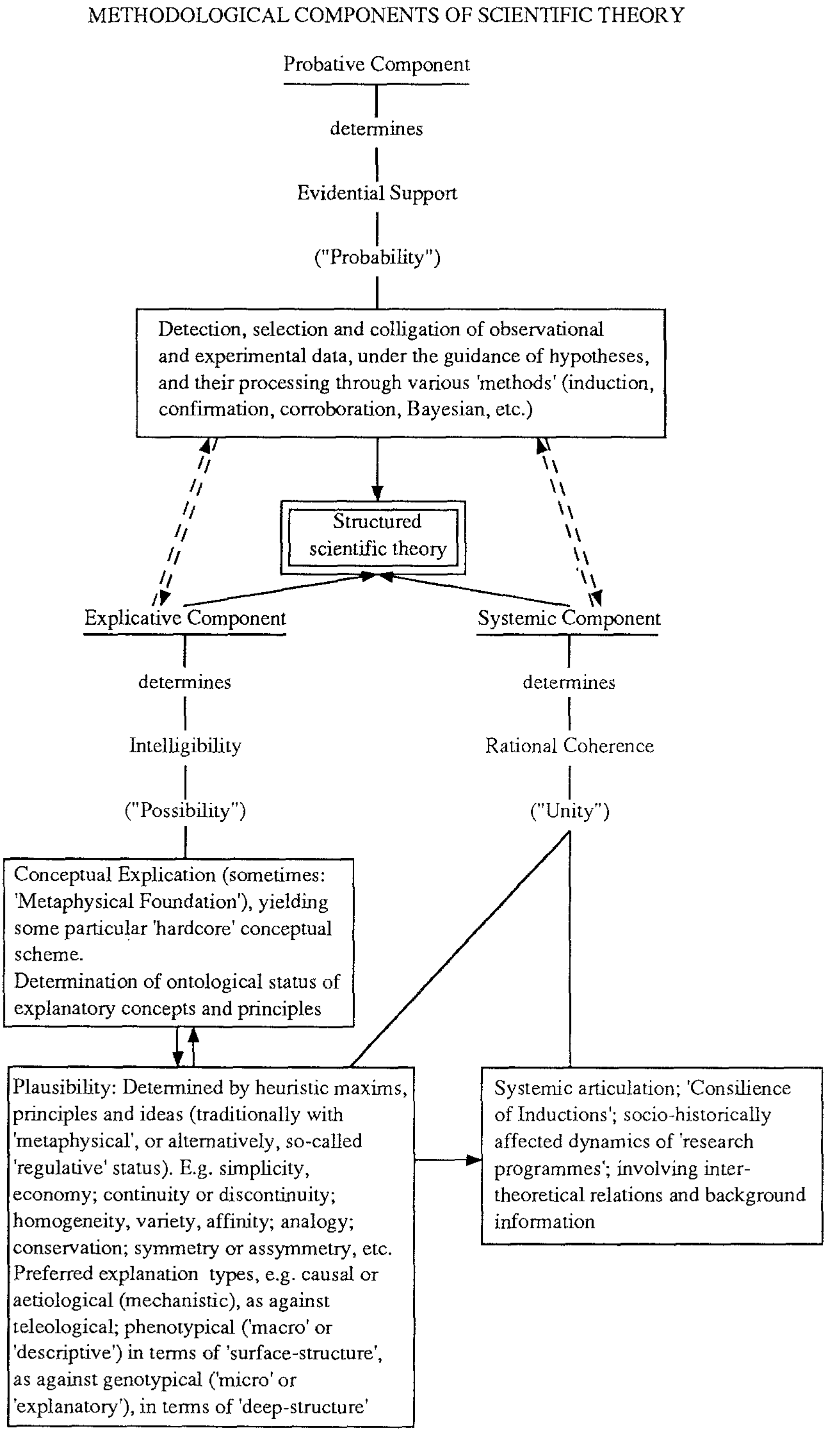
Drawing attention to such (almost ideological) differences in basic styles of physical thinking, linked as they are to preferred methodologies, can go a long way towards disabusing the young student of the belief that his subject consists simply of a recital of facts and theories; instead, it may become clear to him that it involves deeply-held almost 'metaphysical' assumptions which determine the direction of research.

Up to this point I have given the impression that the history of science reveals three quite different and separate strands; expressed moreover via three different methodological approaches towards its subject; three overall 'styles' of methodology: the empiricist, the rationalist and the systemicist. It would however be a mistake to think that science, at any one of its growing stages, has kept these strands in total isolation from one another; instead, it is a question of emphasis, due to a number of different causes both of technical accident and of more deep-lying intellectual preconceptions. Whilst for the Beaconian the centre of gravity of the justification of his hypotheses is located in its inductive foundation, he does not altogether ignore the importance of systematic coherence. Again, whilst a Descartes may seek to place the basis of his dyramics in God's conservative action, he is quite emphatic that his principles are consistent with experience; and that where they fail in this respect, there are material conditions at play, interfering with the idealised account given in the principles. And similarly for the case where systematisation determines the direction of the enquiry.

It therefore seems more appropriate to articulate a well-structured methodology in terms of an account that places the three strands which we have so far distinguished as mutually interacting quasi-vectorial components in an over-all scheme. If we want to describe the three criteria implied in our different strands in summary fashion, we may say that the conditions which any hypothesis has to satisfy in accordance with them, are: does the hypothesis have adequate evidential support? Secondly, is it rationally coherent? And finally, does it make sense?

To explain briefly through a celebrated example: When Newton put forward his gravitational theory, he could claim for it excellent evidential support as well as great systematic power. On the other hand, he himself had grave doubts as to whether action at a distance (implied by the theory) made any sense, expressed any 'real possibility' – indeed he denied this absolutely. Whilst on the Continent this at first led to the rejection of his theory, pressure from the sides of the evidential strength and systematising power subsequently led to attempts to provide alternative conceptual explications of the notion of matter; explications that would demonstrate the real possibility of *actio-in-distans*, thus harmonising with the inductive and systemic components of Newton's theory; one of the most celebrated attempts in this direction being Immanuel Kant's, in his *Metaphysical Foundations of Natural Science*.[4]

Figure 1 indicates the triadic scheme, as explained, and viewed as a set of mutually interacting components; the arrows implying the degree of interaction between them. The first self-conscious account, asserting the requirement of the satisfaction of, not just one, but all three components, seems indeed to have been due to Kant himself, in some of his writings


METHODOLOGICAL COMPONENTS OF SCIENTIFIC THEORY
Probative Component
determines
Evidential Support
("Probability")
Detection, selection and colligation of observational and experimental data, under the guidance of hypotheses, and their processing through various 'methods' (induction, confirmation, corroboration, Bayesian, etc.)
Structured scientific theory
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determines
Intelligibility
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Systemic Component
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Rational Coherence
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Conceptual Explication (sometimes: 'Metaphysical Foundation'), yielding some particular 'hardcore' conceptual scheme.
Determination of ontological status of explanatory concepts and principles
Plausibility: Determined by heuristic maxims, principles and ideas (traditionally with 'metaphysical', or alternatively, so-called 'regulative' status). E.g. simplicity, economy; continuity or discontinuity; homogeneity, variety, affinity; analogy; conservation; symmetry or assymmetry, etc. Preferred explanation types, e.g. causal or aetiological (mechanistic), as against teleological; phenotypical ('macro' or 'descriptive') in terms of 'surface-structure', as against genotypical ('micro' or 'explanatory'), in terms of 'deep-structure'
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Fig. 1.

on scientific methodology;[5] arguing that in addition to the provision of sufficient inductive evidence, we have to show that some suggested hypothesis satisfies also the requirement of systematic coherence as well as that of 'making sense', i.e. of 'real possibility'. A similar methodological scheme is to be found somewhat later in the writings of the historian and philospher of science William Whewell, who held that scientific growth involves the colligation of facts under the guidance of theoretical ideas which themselves only emerge after an extensive period of conceptual explication; culminating at a still later stage in what he calls a period of 'simplification of theories' and 'consilience of inductions', equivalent to a process of systematic integration.[6]

Interestingly, in Whewell's presentation, the methodological scheme is supposed to emerge from a survey of the actual development of science. However, there can be little doubt that his historical account is itself already influenced by the at least vaguely anticipated methodological scheme, serving as a principle of selection for the composition of the history. Just like scientific theorising, so the writing of history evolves together with some corresponding methodological scheme as a mutually involving intellectual enterprise.

Remarkably, after Whewell the triadic approach received little explicit attention in the writings of philosophers of science – until very recent times; due probably to the prevalence of the basically empiricist ideology that dominated the second half of the nineteenth and the first half of the twentieth century. Whilst historians of scientific ideas, e.g. Meyerson and Burtt (already mentioned), and after them, perhaps Alexandre Koyré, emphasise the rationalist aspect of scientific development during the seventeenth century (corresponding to our Explicative Component), the prevailing stress was primarily on the details involved in the Probative Component; whether in the writings of a predominantly logico-positivist strain, or in those – like Popper's – that place the emphasis on testing and falsification of hypotheses. It is only in recent years, with the advent of the more sophisticated methodological ideas of Kuhn, and subsequently Lakatos and Laudan[7] that the need for greater precision, and in particular for a more complex articulation of methodological ideas that would take note of these later developments, has made itself felt; leading in turn to a revival and better understanding of older, non-empiricist, aspects of science and its history. An added factor has been a growing awareness of the importance of the conceptual framework that we find presupposed in most scientific theoretical formulations, and of an equal realisation that the principles which embody such schemes seldom have the status of simply-testable empirical hypotheses. As L. Laudan has formulated this, we find that the problems which we encounter in science are not merely of an empirical nature but frequently conceptual in kind.

However, the clearest application of a triadic approach, and one that has exerted considerable influence on recent methodological thought, we meet with in the writings of Imre Lakatos; distinguishing as he does between what he calls the 'metaphysical hardcore' of a theory, together with its 'negative heuristic' – jointly equivalent to our Explicative Component; the 'positive heuristic', which corresponds to our Probative Component, and finally the nested network of hypotheses and theories, called 'the scientific research programme': equivalent to our Systemic Component. My reason for drawing these comparisons is to emphasise the historical continuity that can be established thereby between our scientifico-methodological past, and present ideas on methodology.

Clearly, the triadic apparatus, and the various ideologies that have inspired its components, can be used to remind the student of physics that his subject is no pure depository of pre-given facts which need only to be 'excavated' by means of scientific-theorising, but that instead the theoretical process itself exhibits a creative historical dynamic, whose methodological inspiration mirrors those philosophical preconceptions which themselves function as presuppositions or necessary conditions for the construction of the web of scientific 'fact' itself. There is no speedier way of 'relativising' the existence of 'fact' than by way of historicising it, and thereby drawing attention to its connections with the over-all scheme of thought – both philosophical and, more generally, ideological.

Which leads me, in conclusion, to a more philosphical, though essential, postscript. I have argued, concerning the background to my scheme, that instead of 'facts' being 'pre-given', it is the scientific theory that yields or 'realizes' such facts in the first place; secondly, that theory can achieve this aim only under the 'control' of some given methodology. Instead of 'realization of facts', let us speak more properly of a realization of the phenomena; or to be more specific, of an 'account of the phenomena', in the sense of their description, classification and explanation; something which the OED defines as "phenomenology". Now the idea of 'realization', and the associated notion of 'style' (in the sense here used) can be given a more philosophically significant formulation, and more importantly, defence, in terms of a transcendental approach which in the recent writings of Hilary *Putnam* has been labelled "internal realism", though its roots (as Putnam notes), and indeed a far fuller account of such a position, goes back again to Kant; such an internal realism forming incidentally also a philosophical backdrop for the relatively subjectivist positions of Kuhn and Lakatos.

Internal realism argues that the notion of fact, or more generally, of 'a world, simpliciter', in abstraction from (what Putnam calls) any 'theory', i.e. a world that would be 'theory-neutral', is logically-otiose; on the contrary, the concept 'world' must always be taken as one that is 'theory-relative'.[8] The advantage of the internal realist position is that it incidentally, and automatically, dissolves the common skeptical complaint of the contrasting 'metaphysical realist', which is that there might be a world, so to speak existing 'in itself' (apart from theory) which for ever escapes the network of scientific theorizing, and of which we would thus *in principle* remain for ever ignorant.

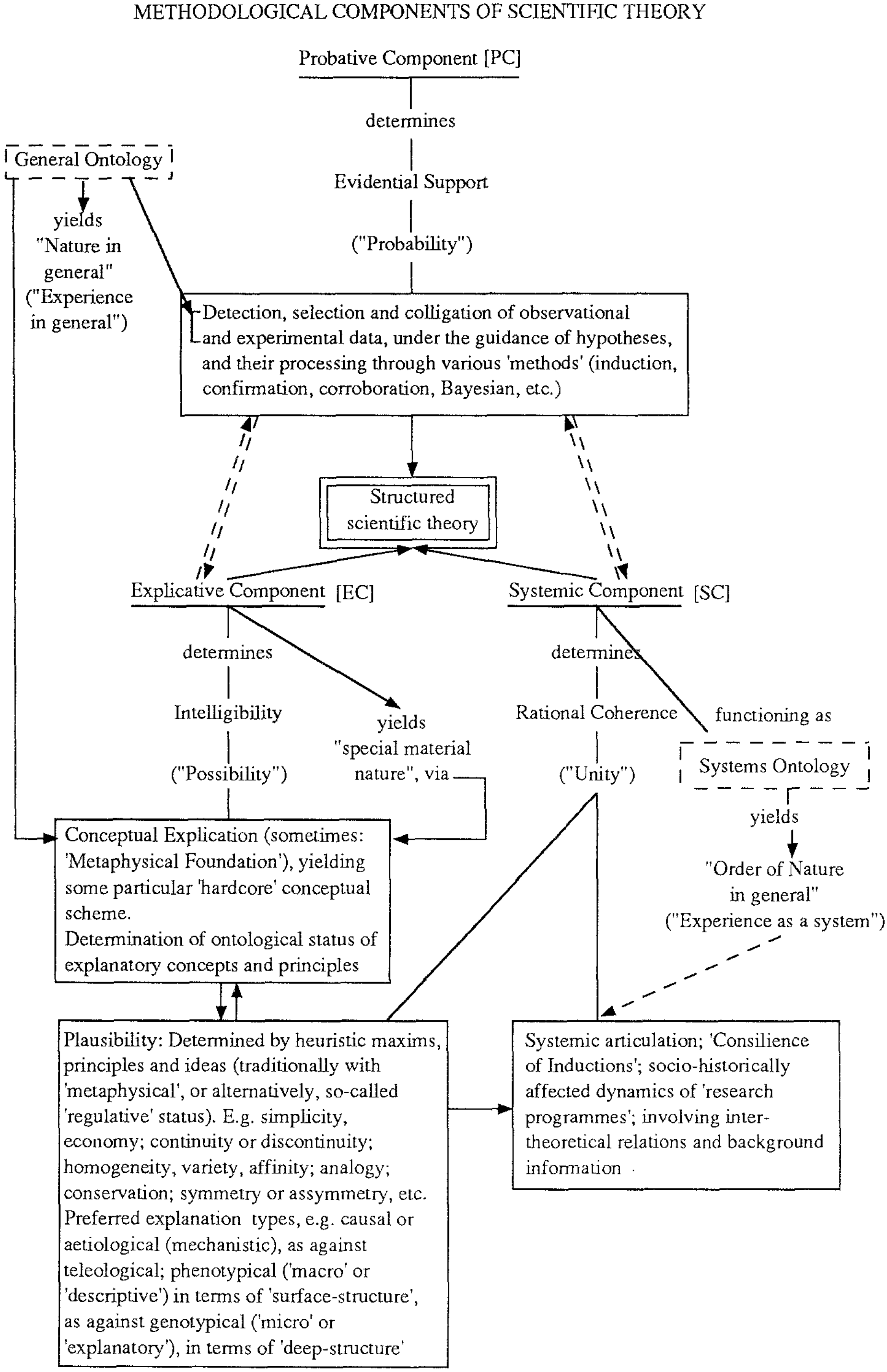
The internal realist transcendental ontology – meaning by this latter term any account of the very possibility of any knowledge of, say, the systematic order of nature – is not unexpectely developed by Kant himself; incidentally yielding thereby also a clearer formulation of what is to be understood properly by the term 'theory', in Putnam's phrase 'theory-relative world'. (See Figure 2, for the ontological level associated with the methodological framework of Figure 1.) Putting the matter extremely briefly: systems methodology (meaning by this the operations of our Systems Component), in Kant's account is postulated as simultaneously functioning as a systems ontology; which is to say that the operations of the principles, ideas and maxims of our systems component are now furthermore invoked in order to 'realize', in the sense of first generating, or making possible, the very notion of an order of nature as such.

As a mnemonic device, we may summarize this as follows: whilst theory, under the control of a given methodology, 'realizes' some given phenomenology (ϕ-realization type), that same methodology is simultaneously given the transcendental ontological function of 'realizing' the very possibility of such a phenomenology as such (t-realization type); thus grounding the ϕ-realizational function in a t-realizational function via the middle term of some chosen methodology.

It is noteworthy that the notion of 'realization', in both the ϕ-sense and the t-sense, operates more straightforwardly and directly in the case of the Explicative Component (as pictured in Fig. 2). On the Kantian account, the process of giving a sense, or of making intelligible, the foundational principles and concepts of some scientific theory – Kant's prime example, as already noted, being Newton's theory, formulated as it is in terms of certain axioms of motion and force – thereby also generates their very 'possibility'. (Thus, as noted, Kant seeks to demonstrate the possibility of action at a distance; or again, of inertial motion, and of momentum transfer.) In other words, in the case of the Explicative Component, ontology is conflated into phenomenology, and *vice versa*.

Actually, Kant's central concern – though of less relevance in the present context – was with what we may call 'general ontology' – i.e. the account of the possibility of empirical knowledge of nature in general, e.g. of objects, of the changes they undergo, and of their coexistence in time and space. In Figure 2 we have also indicated this element; and incidentally noted its relevance for Special Ontology, since on the Kantian account some of the principles of General Ontology, e.g. the principle of causation, are given a specific task in the construction of Special Ontology; thus the principle of causation is invoked in the construction of the principle of inertia.

In sum then, the basic concepts of a science, viewed as material for an ontology of the world, whether in terms of our Systems Component or our Explicative Component, simultaneously generate the phenomenology of things, which thereby becomes relativized to the historical process of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Systemic articulation; 'Consilience of Inductions'; socio-historically affected dynamics of 'research programmes'; involving inter-theoretical relations and background information

Fig. 2.

scientific theorising; the particular 'style' that pervades some given epoch expressing itself in the details of our methodological formulations.

II. APPLICATIONS

In Part I we have indicated the intimate relations between physical science, certain developing views on the status of physical reality, their historical side as an essential ingredient, including the historical dimension of methodology; and finally, a demonstration that a proper understanding of the relationships between these various elements propels us into some of the most complex problems of philosophy proper: e.g. transcendental ontology.

I think anyone teaching should be aware of these ultimate relationships between the phenomenological parts of physics, the significance of its methodological framework (in the ways indicated in Part I) and finally, the historical components of both the phenomenological and the methodological sides of the subject. What would a physics course at College level look like whose ultimate aim might be to lead a student up to a grasp of the various philosophical and historical aspects of his subject? Clearly, one would not want to rush into a course of transcendental philosophy but would want to achieve one's aims in a more moderate and roundabout way.

Assuming that our student has little or no knowledge as yet of the principles of physical science, still less of any historical or philosphical significance of this material, the course would obvicusly have to be designed as a multi-level approach, concentrating through lectures, experimental and discussion classes and readings of relevant source material on the various aspects of the work. One such course was designed at the University of Cambridge some years ago; rather than describing it in detail, it will be sufficient to table a copy of the outline-syllabus which we helped to devise, and which was published subsequently in the Cambridge University Reporter (5 October 1960, pp. 245–49; see Appendix: Schedule III; I have omitted the Biological Syllabus, which was published simultaneously with the Physics course) for discussion by the University and its Faculty Boards. The Syllabus, though getting considerable acclaim, never became functional, the main reason being that it would have required the appointment of extra staff which the University was not in a sufficiently favourable financial position to sanction at that time! Nevertheless, the details and structure of this Syllabus remain as an important document and example whose details may well inspire future teaching experiments, and lead to the adoption of the sort of over-all programme here envisaged. In its combination of informational, historical and philosophical material, treated side-by-side, it is fairly unique.

Thus it will be seen that each of the main-, as well as sub-sections, of two of the courses envisaged (Information and Critical & Historical) always run in parallel. To cite one or two examples, in order to imply something of the relevance of this treatment to what has been discussed in Part I: A.2 would clearly involve historical and critical discussions of the laws of motion, and introduce the student to the difference between the probative and the explicative components of methodology. B.3 discusses the rise of thermodynamics and its principles, whilst the parallel historical and critical section uses this to highlight the difference between rational and empirical approaches to science. Finally, as a last example, C.7 uses the material provided by the study of the kinetic theory of gases for a discussion of the distinction betweena macro- and micro-physics: one of the maxims cited as part of the systemic component. And so on. At any rate, such a syllabus could well serve as a symbol for the sort of objective, a discussion of which it has been the aim of this study to make one of its tasks.

NOTES

1. Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago University Press, 1962).
2. Ludwik Fleck, *Entstehung und Entwicklung einer wissenschaftlichen Tatsache. Einführung in die Lehre vom Denkstil und Denkkollektiv* (Suhrkamp, 1980; Schwabe, 1935). English edn. published as Genesis and Development of a Scientific Fact (ed. Th. J. Trenn Robert K. Merton; with Foreword by Th. S. Kuhn. Univ. of Chicago Press, 1979).
   For a thorough discussion of Fleck, and especially of the relations between Fleck and Kuhn, cf. Daniel G. Cedarbaum, "Paradigms", *Studies in History & Philosophy of Science* Vol. 14, nr. 3, September 1983, pp. 173ff. Section III deals with the relations between the ideas of Fleck and Kuhn.
3. Cf. Ernst Mach, *Die Prinzipien der Wärmelehre* (Leipzig, 1896), where we find a classical locus for the distinction between phenomenological and atomistic theory-types. For the problems of atomism in the nineteenth century, cf. Mary Jo Nye, "The Nineteenth-Century atomic Debates and the Dilemma of an 'Indifferent Hypothesis'", *Stud. in Hist. Phil. of Sci.*, Vol. 7, nr. 3, 1976, pp. 245ff., with further references to the problems involved. An interesting application of the difference between the two theory-types is to be found in a classical teaching text on theoretical physics: Georg Joos, Theoretical Physics (trl.I.M. Freeman, Blackie, London, 1934); cf. especially, pp. fronting Parts III, IV and V of this text, dealing with accounts of the electromagnetic theory, the theory of electricity, and the theory of heat, developed here from the 'phenomenological' and the 'atomistic, statistical' points of view. This textbook was still used in the advanced physics courses at Cambridge University in the 1960's.
4. I. Kant, *Metaphysical Foundations of Natural Science* (trsl. J. Ellington, Indianapolis, 1970), with the Akad. ed. pagination referring to Vol. 4 in margin. For Kant's discussion of the problem of action at a distance, cf. ch. 2 of this work: "Metaphysical Foundations of Dynamics", pp. 96ff. or a further discussion of this, cf. also my "Zum Verhältnis von allgemeiner Metaphysik der Natur und besonderer metaphysischer Naturwissenschaft bei Kant", in *Probleme der 'Kritik der reinen Vernunft'* (ed. B. Tuschling, de Gruyter, 1983), pp. 77–106.
5. Kant, *Logic* (trsl. R. Hartman & W. Schwarz, Indianapolis, 1974), Introduction, sect. X, pp. 92–3. Cf. also *Critique of Pure Reason*, A770/8798.
6. William Whewell, *The Philosophy of the Inductive Sciences*, Part II (in *Works*, ed. G. Buchdahl & L. Laudan, vol. vi, London, 1967) Chaps. II, IV and VI.
7. Larry Laudan, *Progress and its Problems* (London, 1977), Part I, sect. 2: "Conceptual

Problems", pp. 45–70. Imre Lakatos, "Falsification and the Methodology of Scientific Research Programmes", in I. Lakatos & A. Musgrave (eds.), *Criticism and the Growth of Knowledge* (Cambridge, 1970).
8. Hilary Putnam, *Meaning and the Moral Sciences* (London, 1978), pp. 125–35.
9. For further details on the notion of 'realization', cf. also my "Reduction-Realization: A Key to the Structure of Kant's Thought", in *Essays on Kant's Critique of Pure Reason* (ed. J.N. Mohanty & R.W. Shahan, Norman, Oklahoma, 1982), pp. 39–98; especially the Appendix, pp. 80 to 98. This is taken further, with special reference to the notion of 'ontology', in my "Metaphysical and Internal Realism: The Relations between Ontology and Methodology in Kant's Philosophy of Science", in *Proc. of the 7th Int. Congr. of Logic, Methodology and Philosophy of Science* (ed. R. Barcan Marcus et al., North Holland, 1986). All these form part of my *Kant and the Dynamics of Reason* (Blackwell, Oxford UK & Cambridge USA, 1992). I am endebted to a discussion with Fabio Bevilacqua, suggesting the need for a sharper distinction between ϕ-type and t-type realizations.

APPENDIX TO PART II

SCHEDULE III

PROPOSED OUTLINE SPECIFICATION OF THE COURSE IN PRINCIPLES OF PHYSICAL SCIENCE, AND SYLLABUS FOR IT

Outline of courses

The duration of the Course is one year, preceded by a Long Vacation Course of six weeks. It is divided into four main sections, as follows:

I. Long Vacation Course.
   (*a*) Introductory Lectures.
      (i) Origin of natural science to the seventeenth century (6 lectures).
or (ii) The contemporary physicist's view of the world (6 lectures).
   (*b*) Mathematical Introduction (3 lectures per week and 2 hours' examples-class per week).
II. Information Course (4 lectures per week).
III. Experimental and Technical Course (1 class of 2 hours per week).
   (*a*) Worked Theoretical Problems.
   (*b*) Experimental Problems.
IV. Critical and Historical Course.
   (*a*) A Course of 2 lectures per week.
   (*b*) A Study of Original Sources (1 class of 2 hours per week).

Sections II and IV are planned to run in step so that the factual information provided through the former is at the same time supplemented by a critical and historical treatment: and as far as possible the work of Section III will be related to the others in a similar way.

Summary of Syllabus

The syllabus, complete details for which are shown below, is as follows:

Mechanics, heat and laws of elementary chemistry, leading up to ideas of the molecule, periodic table and the kinetic theory of gases. Optics and wave motion. Electricity up to Faraday. Electromagnetic theory of light. Elementary atomic physics.

Detailed Syllabus for the Courses in Principles of Physical Science

I. *Long Vacation Course.* (For details, see below, p. 167.)

II. *Information Course* (approximately 2 lectures per topic).

A. *Mechanics.*

1. The concepts of velocity, acceleration, and their application to the problem of the motion of projectiles.
2. The concepts of mass and force; rotational motion; application to gravitational theory.
3. The conservation of momentum and mechanical energy.
4. The concept of pressure. Boyle's law.

B. *Heat.*

1. The concept of temperature; thermal expansion; Gas laws.
2. The concept of heat; calorimetry.
3. The extension of the law of conservation of energy. The mechanical equivalent of heat. First law of thermodynamics.
4. The second law of thermodynamics.

C. *Elementary Chemistry.*

1. Combustion and the interpretation of chemical change.
2. The emergence of the oxygen theory: conservation of mass.
3. The empirical laws of elementary chemistry
4. Dalton's atomic theory.
5. Avogadro's hypothesis. The writing of chemical equations. The language of chemistry.
6. Valence: the periodic table.
7. The kinetic theory of gases.

D. *Optics*

1. Light. The velocity of light.
2. The laws of reflection and refraction.
3. Rival theories of the nature of light: corpuscle versus wave.
4. The composite nature of white light: spectrum.
5. Interference and waves.

E. *Electricity.*

1. Coulomb's and Gauss's law. The analogous expressions for the magnetic case. The concept of charge. The electrostatic field.
2. The energy concept in electrical theory: potential and potential difference.
3. Charges in motion. Production of electric currents. Electrolysis. Relation between potential difference and current: Ohm's law.
4. The electromagnetic field. Relation between B and the current flow: Ampère's law.
5. Electromagnetic induction: Faraday's law.

F. *The synthesis of Optics and Electrical Theory.*

1. The displacement current.
2. A consequence of Maxwell's equations: the wave-equation of electromagnetic radiation. The electromagnetic spectrum.
3. The constancy of the velocity of light, and relativity.

G. *Atomic Physics.*

(*a*) *Matter and Radiation.*

1. The atomic nature of electricity: Faraday's law of electrolysis and Helmholtz's conclusion. The phenomenon of cathode rays; electrons and protons. The determination of m and e: motion of charged particles in an electric and a magnetic field. The oil-drop experiment.
2. The photo-electric effect.
3. Wave-nature of matter.

(*b*) *The Structure of the Atom.*
4. Scattering experiments and Rutherford's atomic theory.
5. The spectra of gases: empirical formulae. The application of the quantum theory: the Bohr model of the atom.
6. The evidence from X-ray spectra: the periodic table again.
7. The electronic theory of valency.
8. Natural radioactivity.
9. Isotopes and mass-spectrographic separation. Avogadro's hypothesis again.

III *Experimental and Technical Course* (approximately 1 class per topic).

(*a*) *Theoretical Problems* (to be worked in detail).
Orbit of a projectile: Galileo's problem. Newton's proof of Kepler's second law of planetary motion in the *Principia*: expression for centripetal acceleration. Application to planetary orbits. Simple pendulum. The kinetic theory of gases. Huygens's proof of the law of refraction. Thomson's determination of e and m. Perrin's determination of N. Bohr's atomic theory.

(*b*) *Experimental Problems* (for intimate class work).
Testing the law of free-fall. Inclined plane. Atwood's machine: second law of motion. Boyle's law; Charles's law. Calorimetry: specific heat of mixtures. Constant proportions (chemical experiments). Testing the results of kinetic theory: diffusion of gases. Verifying the law of refraction; measurement of refractive index. Measurement of wave-length by means of slit-experiment. Testing Coulomb's law: ice-pail experiment. Microwave physics. Verifying Balmer's formula. Thomson's experiments with discharge tubes. Cloud chamber. Scattering experiments. Mass spectrometer.

IV. *Critical and Historical Course.*

(*a*) Historical and Critical Lectures. (Approximately 1 lecture per topic.) (*Note*: Sections shown run parallel with similar sections in Information Course II.)

A. *Mechanics.*
1. The rise of the seventeenth-century scientific world picture. The mathematization of physics.
2. The discovery of the laws of motion: Descartes and Newton. The logical status of the principles of dynamics. The definition of mass and force.
3. Physical and metaphysical foundations of the principle of mechanical energy: Stevinus, Galileo, Huygens, Leibniz.
4. The rise of the experimental method: the work and thought of Boyle. The notion of scientific law.

B. *Heat.*
1. The definition of temperature: the principle of operational definitions.
2. Heat as a substance and heat as motion: the origin of ideas.
3. Rational and empirical approaches in science: Mayer *v.* Joule. The philosophy of substance and causation.
4. Ideal objects in science: Carnot's heat engine. The struggle for clear conceptions and the resolution of a paradox: Carnot, Thompson, and Clausius.

C. *Elementary Chemistry.*
1. The idea of a closed system in chemistry: alternative interpretations: the logic of the phlogiston theory. The importance of techniques for the growth of ideas.
2. Lavoisier's method of experimental reasoning. Analysis and synthesis.
3. The idea of element and compound: Proust *v.* Berthollet: the quarrel concerning the constancy of proportion.

4. The genesis of Dalton's theory. A comparison of Greek, seventeenth-century and Dalton's approaches. Scientific explanation.
5. On the function of the idea of the molecule: the nature of Avogadro's theory.
6. The place of classification in science.
7. Macro- and micro-physics: a comparison. The concept of a model in science; the importance of analogy.

D. *Optics.*

1. The concept of the light-ray. The history of the idea of the speed of light; the status of the rectilinearity principle.
2. The discovery of the law of refraction: Kepler and Descartes: a contrast in methods.
3. Types of theoretical explanation; Fermat, Huygens, and Newton.
4. Newton's theory of colours and the dispute with Hooke.
5. Young and the wave-theory of light: the puzzle of polarization and the ether: the question of the need for models.

E. *Electricity.*

1. From electric fluids to the concept of charge; quantification procedure. Coulomb's law: direct and indirect methods of verification; Coulomb, Priestley, and the ice-pail experiment (Faraday).
2. From effluvia to fields; Faraday and the field-concept.
3. The background to Ohm's work: the importance of analogical reasoning: laws as 'methods of representation'.
4. Oerstedt's researches: the place of speculation and accident in scientific discovery.
5. The importance of precise numerical determinations.
6. Faraday's work and the discovery of electromagnetic induction: the influence of the scientist's predeliction for symmetry.

F. *The Synthesis of Optics and Electrical Theory.*

1. The logic of scientific prediction: analytic *v.* synthetic prediction. Mechanical models *v.* mathematics.
2. The criticism of absolute space and time. Operationalist attitudes; the views of Mach and Einstein.
3. Empiricism *v.* self-evidence: criticism of the Galilean transformation equations. The operationist criterion of simultaneity.

G. *Atomic Physics.*

1. The history of the discovery of the electron. The logical status of the concept of electron.
3. New conceptions of the relationship of theory to experience.
5. The 'reality of the atom': a contrast between the approaches of Newton, Dalton, Rutherford, and Bohr.
7. The concept of valence: contrasts between chemical and physical reasoning. The 'consilience of inductions'.

(*b*) Study of Original Sources. (A selection, to give 1 topic per class.) (Excerpts, unless otherwise stated.) (*Note:* the numbers relate to those in the Information Course II.)

A. *Mechanics.*

1. *Galileo's Two World Systems*; *Two New Sciences.*
2. Newton's *Principia.*
3. Descartes, *Principles.*
4. Boyle, *Spring of the Air.*

B. *Heat.*

1. Black, *Lectures on the Elements of Chemistry.*

3. Mayer's paper of 1842; Joule's paper of 1850.
4. Carnot, *On the Motive Force of Heat.*

C. Elementary Chemistry.

1. Lavoisier's paper on the elementary composition of water; his paper of 1775 on the place of oxygen in combustion; *Elementary Treatise.*
4. Dalton, *New System*, and other papers.
7. Joule's paper on the velocity of gaseous molecules, 1851. Maxwell's paper on the distribution of molecular velocities, 1860.

D. *Optics.*

1. Roemer's and Fizeau's papers on the velocity of light.
2. Descartes, *Dioptrique.*
3. Newton, *Principia* and *Optics*; Huygens, *Treatise on Light.*
4. Newton's paper of 1672, *New Theory about Light and Colours.*
5. Young's paper of 1803, and the *Course of Lectures.*

E. Electricity.

1. Coulomb's Memoirs of 1785 and 1788.
3. Ohm's paper of 1826.
4. Oerstedt's paper of 1820; Ampère's paper of 1820.
5. Faraday, *Experimental Researches.*

F. *The Synthesis of Optics and Electrical Theory.*

1. Maxwell's Electricity and Magnetism and his paper of 1865.
2. Hertz's paper on waves, 1888.
3. Michelson and Morley's paper of 1887.

G. *Atomic Physics.*

1. Crooke's paper of 1879; Thomson's paper 1897 on cathode rays. Millikan, *The Electron.*
4. Rutherford's paper of 1911.
5. Balmer's paper of 1885; Bohr, *The Theory of Spectra.*
6. Roentgen's papers of 1895.
8. Becquerel's paper on radiation from uranium, 1896.

Books (Essential references marked by an asterisk).

*Holton, G. and Roller, D., *Foundations of Modern Physical Science*, 1958.
Holton, G., *Introduction to Concepts and Theories in Physical Science*, 1952.
Taylor, L.W., *Physics, The Pioneer Science*, 1941.
Bonner, F. and Phillips, M., *Principles of Physical Science*, 1957.
Krauskopf, K., *Fundamentals of Physical Science*, 1948.
Miller, F., *College Physics*, 1957.
Born, M., *Einstein's Theory of Relativity*, 1924.
Speakman, F.C., *Modern Atomic Theory*, 1938.
*Magie, W., *A Source Book in Physics*, 1935.
Knedler, J., *Masterworks of Science*, 1947.
Harvard Case Studies in Experimental Science, 1950f.
Peierls, R.E., *The Laws of Nature*, 1955.
Feather, N., *Introduction to the Physics of Mass, Length, and Time*, 1959.

I. *Mathematical Introduction* (*Long Vacation Course*). (Approximately 1 lecture per topic.)

1. Introduction; 'Foundations of Arithmetic'. The concepts of number and measurement; simple operations.
2. Extensions of the number realm: negative numbers, squares and cubes.

3. Algebra; the binomial theorem.
4. Equations; the concept of a variable of a function and of proportionality.
5. Indices and logarithms.
6. Elements of geometry: the concepts of locus, tangent and normal.
7. The circle: measurement of angles through radians. Plane areas.
8. Trigonometry: circular functions; introduction of the concept of wave-length and period; amplitude.
9. Some trigonometrical formulae and their proofs. Some values of trigonometrical functions. Calculation of components of a vector.
10. Analytical geometry: co-ordinate systems (Cartesian). The equation of a straight line: special and general case. Applications (Boyle's law); equation of a circle.
11. Conic sections. General properties, through concept of directrix. Equations of parabola and ellipse.
12. Polar co-ordinate systems. Equation of ellipse; parabola, etc.
13. Differential calculus. Concepts of limit and differential coefficient.
14. Practical evaluation of derivatives for simple cases, including x^n, sine-functions, log x; e^z and its uses. Simple applications to dynamics.
15. Higher order derivatives. Example: acceleration.
16. Integral calculus. How to integrate. The uses of integration. How to determine s from d^2s/dt^2 = const.
17. The integral as an area. Applications: the work done when a gas is compressed isothermally. An integral of the second law of motion: conservation principle. More advanced applications: Galileo's equation of motion for a missile.
18. Simple harmonic motion and exponential decay.
19. Some simple differential equations. Motion of a simple pendulum.

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