DIFFERENCES IN STYLE AS A WAY OF PROBING THE CONTEXT OF DISCOVERY

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Introduction

How decisive is the "style" of a researcher for discovering new phenomena, developing effective methods or proposing novel explanatory schemata? What is really meant by style and how can styles be differentiated from one another? Is the difference in styles merely an expression of personal idiosyncrasies? And if they are not, can one discern different national styles? Is one justified to even talk about different styles of scientific inquiry when discussing the physical sciences and mathematics, since the "objective" nature of what is being investigated seems to require a methodological uniformity?

I would like to discuss at least some aspects of these questions using Hacking's proposals about different types of scientific discourse by concentrating on the work in low temperature physics done at two remarkable laboratories. On the one hand, I shall discuss some aspects of the work at The Physical Laboratory of the University of Leiden during the directorship of Heike Kamerlingh Onnes whose programs were so deeply influenced by the work of Johannes van der Waals, and on the other, the work at the Royal Institution in London during the later period of James Dewar who was the Fullerian Professor of Chemistry. When Dewar sent a telegram to Kamerlingh Onnes on May 12, 1898 to announce the liquefaction of hydrogen, the telegram read "liquefied hydrogen and helium". It turned out, however, that Dewar had incorrectly thought that he had liquefied helium, and despite his continuous efforts to do so, it was Kamerlingh Onnes who liquefied it on July 10, 1908. Furthermore, Dewar together with Fleming had systematically investigated the variation of the electrical resistance of metals at low temperatures. When reporting their results for the resistance of mercury at the temperature of liquid air where the resistance was found to diminish as the temperature was lowered, they concluded their paper by the following prophetic remark

> "These observations are specially interesting as giving additional proof that in the case of a metal of known purity the variation of resistivity, as the metal is continuously cooled, is such as to indicate that it would in all probability vanish at the absolute zero of temperature.[1]"

Continuing the experiments after the liquefaction of hydrogen with platinum, Dewar found that the resistance started increasing after reaching a minimum, and this led him to change his claim about the vanishing electrical resistance. Ironically, it was again Kamerlingh Onnes who in 1911 was able to show that the electrical resistance of mercury (and of certain other metals) dropped to zero at liquid helium temperatures.

I do not think that one is confronted with a case where one experimentalist simply develops a more ingenious technique and "beats" the other in either being the first to reach a certain range of temperatures or to discover a new phenomenon. It is also not the case of a degenerating program that misses all the opportunities or proceeds to the wrong reading of the data, and of a progressive program whose positive heuristic leads to the rather dramatic developments associated with the work of Kamerlingh Onnes. Though there cannot be a unique way for understanding these developments, examining them in terms of styles and their differences, brings forth quite interesting aspects of the work of Kamerlingh Onnes and Dewar.

Some Remarks about Styles of Scientific Discourse

To try and specify the notion of style I shall follow Hacking who asserts that the style of reasoning associated with a particular proposition p determines the way in which p points to truth or falsehood. "Hence we cannot criticize that style of reasoning, as a way of getting to p or to not-p, because p simply is that proposition whose truth value is determined in this way"[2]. One, then, introduces a range of propositions that are either true or false. Propositions have a positivity in consequence of the styles of reasoning in which they occur. A discourse, in other words, brings into being candidates for truth. The types of discourse are introduced as categories of possibilities. "If positivity is consequent upon a style of reasoning, then a range of possibilities depends upon that style. They would not be possibilities, candidates for truth or falsehood, unless that style were in existence. The existence of that style arises from historical events."[3]. Summarizing his views on the styles of scientific reasoning, Hacking's conclusion is

> "There are different styles of reasoning. Many of these are discernible in our own history. They emerge at definite points and have distinct trajectories of maturation. Some die out others are still going strong ... Propositions of the sort that necessarily require reasoning to be substantiated have a positivity of being true-or-false, only in consequence of the styles of reasoning in which they occur ... Many categories of possibility, of what may be true or false, are contingent upon historical events, namely the development of certain styles of reasoning."[4]

For the purposes of this paper, I am not interested in Hacking's quite convincing answers to Davidson's arguments about the impossibility of different conceptual schemes. Neither will I discuss a rather interesting aspect of Hacking's proposals: the extend to which they provide a way of *reading* history of science. There are, nevertheless, some questions that are not being dealt with in this approach: Is it possible to actually study analytically a particular type of discourse? Is it at all meaningful to compare two different types of discourse? And, if it is, how are those differences to be signified? I would like to discuss one way by which one can attempt an examination of the particularities of a type of discourse and its comparison to other types.

A discourse is really a network of constraints and the kind of reasoning imposed by these constraints. A discourse can be considered as delineating the conceptual boundaries which determine the types of problems that are posed as well as the type of their solutions. A distinction should now be introduced between the object of a discourse and the relation of that discourse to the object. Such a distinction is necessary while attempting to read the development of theories since it becomes as crucial for understanding the specificity of the object as it is to understand the specificity of the relation of a particular discourse to that object.

> "By questioning the specific object of a specific discourse and the specific relationship between this discourse and its object, is to put to the discourse-object unity the question of the epistemological status which distinguishes this particular unity from other forms of discourse-object unity"[5]

It is often the case that the term *problematique* is used for analogous situations, especially those involving the reading of texts. The *problematique* is considered as being the infrastructure governing the production of a text, which, in turn, acquires an autonomy from the author's intentions. It is, then, stated that a theory of reading is necessary in order to explicate the unconscious of an apparently innocent text. It is tempting to extend these ideas to the reading of the development of scientific theories. I am quite sympathetic to such a view, especially if one talks about the *relative* autonomy rather the autonomy of the text - which can prevent the perils of a structuralist determinism and the excesses of phenomenology. Thinking in terms of styles of thinking emphasizes the possibility to reason towards certain kinds of propositions, but which does not of itself determine their truth value.

A discourse possesses a peculiarly self-referential character about the criteria it sets and against which it assesses its own coherence. It is a conceptual coherence characteristic of a set of propositions when they become the allowable possibilities of a particular type of discourse. These propositions can, in fact, be accommodated within another type of discourse, and there are obviously ways for understanding their meaning as well as deciding their truth value within this second type of discourse. But, as a whole, they will not seem to have a coherence within this second type of discourse. It is rather the case that, again as a whole, these propositions do not appear to establish an affinity with the latter discourse. This discourse is "indifferent" towards them, exactly because these propositions, as a whole, do not offer any clues for tracing out the categories of possibilities of the second discourse - even though they were decisive in just doing that in the original discourse.

It is, therefore, possible to define a notion of coherence or affinity of a set of propositions with respect to a particular type of discourse and whose assessment can be achieved only through self-referential means. This self-referential character of a discourse, then, can become a way for dealing with the question of the identity of a particular type of discourse. But there is still a problem, about the practical means for examining this identity, and explicating its characteristic signature. One and by no means the only such probe for understanding the specificity of each discourse, is to examine the relationship - adopted by each discourse - of the mathematical formulations of theories to the physical reality they "refer"[6]. And this means to explore questions about model building, analogy, and above all, the ontological status of theoretical entities, in each discourse. Bringing into being new candidates for truth or falsehood is neither a matter of using language effectively nor of just being imaginative. It is rather a process of realizing the possibilities allowed by the network of constraints – a process which can, at least, partly be examined by studying the relationship of mathematics to physics. Without there being a clear cut distinction, it is the relationship between mathematics and physics that determines the kinds of propositions that are brought into being, whereas their content is determined by the relationship between the object of a discourse and the way a discourse deals with such an object.

Let me now make certain comments about the different styles of Kamerlingh Onnes and Dewar.

Van der Waals, Kamerlingh Onnes and the Uniformity of Substances

It is not possible to understand the work of Kamerlingh Onnes in molecular physics, without a discussion of the program set out by Johannes Diderik van der Waals in the thesis he defended, at the age of 36, at the University of Leiden[7]. It bore the same title as Thomas Andrews's celebrated 1869 Bakerian Lecture: "The Continuity of the Gaseous and Liquid State". In it van der Waals presented an improved solution to the capillarity problem and starting from quite general assumptions and the kinetic theory of gases, he proposed an equation of state which incorporated corrections to Boyle's expression of the ideal gas law. Using van der Waals's equation of state it became possible to derive with impressive accuracy Andrews's experimental results that had quite convincingly demonstrated the continuity of the transition from the gaseous to the liquid state.

In the preface of his thesis van der Waals expressed one of the aims of his program by stating that his results had been "based on the idea that we can proceed continuously from one state of aggregation to the other ... I have, strictly speaking, desired to prove more; that is, the identity of the two states of aggregation ... that there is a continuity may now be regarded as a fact, the identity, however, requires further confirmation."[8]. In 1880 he formulated the answer to this problem that had only been partially resolved by the completion of his thesis. Though he had been reasonably confident about his arguments supporting the *continuity* of the transition from the gaseous to the liquid state, the related problem concerning the *identity* of these two states was resolved only in 1880 by the formulation of the law of corresponding states.[9] One of the successes of van der

Waals's equation of state was the calculation of the expressions for the critical temperature, pressure and volume in terms of the adjustable parameters of the original equation. If one defines three new parameters which are the ratios of the temperature, pressure and volume to their respective critical values, then the equation of state takes a form that is valid for all gases and liquids independent of the nature of each substance. This is the law of corresponding states. It is a law implying a peculiar similarity among all gases and liquids. But the implications of van der Waals's early work went further. The continuity of the transition implied a qualitative identity between two states of matter that appear quite different: the liquid and gaseous states.

Van der Waals's investigations were evidently not motivated by a desire to produce a correction to the ideal gas laws nor by a search for the explanation of the experimental data of the relation between pressure and volume at various temperatures. The answers to these problems, however, became the most celebrated outcome of his doctoral thesis where he set out to solve the problem of capillarity and calculate Laplace's K factor - the factor expressing the cohesive forces in the phenomenon of capillarity. Because of the mathematics involved, K did not appear in the final formulae used for the experimental testing of any theory of capillarity. [Maxwell 1879; Rowlinson 1973; Rowlinsom, Widom 1982; Klein 1973].

Van der Waals's equation of state was derived from very general assumptions. No assumption was made for the particular form of the intermolecular forces, but instead the molecules were treated as entities with shape and finite size, and the cohesive forces were no longer neglected. The proposed equation of state is

$$(p + a/V^2)(V - b) = RT \tag{1}$$

b expresses the repulsive forces and it was found to be four times the volume occupied by the individual molecules. a is a constant included in the expression for the attractive forces that were found to be proportional to the square of the density of the fluid.

Towards the end of his thesis, van der Waals posed a particularly interesting question. After building his case about the continuity of the transition from a gaseous to a liquid state, and treating both states by the same equation, the question he raised was: "when can we call a substance liquid and when gaseous? after all that has been said no one will be found to assert that there is a discontinuous transition from one state to the other"[10]. The continuity of the transition may imply the identity of the two states, but such an identity will have to be understood only after establishing - within such a context - the differences between the two states. To discuss the law of corresponding states without appreciating the methodological significance of this seemingly pedantic preoccupation of van der Waals is - as was invariably done - to reduce this law to being the expression of a mathematical oddity of his equation of state. The gaseous and liquid states seem to differ only in the quantity of certain parameters (eg. density). The paradoxical aspect of van der Waals's program was that after establishing the continuity of the transition from the gaseous to the liquid state, it was not possible to proceed in any straightforward manner to establish the identity between the two states. Their identity could be meaningfully discussed only if a way could be found to articulate the difference between the two states, which are continuously transformed into each other. Van der Waals proposed an operational procedure for understanding the differences between the liquid and gaseous states: the differences depend on the path followed to approach the critical point.

Seven years after he first posed this question, van der Waals presented in 1880 the most coherent argument for the identity of the two states. At the critical point, the isothermal passing through it has a point of inlexion with a tangent horizontal to the axis of the volume. Thus at that point

$$\partial p/\partial V = 0; \quad \partial^2 p/\partial V^2 = 0$$

From the equation of state, Eq.(1),

$$p - a/V^2 + 2ab/V^3 = 0; \quad 2a/V^3 - 6ab/V^4 = 0$$

Solving these equations one finds the following values for the critical points

$$p_c = 1/27 \times a/b^2; \quad V_c = 3b; \quad RT_c = 8/27 \times a/b \tag{3}$$

If one now defines

$$l = p/p_c; \quad m = V/V_c; \quad k = T/T_c \tag{4}$$

then the equation takes the form

$$(l + 3/m^2)(m - 1/3) = 8/3 \times k \tag{5}$$

This "reduced" equation of state holds for all substances (gaseous and liquid) independent of the nature of the substance. "If we express the pressure in terms of the critical pressure, the volume in terms of the critical volume, and the absolute temperature in terms of the critical temperature, the isotherm for all bodies becomes the same ... This result, then, no longer contains any reference to the specific properties of various bodies, the "specific" has disappeared"[11]. The differences in behaviour among the various substances are expressed by the parameters a and b which have been cancelled in eq(5). Thus, if l and m are the same for any two substances, then k must also be the same and the substances are considered to be in corresponding states. If, for example, the behaviour of a gas and its corresponding liquid is known at all temperatures and pressures, then the state of any gas or liquid at any temperature and pressure can be calculated, if the state at the critical temperature is known.

By extending the implications of the simple algebraic result which leads to the reduced equation of state van der Waals formulated the law of corresponding states in order to be able to deal with the identity problem [Gavroglu 1990]. "Elsewhere I have expressed this differently, in words that can be more easily understood: *all substances form one single genus*"[12] (emphasis added). The aim of the law of corresponding states was to establish a "standard" (the reduced equation of state), to which the different states and substances will have to "conform". This was to be the gauge by which identity was to be assessed. And its methodological significance is at two levels. At one level it attests to the coherence and consistency of van der Waals's program, and at the other it sets up the framework for dealing with the various deviations from the equation of state.

Right after his appointment to the Chair of Experimental Physics at the University of Leiden in 1882, Kamerlingh Onnes formulated a program for the change of phase of hydrogen; and after Dewar liquefied it in 1898, he aimed his researches at liquefying helium. His main motivation was that such an achievement would be decisive corroborating evidence for the law of corresponding states and its generalization as formulated in the form of a theorem proved by himself in 1881. The assessment of this important theoretical contribution for the formulation of the program leading to the liquefaction of helium has been frequently overshadowed by Kamerlingh Onnes's momentous experimental contributions.

Kamerlingh Onnes published in 1881 his "General Theory of the Fluid State" where, among other things, he proved a theorem about the law of corresponding states. It was shown that the motion of molecules of all substances, when in corresponding states are dynamically similar

> "All mechanical quantities, the derived absolute units of which can be given as powers of the fundamental units of length, mass and time, will be expressed in these systems of molecules by the same numbers, when measured in the system of absolute units, deduced from the fundamental units of length, mass and time belonging to each substance. And all such mechanical quantities of a substance in an arbitrary state, can be calculated from those observed with the other substance in the corresponding state by the ratio of the derived absolute units, in which these quantities are measured"[13]

If one assumes - as is the case with van der Waals's equation of state - that the molecular interactions are characterized only by size and strength, then the molecular motions in two different systems can be made "dynamically similar": the motion of each molecule in the two substances can be made to differ only by factors in length, time and force scales. When molecular motions can be made to be dynamically similar, then the two substances are in corresponding states. This was a mechanical rather than a statistical argument and, hence, Kamerlingh Onnes formulated the law of corresponding states as

$$1 = F(m,k) \tag{6}$$

This is a form which is independent of the particular equation of van der Waals, and is valid for any equation of state expressed in terms of only two adjustable parameters[14].

The significance of this theorem for Kamerlingh Onnes's work was explicitly stated by him in 1894

> "I was induced to work with condensed gases by the study of van der Waals's law of corresponding states. It seemed highly desirable to scrutinize the isothermal lines of the permanent gases, especially of hydrogen, at very low temperatures"[15].

In a paper in 1896, he exploited to the utmost "[his] theorem concerning the law of corresponding states of van der Waals"[16] in order to explore the possibilities for cooling the hydrogen further by its own expansion. He proposed to examine this possibility by using the law of corresponding states and by actually working with a more suitable substance at a more suitable temperature. He then used his theorem to predict from the known experience with existing apparatus, (especially with oxygen) what is to be expected from the apparatus for the cooling of hydrogen. He introduced the interesting notion of "thermodynamically corresponding operations" to argue that "if an apparatus for liquefying oxygen according to this principle has been found, [his theorem] gives the corresponding hydrogen apparatus"[17]. It was calculated that hydrogen can be liquefied if one can start the operations with the Linde machine at -210°C and that the whole process would "correspond" to the process with oxygen when the latter would be at -20°C. His theorem, however, could be applied to deduce the amount of liquid to be collected after liquefaction has occurred, since the effects of gravity could not be incorporated to his model in a straightforward manner. Finally, it was found that Dewar's experiments that were already in progress did conform with these specifications.

The studies concerning the law of corresponding states were not confined to the improvements of the equation of state, but also induced Kamerlingh Onnes to proceed to extensive measurements of the isotherms of both the diatomic and monatomic gases.

The period 1900-1901 was the start of his researches on the van der Waals ψ-surface, on the isotherms of the diatomic gases and their binary mixtures. These, together with the measurements of the isotherms of the monatomic gases and their binary mixtures and the continuous improvements in the cryogenic apparatus led to the liquefaction of helium[18]. The law of corresponding states was again the "guiding spirit" for all these researches.[19]

According to the van der Waals theory of mixtures, it is possible after a sufficient number of particular observations with mixtures of two known normal substances, to determine the constants which allow the construction of the general equation of state for the mixtures of these substances, and especially to predict the phenomena of condensation by the free energy (ψ) surfaces derived from that equation of state.

The researches examined how far, from an empirically correct representation of the isothermals (and thus of the ψ-lines) at different temperatures for a simple substance, one can find the ψ-lines for mixtures of different compositions at one temperature, and, hence, also the unstable part of the ψ-surface.

There was a three pronged activity in the work involving the isotherms of the diatomic gases and their binary mixtures[20]: the improvement of the instruments, and especially the volumenometer in order to determine the compressibility of the hydrogen vapour; the measurement of the isotherms and various other parameters of hydrogen (density, critical point, compressibility of vapour); and the study of the behaviour of oxygen and nitrogen and their vapour pressures according to the law of corresponding states. Both the isotherms as well as the vapor pressures were measured primarily for the purpose of testing the results against the "predictions" of the law of corresponding states, thus rendering it possible to compare the results with those of other gases. In all these measurements and calculations extensive use was made of the equation of state developed by Kamerlingh Onnes, neglecting the quantum effects which were treated elsewhere. On the other hand, the overall objective of the researches on the isotherms of the monatomic gases[21] was to obtain a mean reduced equation of state by using exclusively the observations on the diatomic gases. There was, however, a difficulty related to the substances with simple molecular make-up, since the region that had been experimentally studied extended over a small range of reduced pressure and reduced temperature. If the law of corresponding states were strictly obeyed, this difficulty could have been overcome by reducing and then combining with each other the regions studied for the various substances. Concerning the objective set for the measurements of the monatomic gases, and unless, in the structure of the various atoms of the monatomic substances further peculiarities were to be discovered which would influence the equation of state, the only influence exerted upon the form of the reduced surface was that of the critical temperature.

Substantial amount of work had been done with argon and this work displayed all three aspects of the overall aim concerning the studies of the monatomic substances. Firstly, the discovery of the monatomic character of the inert gases and especially that of argon provided a very convenient means to probe the outstanding problem concerning the variability of b with volume. If this variability was to be at least partially explained by the compressibility of molecules then the monatomic substances and particularly the inert gases would be ideally suited to test such a hypothesis. Secondly, the monatomic gases were the ones closest to the gas considered by van der Waals to derive his equation of state. Argon was the simplest monatomic gas that had been first liquefied[22] and together with the analogous studies on helium after 1908, a lot of information was gathered to examine the limits of validity of the assumptions used by van der Waals. Thirdly, by formulating an equation of state characteristic of all the monatomic substances and calculating the deviations from the "standard" equation one could attribute the deviations to only the critical temperature. Such an undertaking conformed fully with Kamerlingh Onnes's proposal in 1881 that a separate equation of state be constructed for each group of substances having similar types of molecules.

Kamerlingh Onnes's obsession with the study of molecular activity was guided by these considerations which were to be the dominating heuristic principles in determining the direction of his researches. His extensive use of analogy with the existing classical pictures, the use, that is of this quite abstruse notion of analogy inherent in the law of corresponding states, became decisive in overcoming the limitations built in those very situations which were the basis for his analogies.

Dewar's Monomania with Experimental Techniques

The liquefaction of helium was first and foremost a triumph of the systematic researches of Kamerlingh Onnes on the work started by van der Waals, complemented by the progress in cryogenic techniques. In the first letter Kamerlingh Onnes wrote to Dewar ten days after the liquefaction of helium he is quite explicit on this point:

> All the time the helium apparatus remained perfectly clear ! Nobody but you and myself [knows] what this means. As you know my means are only those of a teaching laboratory ... All - the human force especially - was now strained to the utmost and the result only just got at the end. *It was a good thing to have trusted to the utmost the theory of Van der Waals and to my isotherms, which would only be obtained after many years of preliminary work, but have proved efficient.*[23] (emphasis added)

As I remarked in the Introduction, when Dewar sent a telegram to Kamerlingh Onnes to announce the liquefaction of hydrogen the telegram read "Liquefied hydrogen and helium"[24]. That Dewar was doing its utmost to be able to liquefy helium is evident both in his published papers as well as in his correspondence and notebooks. Can any clues be discerned about Dewar's failure to liquefy helium despite his holding an undoubtedly commanding lead in low temperatures techniques and instrumentation ? How decisive was the law of corresponding states for the progress of Dewar's researches for the liquefaction of hydrogen and his persistent attempts to liquefy helium? Surprisingly, the effect of the law of corresponding states played a rather negligible role in his researches, despite Dewar's statement that he regarded van der Waals's law of corresponding states as a contribution "even more important than his original essay ... and a novel and ingenious development comparable in importance to Carnot's cycle"[25]. And van der Waals in his Nobel speech remarked that the law of corresponding states was "a potent contributory factor in Dewar's determination of the method of liquefying hydrogen"[26].

The bulk of Dewar's work was in spectroscopy and the liquefaction of gases. And in contrast to the work done in Leiden, there was not a single theoretical paper nor was there any published measurement of isotherms, despite the large number of papers reporting the values of various physical parameters at low temperatures (such as, thermoelectric properties of pure metals, magnetic properties of iron and steel, dielectric constants and most notably electrical resistance). There is no evidence that Dewar used the law of corresponding states in a systematic way at any time throughout his researches leading to the liquefaction of hydrogen in 1898. He did, however, acknowledge Wroblewski's exhaustive measurements of the hydrogen isotherms, and in the paper reporting the liquefaction of hydrogen he stated that "the accuracy of Wroblewski's deductions regarding the chief constant of liquid hydrogen following from a study of isothermals of the gas is a signal of triumph for the theory of van der Waals and a monument to the genius of the Cracow physicist"[27]. This is the only indication found in Dewar's papers before 1898 about his opinion on the possibilities offered by the law of corresponding states. Dewar made extensive use of Wroblewski's results and when some years later he measured the density of hydrogen at the boiling point he found that his results "agree with those deduced from Wroblewski's form of the van der Waals equation"[28].

In contrast to the work of Kamerlingh Onnes, Dewar's program on the liquefaction of gases did not include measurements of isotherms.

> I am sure you will sympathize with my attacking the problem of the isotherms. The determination of the isotherms is the rational way to get the data for calculating the critical points, of which you have already made estimations, and exact determinations of isotherms is just in my line of accurate measuring work.[29]

It appears that the liquefaction of helium was, for Dewar, a challenge to be met by trying to devise ways for lowering the temperature. He never succeeded with this "brute force" approach. And even though he had made extensive measurements of various physical parameters at low temperatures, and after 1898 in liquid hydrogen temperatures, he was not as knowledgeable about the behaviour of gases at low temperatures. It is the measurement of isotherms that becomes quite decisive in comprehending such a behaviour. There was one instance, much later in 1904, when Dewar used the law of corresponding states to be able to deduce the ratio of the critical temperature to the critical pressure of hydrogen by using the law of corresponding states with the measured values of these parameters for oxygen and nitrogen (Dewar [1904]). He did not seem to be satisfied with the comparison between the theoretically derived values and the experimentally measured ones, and concluded that the "explanation of the failure between theory and experiment is that despite the fact that these formulas are the best theoretical approximation we have at hand, and while they are useful within short ranges, we can hardly expect the same accuracy over a temperature range of five or six times the critical temperature"[30].

The only other time he used the law of corresponding states was to check the method he had proposed for determining the boiling point of liquid hydrogen by a hydrogen gas thermometer (Dewar [1901]). This was done by applying the method for a gas whose boiling point fell within the range of easily determined temperatures. Oxygen was chosen and "as an additional condition to be noted the initial pressure is made slightly more than an atmosphere, so that it would be in a van der Waals 'corresponding' state"[31] with the hydrogen in the experiments already performed in order to find the boiling point of hydrogen with the gas thermometer. This new method did turn out to be reliable, and it was concluded that a gas at an initial pressure less than one atmosphere may be relied on to determine temperatures down to its own boiling point in a constant-volume gas thermometer.

Dewar's lack of interest in the various issues of kinetic theory and thermodynamics being debated at the time is evidenced not only by the absence of a single theoretical paper of his, but, more significantly, by the way his papers were written where any reference to theoretical results is cursory[32]. In fact, his papers do not even provide any clues about his position on the issues being debated. Even his extensive references to Tait were exclusively about the latter's experimental work. One cannot help wondering whether mentioning Wroblewski's isothermal measurements whenever he refers to the significance of van der

Waals's equation for determining critical points, was more strongly motivated by Dewar's intense dislike of Olszewski (Dewar [1895]; Olszewski [1895]; Mendelssohn [1966]), rather than by a wish to acknowledge Wroblewski's measurements - especially since these very experiments were performed by Wroblewski after the breakdown of Wroblewski's collaboration with Olszewski[33].

It is not without interest to point out that in the extensive correspondence Dewar had with J.D.Hamilton Dickson there is a rather detailed discussion of van der Waals's theory, and especially about the latter's comments concerning some data sent to him by Dewar. Van der Waals argues at length that Dewar's data cannot give credence to the possible liquefaction of helium, but to the opposite since they imply repulsion of the molecules.[34]

Exhaustive measurements of the electrical resistance of various metals (platinum, gold, palladium, silver, copper, aluminum, iron, nickel, tin, magnesium, zinc, cadmium, lead, thallium) were performed by Dewar and Fleming. They measured resistances down to -200°C with the large quantities of liquid oxygen that they could prepare. They found that "all the lines of resistance are more or less curved lines that tend downwards in such a way as to show that if prolonged beyond -200°C they would probably pass through or near the origin of absolute zero"[35]. It was observed that the rate of decrease of the resistance was higher the more pure the metal was and they surmised that for perfectly pure metals "it seems probable that as the temperature is lowered towards absolute zero the specific electrical resistance decreases so that it either vanishes at the absolute zero or reaches a very small residual value"[36]. Alloys, of course, showed a slower rate of decrease of their resistance than the pure metals. And the resistance of the ones whose constituents were chemically different (eg. platinum-silver) decreased slower than that of the alloys whose constituents were chemically similar (eg. platinum-iridium). Bismuth was found to have an anomalous behaviour [Dewar, Fleming 1895; 1896a] in that its resistance showed a minimum (or a maximum depending on how it was prepared) around -80°C. Nevertheless, electrolytic bismuth did show a similar pattern as that displayed in other metals, but it was also found that the resistance increased when subjected to a transverse external magnetic field [Dewar, Fleming 1897]. In 1896 they completed an exhaustive study of the resistance of mercury [Dewar, Fleming 1896b] and their results indicated again the resistance of mercury would vanish at zero degrees Kelvin "these measurements afford a further confirmation of the law which we have enunciated as a deduction from experimental observations, that the electrical resistivity of a pure metal vanishes at the absolute zero of temperature"[37].

There is an interesting turn of events that discouraged Dewar and Fleming from pursuing their researches any further. Even the "verification from experiment" of van der Waals's law of corresponding states by Christine Meyer was not sufficient to convince Dewar to orient his researches on what was suggested by such a corroboration (Dewar [1902]), for he had misread the wider implications of this law.

> Supposing all difficulties to be overcome and the experimenter to be able to reach within a few degrees of the zero, it is by no means certain that he would find the near approach of the death of matter sometimes pictured. Any forecast of the phenomena that would be seen must be based on the assumption that there is a continuity between the processes studied at attainable temperatures and those which take place at still lower ones. Is such an assumption justified?[38]

Dewar's own experiences suggested a negative answer to this question. Extrapolating the results of the exhaustive measurements he performed with Fleming on the variation of the electrical resistance of metals with decreasing temperature, he claimed, as we saw, that the resistance would become zero as absolute zero was approached. But when the measurements were done for liquid hydrogen temperatures with a platinum thermometer, it was found that after reaching a minimum the resistance started increasing.

> The resistance of an unalloyed metal continually diminishes with temperature and in each case appears to approach to a definite asymptotic value below which no further lowering of the temperature seems to reduce it and that the parabolic connection between temperature and resistance is no longer tenable at very low temperatures[39].

It was a disappointing result, but above all it was a result undermining his faith in what he took to be as the more general implications of the law of corresponding states[40].

The reasons for Dewar's not using the law of corresponding states should not only be searched in his being a persistent practitioner in a tradition of using a model as a source for, primarily, finding the range of applicability of the particular approximation represented by the model. Dewar seems to have adopted a methodological implication of the law of corresponding states which was neither warranted nor suggested by the law, and was thoroughly misleading. The law, as we have seen, was a way of clarifying the question related to the identity of the liquid and gas states, since such questions became important when a schema concerning the continuity of the transition from the gaseous to the liquid state was proposed. Dewar's comments, however, suggest that he was regarding the law of corresponding states as *implying the invariance of the trends in an observed behaviour,* as conditions vary in a continuous manner towards a specific limit. Such a position, whose adoption was not justified anyway, became quite indefensible after the experiments measuring the electrical resistance of pure metals in liquid hydrogen temperatures. It was, hence, very difficult for Dewar to retain any faith on the practical usefulness of the law after the liquefaction of hydrogen.

Some Concluding Remarks

I tried to show the decisive role of the law of corresponding states for the development of low temperature physics, and that the style of discourse developed by Dewar was not conducive to exploring the possibilities of the law of corresponding states. Accepting the significance of the law as part of a particular discourse rather than as a corollary to be used only for estimating critical and boiling points, was part of the radically different approach to experimentation that such an acceptance necessitated.

Discussing the relationship of mathematics to physics is one of the ways to probe the distinguishing trends in different types of discourse. There was one aspect in the work of van der Waals and Kamerlingh Onnes which undermined the methodological constraints inherent in the reductionist approach. And this aspect was expressed by the *problematique* around the law of corresponding states. A novel way of introducing uniformity was adopted. The law of corresponding states became a way of understanding the macroscopic uniformity of substances since, as aggregates they all obeyed the same (reduced) equation independent of their specific make up. One can appreciate this better in Kamerlingh Onnes's extension of this idea and his proposal of the principle of dynamical similarity: by scaling with molecular parameters rather than with the critical parameters Kamerlingh Onnes was able to formulate the law in a form which was independent of the particular formula of van der Waals -

and found to have an improved experimental corroboration.

The notion of coherence and affinity of a set of propositions with respect to a particular type of discourse is crucial in understanding the ways a particular discourse deals with its categories of possibilities. It was not the case that Dewar was not aware of the law of corresponding states. It was rather the case that the law did not have the "needed" affinity with respect to his type of discourse - an affinity which it had with respect to the type of discourse developed by Kamerlingh Onnes.

In coming to understand the various developments in terms of types of discourse one realizes a truly liberating lesson: There are no good or bad styles; nor are there any correct and wrong types of discourse. It is rather the categories of possibilities each one offers and the attempts to explicate the possibilities of each discourse that are so significant in examining the development of theories. And it is exactly for that reason that understanding failures becomes as intriguing as appreciating successes.

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NOTES

1. Dewar and Fleming [1896], p. 81.
2. Hacking [1985], p.146.
3. Ibid., p.155.
4. Ibid., p.162.
5. Smith [1984], p.44.
6. There are other probes that can be used to understand the differences between discourses. Such a probe is the experimental practice of a particular group and what sets it apart

from that of other groups. The study of the experimental practice does not only involve the study of the apparatus and the techniques. It is primarily the investigation of the theoretical approach to the issues under investigation and particularly of the manner by which *new* phenomena are treated. For a taxonomy of "new phenomena" and a discussion of related methodological issues see Gavroglu, Goudaroulis [1988], especially chapter 1.

7. He was able to take the academic examinations only after new legislation exempted science students from knowing Latin and Greek.
8. J. D. van der Waals [1888], p.iv.
9. This paper is included as chapter XII in all the translations of his thesis.
10. Ibid., p.431.
11. Ibid., p.454.
12. Quoted in E. Cohen [1927], p.1203.
13. Kamerlingh Onnes [1896], p.5.
14. De Boer [1974];Levelt Sengers [1974].
15. Kamerlingh Onnes [1894], p. 4.
16. Kamerlingh Onnes [1896], p.5.
17. Ibid., p.23.
18. An excellent presentation of some aspects of the development of instrumentation can be found in de Bruyn Ouboter [1986].
19. "In sketching the meaning and extent of the work which is awaiting for us .... I was guided by the law of corresponding states. Also our method of procedure is pointed out by this law" Kamerlingh Onnes [1904], p.18-19.
20. Between 1901 and 1928 there were 35 publications on the isotherms of the diatomic gases and their binary mixtures.
21. Between 1907 and 1927 there were 26 publications on the isotherms of the monatomic gases and their binary mixtures. See for example Kamerlingh Onnes [1909].
22. Olszewski [1895].
23. Letter of Kamerlingh Onnes to Dewar July 20, 1908.
24. Dewar to Kamerlingh Onnes May 12, 1898.
25. Dewar [1902], p.29.
26. Van der Waals [1910], p.264.
27. Dewar [1898], p.681.
28. Dewar [1901], p.727.
29. Letter from Kamerlingh Onnes to Dewar June 8, 1905.
30. Dewar [1904], p.864.
31. Dewar [1901], p.725.
32. It is interesting to note in this respect the extensive correspondence between Dewar and J.D.H.Dickson. The latter ap-

pears to be an alter ego of Dewar for all the theoretical calculations, and relevant discussions. See especially letters to Dewar from Dickson dated March 24, 1895;January 13, 1900; April 24, 1902; April 29, 1902; June 24, 1902; January 6, 1903 and January 8, 1903.

33. This is even more so, if we realize that Dewar was much more at ease - and had used successfully - Trouton's rule for determining critical points.
34. Letters to Dewar from van der Waals January 9, 1900; January 11, 1900; January 13, 1900. Dickson January 13, 1900.
35. Dewar, Fleming [1892], p. 342. Burton in 1894 proved that at 0°K every substance must have either infinite resistance or infinite conductivity.
36. Dewar, Fleming [1892], p.342. Such a suggestion was made in 1858 by Clausius (Pogg. Ann. civ 650) that the electrical resistance for all pure metals is proportional to the absolute temperature.
37. Dewar Fleming [1896b], p.491.
38. Dewar [1902], p.35.
39. Dewar, Fleming [1904], p.247.
40. This situation led him to adopt Lord Kelvin's proposal that the resistance initially decreases because the electrons encounter fewer obstacles due to the dampening of thermal motion, but when the temperature is further reduced, the electrons themselves freeze onto their atoms and, hence, the resistance will start increasing and become infinite at absolute zero!

REFERENCES

T. Andrews, [1869], "On the Continuity of the Gaseous and Liquid States of Matter". The first Bakerian Lecture, in *Scientific Papers,* edited by P.G.Tait, Grum Brown. London:MacMillan. pp.296-317.

R. J. E. Clausius, [1857], "On the Nature of Motion we Call Heat", *Phil. Mag.*, 14, pp.108-127.

------- [1870], "Über einen auf die Warme anwendbaren mechanischen Satz", *Annalen der Physik*, 141, pp.124-130.

J. De Boer, [1974], "Van Der Waals in his Time and the Present Revival. Opening Address", *Physica,* 73, pp.1-27.

R. de Bruyn Ouboter, [1986], "Superconductivity: Discoveries During the Early Years of Low Temperature Research at Leiden 1908-1914", Paper presented at the "Kamerlingh Onnes Symposium on the Origins of Applied Superconductivity", October 1, 1986, Maryland, USA.

E. Cohen [1927], "Kamerlingh Onnes Memorial Lecture", *Chemical Society Journal,* pp.1193-1209.

J. Dewar [1895], "On the Liquefaction of Gases", *Phil. Mag.,* XXXIX, pp.298-305.

------- [1899], "Liquid Hydrogen", *Proc. Roy. Inst.,* XVI,pp.1-14.

------- [1901b], "The Boiling Point of Liquid Hydrogen Determined by Hydrogen and Helium Gas Thermometers", *Proc. Roy. Soc.,* LXVIII, pp.44-54.

------- [1902], Presidential Address to the British Association for the Advancement of Science, *Brit. Ass.,* LXXII, pp.1-47.

------- [1904b], "Physical Constants at Low Temperatures. The Densities of Solid Oxygen, Nitrogen and Hydrogen", *Proc. Roy. Soc.,* LXXIII, pp.251-261.

J. Dewar, J. Fleming [1896a], "Electric and Magnetic Research at Low Temperatures", *Proc. Roy. Inst.,* XV, pp.239-268.

-------- [1896b], "On the Electrical Resistivity of Pure Mercury at the Temperature of Liquid Air" *Proc. Royal Society,* 60, 76-81.

-------- [1904], "On the electrical resistance thermometry at the temperature of boiling hydrogen", *Proc. Royal Society* lxxiii, pp. 244-251

K.Gavroglu [1990], "Reaction of the British Physicists and Chemists to van der Waals's Early Work" *Historical Studies in the Physical Sciences*, 20, pp. 2-39.

K.Gavroglu, G.Goudaroulis, [1988], "Heike Kamerlingh Onnes's Researches at Leiden and their Methodological Implications", *Studies in the History and Philosophy of Science,* 19, pp.243-274

-------- [1989], *Methodolgical Aspects in the Development of Low Temperature Physics 1881-1957,* Dordrecht, Holland: Kluwer Publications.

I. Hacking, [1985], "Styles of Scientific Reasoning", in *Post-Analytic Philosophy,* eds. John Rajchman, Cornel West. Columbia University Press. pp.145-165.

H. Kamerlingh Onnes [1882], "Theorie Générale de l'Etat Fluide", *Extrait des Archives Néerlandes,* XXX, pp.1-36 (This is a translation of the original article published in Dutch in 1881).

-------- [1894],"On the Cryogenic Laboratory at Leiden and on the Production of Very Low Temperatures", *Communications from the Physical Laboratory of the University of Leiden* (hereafter denoted as CPL), no. 14.

-------- [1896], "Remarks on the Liquefaction of Hydrogen, on Thermodynamic Similarity, and the use of Vacuum Vessels", *CPL,* no.23.

-------- [1901], "Expression of the Equation of State of Gases and Liquids by Means of Series", *CPL,* no. 71.

-------- [1904], "The Importance of Accurate Measurements at Very Low Temperatures", *CPL(supplement),* no.9.

-------- [1909], "Isotherms of Monatomic Gases and Their Binary Mixtures III. Data Concerning Neon and Helium", *CPL,* no.112.

-------- [1923] Obituary for van der Waals, *Nature*, 111, pp.609-610.

H. Kamerlingh Onnes, C. Dorsman, G. Holst [1914], "Isothermals of Diatomic Substances and their Binary Mixtures.XV. Vapour-pressures of Oxygen and Critical Point of Oxygen and Nitrogen", *CPL*, no.145b.

M. J. Klein, [1974], "The Historical Origins of the Van Der Waals Equation", *Physica*, 73, pp.28-47.

J. M. H. Levelt Sengers [1974], "From Van Der Waals Equation to the Scaling Laws", *Physica*, 73, pp.73-106.

J.C.Maxwell [1879], "Capillary Action" *Encyclopedia Brittanica* 9th edition.

K.Mendelssohn, [1966],"Dewar at the Royal Institute", *Proc. Roy. Inst.* 41, pp.212-233.

C. Olszewski [1884a], "Essais de Liquéfaction de l'Hydrogene", *Comptes Rendus,* xcviii, pp.365-383.

-------- [1884b], "Nouveaux Essais de Liquéfaction de l'Hydrogène, Solidification et Pression Critique de l'Azote", *Comptes Rendus,* xcviii, pp.913-928.

-------- [1895], "On the Liquefaction of Gases", *Phil. Mag.,* 39, pp.188-212.

J. S. Rowlinson, [1973], "Legacy of van der Waals", *Nature,* 244, pp.414-417.

J. S. Rowlinson, B. Widom, [1982], *Molecular Theory of Capillarity,* Oxford: Clarendon Press.

S. Smith, [1984], *Reading Althusser,* Ithaca,New York: Cornell University Press.

J. D. van der Waals, [1873] "Over de continuiteit van den gas- en vloeistoftoestand" (Doctoral thesis at the University of Leiden).

-------- [1881], "Die Continuität des Gasformingen und Flussigen Zustandes", translation of the thesis in German by F.Roth; Leipzig.

-------- [1888], "The Continuity of the Liquid and Gaseous States", translation of the thesis in English by R.Threlfall ans J.Adair; London: Physical Memoirs of the Physical Society of London.

-------- [1890], "Théorie Moléculaire d'une Substance Composée de Deux Matières", *Arch. Néer.,* 24, pp.1-56.

-------- [1910], "The Equation of State for Gases and Liquids" in *Nobel Lectures (Physics) 1901-1921,* New York: Elsevier Publishing Company.