‘Structural Realism versus Standard Scientific Realism: The Case of Phlogiston and Dephlogisticated Air’[1]

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Abstract: The aim of this paper is to revisit the phlogiston theory to see what can be learned from it about the relationship between scientific realism, approximate truth and successful reference. It is argued that phlogiston theory did to some extent correctly describe the causal or nomological structure of the world, and that some of its central terms can be regarded as referring. However, it is concluded that the issue of whether or not theoretical terms successfully refer is not the key to formulating the appropriate form of scientific realism in response to arguments from theory change, and that the case of phlogiston theory is shown to be readily accommodated by ontic structural realism.

1. Introduction

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[1] This paper is based on a talk with the same title given at the Theoretical Frameworks and Empirical Underdetermination workshop at the University of Düsseldorf on 10th-12th April 2008. I am extremely grateful to Gerhard Schurz and Ioannis Votsis for organizing the event and inviting me, and to the participants for their comments. I am also heavily indebted to Andrew Pyle for generously sharing his extensive knowledge about the history and philosophy of phlogiston chemistry, and also to my student Bon Hyuk Koo for discussion of the place of phlogiston in the scientific realism debate.

The term ‘phlogiston’ is commonly cited as an example of a theoretical term from the history of science which does not refer to anything. In the contemporary debate about scientific realism, successful reference of its central theoretical terms is often taken as a necessary condition for the approximate truth of a theory. Those wishing to defend scientific realism against the pessimistic meta-induction and related arguments have largely concentrated their efforts on showing either that the putative examples of non-referring terms are either not central to the theories in question, or that the terms do after all refer. While a simple causal theory of reference has been agreed to make successful reference too easy, it is often claimed that causal descriptivist accounts of reference get the balance right by only allowing for successful reference when the core causal aspects of the description associated with a term are preserved. One reason why this might be thought necessary is to ensure that ‘phlogiston’ cannot be said to refer to oxygen because that is the real causal agent in combustion (see Psillos 1999, Bird 2000). However, not everyone denies the successful reference of all the theoretical terms of phlogiston theory. In particular, Philip Kitcher (1993) argues that sometimes some of these terms do refer. The aim of this paper is to revisit the phlogiston theory to see what can be learned from it about the relationship between scientific realism, approximate truth and successful reference. It is argued that phlogiston theory did to some extent correctly describe the causal or nomological structure of the world, and that some of its central terms can be regarded as referring. However, it is concluded that the issue of whether or not theoretical terms successfully refer is not the key to formulating the appropriate form of scientific realism in response to arguments from theory change, and that the case of phlogiston theory is shown to be readily accommodated by ontic structural realism.

In the next section, the essentials of phlogiston theory are explained and the connection between them and the empirical facts emphasized. In section 3, the role of phlogiston theory in classic debates about scientific revolutions and progress are briefly reviewed. In section 4, the more recent debate about scientific realism is discussed and the key arguments from theory change are clarified. Various accounts of what realists should say about the reference of phlogiston theory are discussed. Finally, section 5 makes the case for an ontic structural realist view of phlogiston theory.

2 The Phlogiston Theory

The heyday of phlogiston was between around 1700 and 1790 but its origins lie in the work of Johann Becher (1635-1682) who modified the alchemical theory according to which minerals consist of varying proportions of the three elements of salt, sulphur and mercury. Becher saw an analogy between the production of a calx from a metal by heating, and the production of sulphuric acid from pure sulphur by combustion. He regarded the latter as consisting in part of an active principle (which he dubbed 'terra pinguis') that was released on combustion. Georg Stahl (1660-1734) then systematized and generalized this analogy and proposed that all flammable materials contain this combustible earth, that is, for example, released from metals leaving the appropriate calx as residue. Stahl coined the term 'phlogiston' (from the Greek for flame) for the principle of combustion in 1697 (which is coincidentally the year the world's first heat engine was manufactured). The similarities between the calcination of metals and ordinary combustion, for example, of wood, were clear. Both processes involve the creation of dust and light and require lots of air to happen. However, there is a very important disanalogy too that would greatly occupy phlogiston theorists, namely that combustion of wood does indeed seem to amount to the giving off of something since the residue (ash) is much less in weight and volume than the fuel; on the other hand, some metal calxs weigh more than the uncalcinated metal (as both Becher and Stahl knew[2]). That this should refute the emission conception of combustion immediately was not obvious however, since phlogiston could be conceived as a principle rather than a substance, similarly to how caloric was sometimes thought of, and it was an open question whether such a principle might impart buoyancy rather than weight. Alternatively, the excess weight of calxs could be attributed to the presence of impurities, or to phlogiston having negative weight.[3]

The most important aspect of the phlogiston theory is the way that it unified different processes by categorizing them in terms of the reciprocals of phlogistication and dephlogistication. Combustion and calcination involve the dephlogistication of the fuel or metal and the phlogistication of the air, and the addition of an acid to a metal involved the

[2] This was established by Rey in 1630 (and was known even earlier by Arabian chemists according to Kuhn, 1970).

[3] As Musgrave (1976) points out this is a classic case of the Duhem problem of localizing falsification. For the history of attempts by phlogiston theorists to accommodate the weight increase of cases of supposed dephlogistication see Musgrave and also Carrier (2004) and Pyle (2000).

dephlogistication of the metal to leave the base. This unification is retained in contemporary chemistry by the duality between oxidation and reduction reactions.

Some of the important early successes of the phlogiston theory were as follows:

(1) Charcoal combusts almost completely so it was regarded as very nearly pure phlogiston. The presence of phlogiston was thought to be what distinguished metals from calxs, hence phlogiston was supposed to have a metallic quality and to explain what all metals have in common (being shiny, malleable and so on) despite their calces lacking these qualities.[4] Hence, if a metal calx (ore) is burnt in charcoal it ought to be become more metallic. Stahl advised those extracting of copper from copper ore to make sure to add enough charcoal and this advice worked. In general, the addition of charcoal (conceived as a source of phlogiston) is necessary for the extraction of metals from ores in most cases.

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[4] This is one of Kuhn's classic examples of what Heinz Post dubbed a 'Kuhn loss', namely a loss of explanatory power after a scientific revolution (1971, 229). Paul Honyningen-Huene (2008) endorses Kuhn on this point and argues in general that the chemical revolution illustrates Kuhn's theory of scientific revolutions very well. However, I am very sympathetic to Pyle's (2000) claim that the answer to the question as to whether the chemical revolution was a Kuhnian paradigm shift is a "definite 'no'" (99-100).

(2) Combustion ceases after a while in a closed chamber. This was explained in terms of the saturation of the air with phlogiston.

(3) Animals in a sealed chamber eventually cause the air to be unable to support combustion (this was known to Robert Boyle). On the other hand, air in which plants are grown is better able to support combustion.

The phlogiston cycle between plants and animals was discovered by Joseph Priestley (1733-1804), and he regarded it as an example of divine providence; plants dephlogisticate the air, and air without any phlogiston is air whose potential to be burnt is maximal, and which is apt for respiration by animals including humans who then phlogisticate the air and so on. Priestley produced what he termed 'dephlogisticated air' by heating a calx (red mercury) in 1774, performing what we would now refer to as a reduction of a metal oxide to release oxygen, and he famously described how pleasant it is to breathe dephlogisticated air. His dephlogisticated air [oxygen] is what Carl Scheele (1742-1786) referred to as 'fire air' (in his experiments of 1771-2, published 1777).

The discovery of so-called 'inflammable air' [hydrogen] (by Henry Cavendish (1731-1810) in 1766) led to renewed controversy about the nature of phlogiston because inflammable air is obviously not just ordinary air with phlogiston in higher concentration, since the latter would not burn or support combustion (it contains a lot of what we now think of as carbon dioxide which was dubbed 'fixed air' by Priestley). Nonetheless, Cavendish thought that inflammable air was pure phlogiston. He produced dephlogisticated air and inflammable air from water (1783) (and vice versa), showing that it is a compound substance. Priestley also heated some metal oxides in inflammable air to make pure metals (and water) (this works for some oxides, for example, that of lead, but not all, for example, that of iron). Priestley found that some of what he thought of as phlogisticated air dissolves in water (carbon dioxide) and some does not (mostly nitrogen). Neither supports ordinary combustion (like oxygen) or reduction (like hydrogen).

Despite its problems the phlogiston theory captured one great truth retained by Antoine Lavoiser (1743-1794) in his oxygen theory, namely that combustion, respiration and calcification are all the same kind of reaction (oxidization), and that these reactions have an inverse namely reduction. Lavoiser worked quantitatively and very precisely (although he was not the first to do so and Cavendish in particular was meticulous). He determined the increase in mass of some residues from combustion, and introduced the principle that mass is conserved in chemical reactions. In 1789 he defined a chemical element as the endpoint of the chemical process of analysis and concluded that metals were elements (where Stahl had argued that there were not elemental since he thought that had to have phlogiston as a constituent). According to Lavoisier oxygen is a component making up the compound ordinary air, and those processes such as burning, respiration and the rusting of iron previously categorized in terms of the release of phlogiston are all oxidisation reactions (note however that Lavoisier did not think gaseous oxygen was elemental).

Lavoisier's theory was not without its problems however, not least of which is that he thought that oxygen was the principle of acidity (phlogiston theorists had thought that earths such as carbon and sulphur which had been dephlogisticated were acidic), and thus he could not account for acids like hydrochloric acid which do not contain oxygen. Recall also that prior to Lavoisier's theory, the supposed presence of phlogiston explained what all metals have in common, whereas Lavoisier could offer no explanation and indeed none was forthcoming until the theory of electronic orbits and free electrons in the twentieth century.

3 Classic Views of Phlogiston

According to some histories of science phlogiston theory was of no value. William Whewell cites this opinion among some of his contemporaries (1866) (Herschel famously regarded phlogiston theory as evidence of the "perversity of the human mind", 1830, 300), and it was expressed more recently by the 'Whig' historian of science White in 1932.[5] It is easy to make fun of a theory that contains terms ('phlogiston', 'principle') that fail to refer to the world, and that was replaced by the successfully referring theory ('oxygen', 'element') of Lavoiser to which we still adhere. Many people think of the demise of phlogiston theory as the start of properly scientific chemistry since it roughly coincided with the use of modern chemical apparatus and the precise measurement of masses and volumes. Phlogiston theory was qualitative, and still related to the

[5] Andrew Pyle (2000) cites the latter work as exemplary of the Whiggish history of science against which Kuhn and his followers rebelled.

Renaissance and Aristotelian ideas of principles, qualities and virtues. Note also that phlogiston theory is not mathematicised unlike most mature science. It was prima facie falsified by the fact that oxides are heavier than pure samples of the relevant metal, and was the locus of what many still regard as a classic ad hoc modification, namely the positing of negative mass for phlogiston.[6]

However, as we have seen above, phlogiston theory did have a lot going for it. For Kuhn in *The Structure of Scientific Revolutions,* the transition from Priestley to Lavoisier is a central example of a scientific revolution that illustrates his prime message that superceded theories usually have many virtues that are easily neglected or forgotten in the histories told by the victors. Kuhn is also right that the simplistic story of Lavoisier's inauguration of modern chemistry is misleading. The latter believed that oxygen as the principle of acidity, only became oxygen gas when united with caloric (the matter of heat) (1970, p. 55). On the other hand, there is no sense in which Priestley and Lavoisier were living in different worlds with incommensurable modes of thought each bound to their respective paradigms. On the contrary, Lavoisier gave a very clear and state of the art exposition of the various phlogiston theories as a part of his critique of them and advocacy of his own theory. Furthermore, as Pyle (2000) documents, phlogiston theorists did not die out clinging to their cherished theory as Kuhn's view might lead us to expect, but rather converted almost unanimously and within a decade once Lavoisier's theory was complete.

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[6] As mentioned above, there are other more plausible modifications to the phlogiston theory that make it compatible with the heaviness of oxides. See the references in note 3.

Kuhn’s talk of adherents of different paradigms living in different worlds and the interpretation of it is broadly Kantian terms according to which the phenomenal world of Priestley and Lavoisier were different, might lead one to argue that for Priestley ‘phlogiston’ referred to phlogiston. This may be regarded by some as a reductio of Kuhn’s view or at least of an extreme ontological relativist interpretation of him. The idea that phlogiston existed for Priestley is too much for most philosophers of science. The need to respond to the prevalence of constructivism and relativism about ontology in the wake of the influence of *The Structure of Scientific Revolutions* inspired many philosophers of science to examine the historical record carefully to see whether it really supported Kuhn’s theory. George Gale (1968) agreed with Kuhn that phlogiston theory produced many extremely good explanations including of the loss of weight of wood, coal and ordinary substances when burnt, of the fact that charcoal leaves hardly any ash because it is almost pure phlogiston, and that metals are alike because they all contain phlogiston. But he also argued for the standard view that the theory is wrong because phlogiston is nonexistent. Other scholars examining Kuhnian case-studies found continuity and rationality where Kuhn found revolution and external factors. Alan Musgrave (197?) explains why inductivist and naïve falsificationist accounts of the ‘Chemical Revolution’ are inadequate but also criticizes the Kuhnian ‘conventionalist’ account of it, and argues that it can be straight-forwardly understood in Lakatosian terms as the triumph of a progressive research programme over a degenerating one, and hence as an entirely rational theory choice by the scientific community. Noretta Koertege (1969) argued that phlogiston theory was an example that supported Heinz Post’s ‘general correspondence principle’ according to which the well-confirmed empirical generalizations of old theories are retained by their successors, and there are no ‘Kuhn losses’. We have already seen how much of phlogiston theory is indeed retained in contemporary chemistry. In the next section, the response of contemporary scientific realists to phlogiston theory is discussed.

4 Phlogiston and the Contemporary Scientific Realism Debate

4.1 The Pessimistic Meta-Induction versus the Argument from Theory Change

The term ‘pessimistic induction’ was coined by Putnam (1978, 25) for something like the following argument:

(i) There have been many empirically successful theories in the history of science which have subsequently been rejected, and whose theoretical terms do not refer according to our best current theories.

(ii) Our best current theories are no different in kind from those discarded theories, and so we have no reason to think they will not ultimately be replaced as well.

So, by induction we have positive reason to expect that our best current theories will be replaced by new theories according to which some of the central theoretical terms of our best current theories do not refer, and hence, we should not believe in the approximate truth or the successful reference of the theoretical terms of our best current theories.

The standard response to the PMI is to attempt to reduce the size of the inductive base by ruling out theories on the basis of some criteria. These are typically those of maturity, which is the reliance on well-entrenched background theories, mathematicization and precision, and a strong form of empirical success usually novel predictive success.[7] It is indeed plausible to argue that contemporary science as a whole is very different in kind from the science of the past in so far as it is highly mathematicised, and hugely integrated and unified especially with respect to the macrosciences and the chemistry of the periodic table. It also features theories that are extremely quantitatively accurate, for example, QED is accurate to 13 significant figures.[8] Furthermore, Ludwig Fahrbach (this volume) points out that the exponential growth of the history of science to date (almost all scientists are living now) makes episodes from the history of physics or chemistry of previous centuries a very unrepresentative sample if one is trying to learn lessons about

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[7] Recently there have been criticisms of PMI as a probabilistic argument with Peter Lewis (2001) arguing that it commits the 'base-rate' fallacy (Magnus and Callender 2004 agree), and Marc Lange (2002) arguing that it commits the 'turnover' fallacy. These critiques have no force against the version of the argument from theory change presented below.

[8] By any measure of success surely Newton's theory of gravity counts (accurate to one part in 10^7 although based on data accurate to one part in 10^3, according to Penrose 2004, 390).

the realism debate and contemporary science. This notwithstanding, it is argued in what follows that the most defensible form of argument from theory change is not a probabilistic or inductive argument, and that what matters is the existence of a few examples rather than a large inductive base.

Laudan's (1981) much cited paper that is usually taken as the locus classicus of the PMI did not propose a free standing argument against scientific realism like the PMI above, but rather was intended to undermine the realist abductive arguments for realism such as the No-Miracles Argument. Where realists argue that approximate truth and successful reference both explain empirical success, Laudan argues that there can be approximate truth without empirical success, and successful reference without empirical success. He seems to be right about this since, for example, Aristarchus' theory that the Sun was the centre of the solar system enjoyed no particular empirical success but was clearly approximately true, and clearly one can successfully refer to, say, electrons as the smallest units of electric charge, while not having an empirically successful theory of them. In general it is clear that the approximate truth of some hypothesis will only lead to empirical success in conjunction accurate background theories and auxiliary hypotheses, and that successful reference does not entail approximate truth or empirical success unless some form of descriptivism about reference is assumed.

Laduan also argued that the successful reference of its theoretical terms is *not* a necessary condition for the novel predictive success of a theory (1981, 45), and so that there are counter-examples to the no-miracles argument. It is clear therefore that the argument against scientific realism from theory change need not be an inductive argument based on Laudan's list. This is why Stathis Psillos' (1999) celebrated defence of scientific realism did not halt once he had argued that Laudan's list could be reduced to a few cases on the basis of the above criteria. Rather he said that his divide and conquer strategy is needed because even if there are only a couple of examples of false and non-referring, but mature and strongly successful theories, then the "explanatory connection between empirical success and truth-likeness is still undermined" (1999, 108).

As well as the PMI then there is also the following 'Argument from Theory-Change': There are cases of mature theories that enjoyed strong predictive success by anyone's standards, namely the ether theory of light and the caloric theory of heat. If their central theoretical terms do not refer, the realist's claim that approximate truth explains empirical success will no longer be enough to establish realism, because we will need some other explanation for their success. If this explanation is adequate for these cases then it ought to do for other cases where the central theoretical terms have been retained, and then we do not need the realist's preferred explanation that such theories are approximately true and successfully refer to unobservable entities. (C.f. Ladyman and Ross (2007), 84-85, Ladyman (2002), chapter 8). Call this the 'Argument from Counterexamples to the No-Miracles Argument'. It can be put more explicitly as follows:

1. Successful reference of its central theoretical terms is a necessary condition for the approximate truth of a theory.

2. There are examples of theories that were mature and had novel predictive success but whose central theoretical terms do not refer.
3. So there are examples of theories that were mature and had novel predictive success but which are not approximately true.
4. Approximate truth and successful reference of central theoretical terms is not a necessary condition for the novel-predictive success of scientific theories

So, the no-miracles argument is undermined since, if approximate truth and successful reference are not available to be part of the explanation of some theories' novel predictive success, there is no reason to think that the novel predictive success of other theories has to be explained by realism.

There are two standard responses to this argument that may be combined. The first is to develop an account of reference according to which the abandoned theoretical terms successfully refer after all. Causal theories of reference were introduced into the philosophy of science to explain how there can be continuity of reference of terms such as 'atom' or 'electron', despite the fact that there have been major changes in the theoretical descriptions of atoms and electrons. It is natural to then extend the causal theory to cases involving terms such as 'ether' and 'caloric' even though they are no longer used in contemporary science. C.L. Hardin and Alexander Rosenberg (1982) argue that the causal theory of reference may be used to defend the claim that terms like 'ether' refer to whatever causes the phenomena responsible for their introduction. The obvious problem with this view (see Laudan 1984) is that it threatens to trivialize the successful reference of theoretical terms; any term will successfully refer to the relevant cause or causes providing that some genuine phenomena prompt its introduction. There is also the problem that too great a gap seems to open up between what a term refers to and its associated description, so that, for example, Aristotle would be counted as referring to geodesic motion in a curved spacetime when he talked about the natural motion of material objects. These problems lead Psillos (1999) to argue for a hybrid of the causal theory and descriptivism.

The second response is to adopt what Kyle Stanford (2003a) calls 'selective confirmation'. The idea is to restrict realism to those parts of theories which play an essential role in the derivation of subsequently observed (perhaps novel) predictions, and then argue that the terms of past theories which are now regarded as non-referring were non-essential so there is no reason to deny that the essential terms in current theories will be retained. Philip Kitcher says that: "No sensible realist should ever want to assert that the idle parts of an indvidual practice, past or present, are justified by the success of the whole" (1993, 142).

The most detailed and influential response to the arguments from theory change is due to Psillos (1999) who combines strategies (I) and (II) to show that the second premise is false by showing that in the crucial cases, either the terms in question do refer after all ('ether'), or they were not after all central to the theory ('caloric').[9]

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[9] Hasok Chang (2002), Kyle Stanford (2003a and 2003b), Mohammed Elsamahi (2005) and Timothy Lyons (2006) criticize Psillos's account.

4.2 The flight to reference and recent accounts of the phlogiston case

It is not plausible to claim that ‘phlogiston’ was not central to phlogiston theory, but it has also not been thought plausible to claim that the term ‘phlogiston’ refers to anything that is recognised to exist by contemporary science. This has led many scientific realists to discount the worth of phlogiston theory and to ignore the merits of the claim that it is in fact approximately true. Hence, prominent scientific realists have tended to cite ‘phlogiston’ as an example of a theoretical term that does not refer (for example, Putnam 1978 and Lewis 1970), and leave the discussion of phlogiston theory at that. Hardin and Rosenberg (1982) claim that phlogiston theory is pre-paradigmatic science and hence do not consider its merits in the light of the causal theory of reference they propose in response to Laudan. Psillos (1999) says that “a phlogiston-based taxonomy is wrong because no natural kind has the kind-constitutive properties attributed to phlogiston” (288), and that “phlogiston refers to nothing” (291). He also mentions ‘phlogiston’ as a counterexample to the simple causal theory since then it would refer to oxygen (whatever is involved in combustion). Bird (2000, 184-5) gives exactly the same argument against the simple causal theory of reference, and is sanguine about the idea that phlogiston theory fails to refer.

In the light of the discussion in section 2 it seems clear that it is too simplistic to dismiss phlogiston theory entirely when it comes to cutting nature at its joints, because according to contemporary science oxidation and reduction are genuine natural kinds of processes, and phlogiston theory successfully classified known chemical reactions in a similar taxonomy based on the movement of phlogiston. It also offered a taxonomy of phlogisticating and dephlogisticating agents that corresponds to the modern taxonomy of reducing and oxidising agents. Lavoisier's oxygen theory incorrectly classified acids as compounds containing oxygen, but we are not inclined to deny that his usage of the term 'oxygen' failed to refer. Furthermore, contemporary chemistry uses the term 'oxidization' for the gain of electrons even when oxygen is not present in the reaction.

The case of phlogiston chemistry is an example of the more general problem of what to say about derived theoretical terms where it is assumed that the principle theoretical term does not refer.[10] Supposing phlogiston does not refer, what of derived terms such as 'dephlogisticated air'? The latter term has been discussed in the recent debate about scientific realism since Kitcher's *Advancement of Science* (1993). As Christina MacLeish (2005) explains, Kitcher's goal is to reconcile two apparently conflicting claims: firstly, that Priestley had many false theoretical beliefs about combustion and related processes, not least that there is a substance called phlogiston; and secondly, that Priestley successfully said true things about oxygen using the term 'dephlogisticated air'. According to accounts of reference according to which no term related to phlogiston theory referred, it is not possible for Priestley to say anything truth-valued using the term

[10] Another good example of this is where what would have been described as the flow of caloric is still described as the flow of heat even though there is no such substance as caloric. It is absolutely standard in thermodynamics for the heat flow dQ to appear in equations. The similarities between caloric and phlogiston theories are returned to below.

‘dephlogisticated air’. On the other hand it is not viable to claim that the term ‘dephlogisticated air’ always refers to oxygen since sometimes the term is used to denote “the substance obtained when the substance emitted in combustion is removed from the air” (1993, 102), and there is no such substance. Kitcher’s solution is to argue that the reference of a token of theoretical term such as ‘dephlogisticated air’ could be sometimes successful and sometimes not depending on the context of utterance (this is ‘heterogeneous reference potential’).

According to Kitcher’s theory, reference for tokens is fixed by baptism, descriptivist or conformist modes of usage. Baptism is the familiar Kripkean notion of reference being fixed by an act or utterance of ostension that establishes a causal connection between the world and the usage of a term. Sometime it seems very clear that Priestley means by ‘dephlogisticated air’ the stuff he prepared and then breathed himself. Kitcher argues that Priestley was referentially successful in his uses of the term on the occasions on which he makes it clear that he intends to talk about whatever it is that he has in some container, and where a contemporary chemist would say that he had prepared a pretty pure sample of oxygen and was engaged in putting animals in it or breathing it. The conformist mode is the extension of the baptisim mode when usage is parasitic on someone else’s baptist usage. On the other hand, the descriptivist mode is usage that is tied to a theoretical description as when one refers to phlogiston as the substance that is released on combustion of a flammable material.

MacLeish (2005) argues that Kitcher faces the ‘discrimination problem’ of providing a criterion to determine which mode is appropriate for a given token usage and thus to demarcate cases of successful and unsuccessful reference for tokens of terms. Kitcher anticipates this problem and proposes Grandy’s (1973) ‘principle of humanity’ as the solution, where the latter states that we should attribute our own beliefs and relations with the world to agents whom we are interpreting. MacLeish argues that the three possible solutions to the problem she considers: namely what we would say; what was really the case; what Priestley would have said; are all inadequate. The latter because there is no determinate fact of the matter about what Priestley would have said; the first two because the issue is not whether we can understand what Priestley was doing but whether he was successfully referring at the time. In sum, MacLeish objects to the Whiggishness of Kicther’s account and criticizes the idea that whether or not Priestley successfully referred to oxygen should depend on the beliefs of subsequent generations of scientists. She argues that there are no satisfactory grounds for making the distinction between referring and non-referring tokens. In her 2006 she then argues that abandoned theoretical terms like ‘ether’ partially refer and partially fail to refer building on the work of Field (1973) on partial denotation.

MacLeish certainly makes a good case against Kitcher, but we are left with the conviction that, whether or not we can theoretically justify it, sometimes Priestley successfully referred to oxygen, and that similarly that Scheele’s preparation of what he called ‘dephlogisticated marine acid’ was the oxidation of hydrochloric acid to what we would call ‘chlorine’. It seems just as reasonable to makes these claims as to claim that ‘fixed air’ referred to carbon dioxide (used by Priestley to make soda water), and that ‘light inflammable air’ referred to hydrogen. We cannot avoid considering what we would say because we must use our best scientific understanding of the work of past scientists to interpret what they were doing. Everybody now agrees that heating precipitate of red mercury produces oxygen and everyone agrees that Priestley did so and breathed it. MacLeish herself offers a positive account that depends in part on appealing to what we would say about what Priestley was referring to, since she agrees that some of his utterances of ‘dephlogisticated air’ at least partially to oxygen. Furthermore, her theory of disjunctive partial denotation has the consequence that sentences about dephlogisticated air can be both true and their negations also true.

The debate about the reference of theoretical terms and scientific realism has become somewhat epicyclic, and there is no consensus among those defending standard realism in the face of theory change about the key cases discussed in the literature. It is therefore worth revisiting the issue of just how important successful reference is for scientific realism. The argument from theory change threatens scientific realism because if what science now says is right, then the ontologies of past scientific theories are far from accurate accounts of the furniture of the world, even though they were predictively successful. It follows that the empirical success of our best current theories does not imply that they have got the nature of the world right either. The structural realist solution to this problem is to reject the claim that the nature of unobservable entities is successfully described by science, and to argue instead that successful scientific theories give increasingly accurate descriptions of the structure of the world. Theories can be very different and yet share all kinds of structure. The task of providing an adequate theory of approximate truth that fits the history of science and directly addresses the problem of ontological continuity has hitherto defeated realists, but it is easily possible to display the structural commonalities between different theories. Hence, a form of realism that is committed only to the structure of theories might not be undermined by theory change. In the next section it is argued that the case of phlogiston is readily accommodated by structural realism.

5 Structural Realism and Phlogiston

As is well known there are two kinds of structural realism known as epistemic and ontic structural realism (ESR and OSR respectively) and first distinguished by Ladyman 1998. The former is defended by John Worrall (the originator of structural realism in contemporary philosophy of science in his 1989). While there are many differences between the various forms of structural realism there are also common commitments:

(i) ESR and OSR both involve commitment to the claim that science is progressive and cumulative and that the growth in our structural knowledge of the world goes beyond knowledge of empirical regularities.

(ii) ESR and OSR both depart from standard scientific realism in rejecting term by term reference of theories, and hence standard referential semantics, and any account of approximate truth based on it.

(iii) According to both OSR and ESR, scientific theories do not give us knowledge of the intrinsic natures of unobservable individual objects

Two versions of ESR can be contemplated. According to ESR_1 there are such objects but we cannot know them, and according to ESR_2 there may or may not be such objects, but we cannot know either way, and if there are such objects we cannot know them. (It seems that Worrall now advocates ESR_2.) Either way ESR is so-called because in either case it is an epistemological revision of standard scientific realism. On the other hand, OSR is characterized by an inflationary ontology of relations and structure and a deflationary view of objects and intrinsic properties although there are many forms this can take (for a taxonomy and references see Ladyman 2007). It is argued below that phlogiston supports all of the above three components of structural realism.

The case of phlogiston is like that of caloric in the following respects: both were supposed to be material substances and central explanatory entities; both were involved in explanations in terms of their movement in space; and both were ideas from earlier science that were eliminated. Gale (1968) calls this the basic form of Democritean explanation. The properties of phlogiston were purely descriptive and qualitative. The domain of application was that of chemical reactions involving qualitative change. In the case of caloric mathematization and quantitative reasoning was successfully pursued to an extent and used, for example by Laplace's calculation of the speed of sound in air. Nonetheless, it is clear that the Democritean theory of heat could never have been made adequate given what we now know about thermodynamics. Similarly, there just is no single material stuff given off in all cases of combustion. However, there is unification of generalizations and relations among the phenomena by description in terms of the release or absorption of phlogiston (oxidation/reduction), and similarly many phenomena can be unified in a thermodynamic theory involving heat flow. Psillos says hypotheses about the nature of 'caloric' were not really essential to the empirical success of the caloric theory of heat. Similarly, one could argue that the existence of phlogiston was not essential to the empirical success of phlogiston theory.

However, phlogiston theory must be taken seriously by the realist, for as we have seen, it enjoyed considerable empirical success. Here is a summary of the empirical regularities subsumed by phlogiston theory.

- metal + heat (in air) ⇒ calx [metal oxide] + phlogiston [de-oxygenated air]
- calx + charcoal (source of phlogiston) ⇒ metal (+ fixed air [carbon dioxide (Joseph Black (1728-1799) 1754)])
- metal + acid = salt + inflammable air
- metal + water = calx + inflammable air
- water = inflammable air [hydrogen] + dephlogisticated air [oxygen]
- Animals and plants have opposite effects on the air; the former phlogisticate it and the latter dephlogisticate it.

These were explained by:

metal = calx + phlogiston (explaining what metals have in common)

charcoal = fixed air + phlogiston

salt = calx + acid

Furthermore, scientific realists often argue that it is really novel predictive success that counts in favour of a realism about theories (that is Psillos' view). It is important to note therefore that there were several novel predictions of phlogiston theory including Priestley's prediction that one could heat some calces in inflammable air to get the pure metal, and the prediction of the existence of several new acids by Scheele (such as formic acid and lactic acid) .

Any form of scientific realism must be differentiated from constructive empiricism, where the latter posits only that successful scientific theories must be empirically adequate in the sense of saving the phenomena. Phlogiston theory subsumed the regularities in the phenomena above by categorizing them all as either phlogistication or dephlogistication reactions where these are inverse to each other. This is a prime example of a relation among the phenomena which is preserved in subsequent science even though the ontology of the theory is not; the inverse chemical reactions of reduction and oxygenation (as pointed out by Martin Carrier (2004 and this volume) and Gerhard Schurz (2009 and this volume). So (i) above is supported by the case of phlogiston theory. The empirical success of the theory was retained in subsequent chemistry since the latter agrees that combustion, calcification and respiration are all the same kind of reaction, and that this kind of reaction has an inverse reaction, and there is a cycle between plants and animals such that animals change the properties of the air in one way and plants in the opposite way. Furthermore, it is worth noting that inflammable air [Hydrogen] really is considered metallic by contemporary chemistry.[11]

Solutions to the phlogiston problem based on defending the reference of the theoretical term ‘phlogiston’ to whatever is involved in combustion are not plausible as mentioned

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[11] A further correspondence is that between the chemical affinities represented by Torbern Bergman in his 1785 dissertation and the affinities represented by Lavoisier and the contemporary understanding of electrochemical series.

above, and while the claim that some tokens of ‘dephlogisticated air’ may well refer to oxygen, this does nothing to explain the empirical success of phlogiston theory. A more sophisticated recent view of the referential status of phlogiston theory is that of Schurz (2009). He argues that the theoretical terms ‘phlogistication’ and ‘dephlogistication’, that were understood by those who used them in terms of the assimilation and release of the substance phlogiston, can be regarded as referring to the processes of oxidation and reduction, where these are understood in the general sense of the formation of an ionic bond with an electronegative substance, and the regaining of electrons respectively. If the oxidising agent is oxygen, and the oxidised compound is a source of carbon then the product is carbon dioxide i.e. fixed air. If the oxidising agent is an acid, then hydrogen is emitted. We could go further and allow that ‘phlogiston rich’ and ‘phlogiston deficient’ refer too, namely to strongly electro-negative and electro-positive molecules respectively. Andrew Pyle has even suggested to me in conversation that one could argue that ‘phlogiston’ refers to electrons in the outer orbital of an atom. Indeed there is a kind of underdetermination about the reference of ‘phlogiston’ to either antioxygen or spare electrons.

The point about Schurz’s and Pyle’s proposals however, is that they are not plausible accounts of what the historical actors were referring to with their use of the theoretical terms of phlogiston theory. Rather they are best taken as showing that there is a good deal of theoretical structure retained from phlogiston theory by contemporary science. When we consider various other examples from the history of science it starts to look quite arbitrary whether a theoretical term is regarded as referring or not. The term ‘ether’ was abandoned because it was associated with the idea of an absolute frame of reference, but special relativity refers to the electromagnetic field, the term ‘atom’ was not abandoned but was originally supposed to refer to indivisible ultimate constituents of matter. The term ‘electron’ was supposed to refer to a particle that carried the smallest unit of charge, but electrons are not really like particles and quarks have smaller units of charge. The term ‘mass’ was supposed to refer to an intrinsic property of material particles not to a disjunctive kind, and so on. It seems wise to agree with Hardin and Rosenberg that the approximate truth of a theory does not require the successful reference of its central theoretical terms, and hence to agree with (ii) above.

(iii) is also supported by the case of phlogiston theory. The Democritean style of explanation is not preserved by fundamental physics, and the phlogiston case further supports the induction that science will replace material explanations with structural ones.

So far then phlogiston theory has been argued to support the common tenets of ESR and OSR. However, it is arguable that the case of phlogiston fits better with OSR than with ESR on the following grounds:

(a) Ramsefying phlogiston theory leads to a sentence that asserts the existence of something that is released on combustion and there is no such thing.
(b) The core theoretical structure that is correct in phlogiston theory is not the unknowable entity that we know relationally as what is released on combustion but rather the relational structure expressed by the theory of Redox reactions.

In the terminology of Ladyman and Ross (2007) following Dennett (1991) we can say that phlogiston theory identified a number of real patterns in nature and that it correctly described aspects of the causal/nomological structure of the world as expressed in the unification of reactions into phlogistication and dephlogistication. As William Whewell so wisely said in his *History of the Inductive Sciences*:

"[w]e must not forget how natural it was to suppose that some part of a body was destroyed or removed by combustion…It would be easy to show, from the writings of phlogistic chemists, what important and extensive truths their theory enabled them to express simply and clearly." (1837, 120)

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