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James Hutton and Phlogiston

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James Hutton defended the doctrine of phlogiston in two lengthy dissertations in 1792 and 1794. Empirical, biographical and disciplinary contexts jointly explain his position. Observationally, Hutton based his argument on facts about heat, light and the storage of energy, explicitly contrasting them to concerns about weight relationships. Hutton's intellectual development shows how he found these particular problems centrally relevant, and focusing on phlogiston indicates how his better known geology fits into more fundamental thinking about the natural economy. The resonance of Hutton's views with many contemporaries highlights the significance of his views and suggests how we might reconsider the role of phlogiston in late 18th-century chemistry.

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> The phlogistic doctrine impeded the progress of science, as far as science of experiment can be impeded by a false theory, by perplexing its cultivators with the appearance of contradictions, . . . and by involving the subject in a mist of visionary and hypothetical causes in place of true and acting principles.
>
> ---Sir John Herschel, 1830

> We have only to regret that the valuable truth embodied in it [the phlogistic theory] should have been lost sight of; that the antiphlogistonistic chemists, like other reformers, destroyed so much of what was good in the old system.
>
> ---Alexander Crum Brown, 1864

I. Introduction

In publications in 1792, and again in 1794, James Hutton staunchly defended the doctrine of phlogiston:[1] why? To understand Hutton's position fully, one must integrate several historiographic perspectives (see Appendix below). First, there is the empirical evidence Hutton himself presented and, coupled with this, the framework of questions in which these observations were particularly relevant. Further, one must probe the cognitive contexts (conceptual and biographical) in which these questions, in turn, were significant for Hutton. By unfolding this context, in fact, one can appreciate more deeply the themes that permeated Hutton's thinking more generally. Finally, a disciplinary context highlights how Hutton's claims fit among other contemporary thinkers. Here, Hutton epitomized an ensemble of late defenses of phlogiston. Collectively, they suggest how we must (re)interpret the conceptual dynamics of the Chemical Revolution.[2] These two documents, then, not only illustrate Hutton's conceptual framework, but well understood, they also have implications for the broader history of chemistry.

Hutton (1726-1797) is traditionally most known for his geology, such as his explanation of the striking angular unconformity at Siccar Point.[3] Some have addressed Hutton's chemistry, but often in the context of articulating his geological views more fully.[4] Donovan and Prentiss, by contrast, have emphasized his chemical (and alchemical) approach, especially in his M.D. dissertation.[5] The two dissertations on phlogiston, however, have remained largely peripheral to assessments of Hutton's overall thinking.[6] By using them as a focal point, instead, one can see more clearly how chemistry, especially regarding heat and light, was central for Hutton. The documents also underscore the theological importance of the natural economy and the cycles that sustained it.[7]

Hutton's works also intersect with the conceptual developments surrounding the Chemical Revolution. Even within the history of chemistry, Hutton's chemical publications have not been regarded as significant landmarks. Partington and McKie in their classic overview of the history of phlogiston address them, but merely synopsize their content.[8] Hutton's defenses of phlogiston are noteworthy, however, partly because Hutton accepts the discovery of oxygen (though he continues to refer to it as `vital air'). Indeed, Hutton does not shy away from lauding Lavoisier's finding, noting that it `is to be ranked among the greatest discoveries in physics'. He praises the *Elementary System of Chemistry* and even its author.[9] Still, Hutton insists, there is a role for phlogiston. Nor is Hutton unique in his criticism (see `Disciplinary Context' below). Hutton's works are thus critical for understanding how phlogistonists and "anti-phlogistonists" might not best be framed as mutually exclusive. Analysis of Hutton's arguments may thereby contribute (in the spirit of Brown's assessment, above) to an interpretation of the Chemical Revolution (unlike Herschel's) in which the central feature was neither the replacement or `supplanting' of an inadequate theory of combustion, nor `the overthrow of the phlogiston theory'.[10]

II. Hutton's Argument and its Observational Context

Hutton presents his case for phlogiston[11] through primarily empirically based arguments. In the 1792 document, he offers two general lines of reasoning: one based on bodies burning and creating heat and light--the decomposition of phlogiston; and the other on how such bodies are formed--the composition of phlogiston.[12] Both arguments rely on a rich collection of observations--ones which, Hutton emphasizes, are not addressed by Lavoisier. He plainly announces that his purpose is:

> to show, that some important facts, or essential phenomena in the burning bodies, are not explained in the antiphlogistic theory; and that, until these be explained, it must be necessary to retain the term phlogiston, which expresses something material in the knowledge of nature, or generalizes certain phenomena, which the new theory does not explain.[13]

Thus, even while Hutton can accept the existence of oxygen, there are other events, such as ignition, the generation of light and the color of flames, that cannot be overlooked, `however ingenious the thought, or however learned in other respects may be our scientific language'.[14] Hutton's defense of phlogiston, then, is less a rejection of the new discoveries or nomenclature, than a critique based on explanatory inadequacies for certain phenomena.

Especially in the first half of his second 1792 chapter, `The reality of Phlogiston maintained, by Arguments taken from the decomposition of that Substance', Hutton endeavors to show how the new interpretations of combustion are incomplete. When coal burns, for example:

> there are produced two distinct effects; first, by the oxigenating of the gravitating carbonic substance, there is produced fixed air, or carbonic acid in an elastic state. Secondly, in thus changing the nature of the coal, there is produced a great quantity of light and heat; it is only this last event, or effect, with regard to which there is any difficulty, or any dispute to be made.[15]

His strategy is thus to show that the recombination of material elements is distinct from the generation of heat and light--where phlogiston functions.

Hutton addresses in detail Cavendish's 1783 demonstration that water is produced from vital air and inflammable air--what he admits is a significant experiment. But for Hutton, there is a problem in explaining ignition. The simple co-presence of the two gases, he notes, is not sufficient for their composition or reaction. If oxygen were the key factor in combustion, and had an affinity for hydrogen, why does the reaction need a spark to initiate it? Hutton concludes that inflammable air must be a compound substance, and that additional heat is necessary to break the affinity of its parts before it can react (through elective action) with vital air.[16] That is, one cannot adequately describe the event as merely the combination of gases alone: one needs to understand what additional element in hydrogen is responsible for ignition--namely phlogiston.

Hutton concentrates especially on how the fixation of oxygen gas and the release of `calorique' cannot account for many cases where heat or light is produced. Hutton denies `that vital air contains in itself the principle of fire, that is, heat', or that it has a chemical affinity for a substance in the burning body with which it combines, releasing heat. He notes that in Cavendish's experiment, the formation of water from the combined gases corresponds to the condensation of steam. Thus, what Lavoisier sees as the release of caloric in changing from gas to liquid is merely the release of latent heat.[17] But the latent heat alone cannot account for the magnitude of the extraordinary light and heat in Cavendish's experiment. And if caloric does not mean latent heat, what else can it mean besides what is already meant by phlogiston? Hutton concludes that `the light and heat of fire does not proceed from the condensation of vital air in burning', and that the inflammation is distinct from the formation of water. They are merely `collateral' events.[18]

Hutton further considers reactions in which oxygen is not fixed from its gaseous state. When charcoal combines with vital air, for example, and forms fixed air, the oxygen does not become fixed, but remains as a gas.[19] When charcoal and nitre react, the oxygen (as a component of the nitre) is already `found in a solid concreted state'. In the ensuing explosion or deflagration, light is produced precisely as oxygen is transformed from a solid to a gas--in a manner quite opposite to Lavoisier's claims about caloric.[20] The release of caloric from oxygen in its transition from gas to liquid or solid thus cannot account for the heat.

Even more dramatically, heat may be released in combustion in the total absence of oxygen itself. Iron and sulfur, for example, react and produce heat, but again, no oxygen (nor any other gas) is fixed. Hutton returns to the sulphurating of metals in another key paper in 1796. There he notes new investigations by Dutch chemists in 1793, emphasizing that incandescence occurs without the presence of vital air:

> In the whole process these is no oxygenation; no production of fixed or carbonic air; no apparent waste; nor any thing emitted from the [sulphurating] mass, except the light of incandescence.[21]

Hutton concludes that burning is independent of oxygen, but that burning bodies must nevertheless contain a specific inflammable and heat-generating substance, which he identifies as phlogiston.

Having presented the difficulties in the antiphlogistic theory, Hutton then addresses the criticisms that phlogiston does not appear in measurements of weight. For Hutton, this is not a problem because not all matter gravitates:

> the matter of heat differs essentially from the gravitating matter of a body, as acting upon another principle; . . . heat must be separable from a body, or variously dispersed and apportioned in bodies, while gravitating matter is, on the contrary, inseparable in its nature, or cannot be translated in the manner of light and heat.[22]

Hutton explains how we nevertheless detect the presence of phlogiston indirectly through the production and retaining of light.[23] Hutton's arguments about weight, here, are not *ad hoc*, as generally portrayed by Lavoisier. They are embedded in a theory of forces of attraction and repulsion, akin to a Newtonian theory of matter, and he discusses these notions more fully both in another part of the 1792 volume, `Physical Dissertations on the Powers of Matter and Appearances of Bodies', and in the 1794 dissertation (chapters 5 and 6).[24] Hutton is careful to distinguish, in particular, between sensible heat (which is felt), latent heat (which expresses itself as fluidity or elasticity), and `heat' or fire (which is stored materially in bodies and given off during burning).[25] He criticizes those who suppose that light and heat `cannot be material things, but only a modification of the substances concerned, or the motions or vibrations of the matter in those bodies'.[26] He cites phosphoretic bodies as evidence that light can be retained in bodies and later be emitted.[27] Phlogiston is `a peculiar substance different from any species of heat, a substance which does not gravitate' and which, therefore, is not detected when a balance is used.[28] Matters of phlogiston are distinct from matters of gravity. For us, crudely, energy and mass may be considered separately.[29] Hutton can thus hold both phlogistic and "anti-phlogistic" positions because he sees them as addressing separate problems or distinct variables.

Hutton then reflects on the reasons why some chemists disregard these conclusions. He sees them as preoccupied with weight considerations. The `admiration and contemplation' of the discovery by the balance of the composition of water has led them to the neglect the rest of the circumstances involved in Cavendish's experiment. By contrast, a true philosopher `considers the gravitating matter as a thing of little importance, compared with the wonderful production of light and heat'. While admitting the accuracy of their analysis, Hutton suggests that it nonetheless leads one astray:

> There may be no error in the explanation of phenomena, so far as regards their assumed principles; but the greatest when their principles should be considered as comprehending all the appearance.[30]

Hutton thus acknowledges the new discoveries, but insists that we must also fully explain the details of how of light and heat are produced in combustion.

Having considered the problem of heat and light from the perspective of their appearance during burning (the decomposition of phlogiston), Hutton shifts to the parallel problem of `composition': `the production of Inflammable Bodies', or how matter acquires the ability to generate light or heat. Most centrally, Hutton asks, how do plants obtain their phlogiston, or their ability to provide fuel for animal heat? It is not from the soil, he answers: the phlogiston-rich resinous fir grows even in sand. Nor does it come from the atmosphere, nor is it transfered from other bodies. Rather, plants must `generate it within themselves, by means of the materials they have received from without'.  In the process, they produce vital air, a fact `now verified, from that accurate investigation of the vegetable oeconomy, in relation to this subject, by M. Ingen-housz'. In other words, the process of composition in plants appropriately reverses their decomposition in almost every respect. Combustion (as in Cavendish's experiment) requires heat, in order to separate the phlogiston from its body; plants, by contrast, are cool (further proving that they do not take their phlogiston from other sources). In burning, bodies are dephlogisticated and their remaining material parts combined with each other; in the action of plants, compound bodies are separated, and one part is joined with phlogiston, or the matter of light.[31] Plants take the gravitating part of the hydrogenous principle from water, and release the remaining vital air. Also, to provide a material for the phlogistic substance, the `base' of fixed air must be separated its component vital air. That is, plants incorporate that part of coal or charred substances which later burns and combines with vital air to produce fixed air (carbon). Each of these materials (hydrogen, carbon) is united with phlogiston, forming two species of phlogistic bodies in plants, volatile and fixed (inflammable and combustible).[32] As material intermediates, they link the processes of composition and decomposition.

But even more significantly, the symmetries of phlogistic reactions reveal the critical role of light. Light is a consequence of burning, but it is a necessary contributing element in the composing operation of plants.

Upon examining accurately this subject, the growth of plants, we find, that, though

> vegetation proceeds in the dark, by means of heat and moisture, yet, no phlogistic substance is produced, in those living growing bodies, unless they are exposed to the light of day.

Hutton notes that Ingen-Housz showed this dramatically in his experiments, in which vital air is released precisely when the plants are exposed to light. Light becomes materially combined (`composed') in plants:

> It is the light of the sun which is stored up in the substance of vegetable bodies, as fixed light, or phlogiston, the principle of fire.[33]

Hutton has accordingly dubbed phlogiston the `solar substance' (or sometimes a variation of the solar substance).[34] The concept of stored light organizes our understanding of the balanced interactions of vital air, fixed air, inflammable air and water, with the generation of heat in combustion. And for Hutton, this is why (most centrally) we must preserve the concept of phlogiston.

In summary, then, Hutton addresses Cavendish's experiment in detail, `as this is the fundamental experiment upon which the antiphlogistic theory has been built'. But the case for phlogiston does not rest on that,

> because no theory whatever of heat explains the light emitted in the burning of bodies; nor any other theory, besides that of phlogiston, as thus explained, shows us the reason for the increase of plants or production of inflammable matter in those vegetating bodies.

He dismisses his adversaries with a metaphoric flourish:

> To leave out this term in a nomenclature of chymical properties . . . would be like a noxious use of the pruning knife, lopping off the bearing branches with the useless wood.

Banishing the concept of phlogiston is `a hasty conclusion, drawn from a narrow or imperfect view of things, although it is founded upon truly valuable discoveries'.[35] Hutton defends phlogiston because, as he tells us explicitly, it still explains certain observable phenomena that the anti-phlogistic theory cannot and that Hutton sees as important in understanding nature.

III. Cognitive Context

Articulating the empirical context of Hutton's arguments, of course, merely introduces a deeper contextual question: namely, why did Hutton seek so resolutely to explain light and heat? More broadly, why was Hutton concerned with phlogiston, whether for or against its existence? Why was he writing in the domain of heat and combustion at all? To understand Hutton's particular orientation, one must identify his `cognitive resources',[36] including his other theoretical commitments and philosophy of inquiry. For these, in turn, one must probe deeper into the context of his theology, intellectual development and biography. Together, the content of Hutton's geological theories, his methodology, and his professional development all establish a personal frame of reference which make further sense of why--and how--Hutton defended phlogiston.

In searching for conceptual foundations, of course, one ought not to disregard or dismiss Hutton's interests in chemistry itself. Though we often tend to view Hutton in terms of the geology that Lyell later made famous, recent examination of Hutton's non-geological writings has increased our awareness of Hutton's knowledge and familiarity with chemical matters.[37] As Donovan and Prentiss have nicely documented, it is proper to view Hutton just as Playfair described him in 1802: as `a good chemist', even apart from his geological work.[38] In fact, one may well view Hutton primarily as a chemist and only secondarily as a geologist.[39] In the current context, we may be especially impressed by Hutton's familiarity with the concepts of heat introduced and researched by Joseph Black, with whom Hutton maintained a close relationship. Throughout his writing Hutton is fluent in the concept of latent heat. He distinguishes between the latent heat of elasticity (gases) and the latent heat of fluid elasticity (liquids).[40] Understanding these concepts enabled him, for instance, as Playfair tells us, to invent the wet-dry hygrometer.[41] In one paper, Hutton railed against the `fallacious and unphilosophical' doctrine that one can change a substance's capacity for heat (`viz.

the difference of the specific heat of bodies, or the unequal quantities of heat contained in different substances, when their masses and temperatures are equal'). That is, he disagreed with those who contended that bodies absorb or emit heat by changes in heat capacity.[42] Hutton is clearly an expert on heat and his interest in phlogiston could well have emerged naturally from merely chemical concerns about understanding heat.

But one may find sources of Hutton's interest in heat in other contexts, as well. For example, the notion of heat was central in Hutton's geology. In his `Plutonist' theory of the earth, heat fused sediments into rock and then lifted those rocks from beneath the ocean to create mountains:[43]

> Fire, and the consumption of phlogistic substances, is a great and necessary operation in the oeconomy of this world. There is constant fire in the mineral regions;--fire which must consume the greatest quantities of fuel; the consolidation of loose materials, stratified at the bottom of the sea, depends upon the heat of that fire.[44]

Moreover, the mechanism of producing this subterranean fire was the main focus of contemporary attacks on Huttonian theory by Murray, Thomson, Kirwan, Deluc (all chemists), and others.[45] Thus, there was a theoretical (still scientific) need for Hutton to articulate a theory of subterranean heat, or of heat in general.

Heat also played another, supplemental role in Hutton's theory of the earth. The structure of Hutton's argument (both 1785 and 1795 versions) clearly invokes the formation of soil as an *a priori* problem.[46] Rain is central as an erosive element. But how does water evaporate and what produces rain?: heat, again. Here, Hutton's theory of the earth is integrated on another level with an original theory of rain, presented in the same (1792) volume which includes his defense of phlogiston.[47] Heat itself, however, remains unexplained.

Thirdly, heat was an important factor in plant growth. Hutton was no doubt sensitive to such factors from his experience in farming. For fifteen years (1753-1768) Hutton managed the farms he had inherited. He recorded his experience, including the effect of heat on plants, in a treatise on agriculture, though it remained unpublished when he died.[48] Contingent features of Hutton's biography thus contributed to the cognitive resources that Hutton brought to the problem of heat. Heat was clearly multiply important for Hutton as a geological, meterological and agricultural agent.

But a theoretical role for heat alone is not sufficient to explain why Hutton would have attempted to address it in more detail. One must see an intellectual framework which seeks to explain heat rather than to merely accept it *a priori*, or cast is as a problem for others to solve. Here, Hutton's philosophical approach emphasized the synergy of understanding both means and ends. Indeed, if one wants to make sense of the contradictory claims of Hutton as a great inductivist (e.g., Geikie, n. 3) and as an *a priori* natural theologian (e.g., Gould, n. 7), one must appreciate Hutton's view of robust explanation, in which separate explanations should complement each other using different (reductionistic and holistic) approaches. `The proper purpose of philosophy', he writes, `is to see the general order that is established among the different species of events, by which the whole of nature, and the wisdom of the system, is to be perceived', to find the `perfect adjustment of ends and means', `to trace the efficient as well as the final cause'.

> In taking this view of things, where ends and means are made the object of attention, we may hope to find a principle upon which the comparative importance of parts in the system of nature may be estimated, and also a rule for selecting the object of our enquiries. ... Under this direction, science may find a fit subject of investigation in every particular, ...and which without a proper attention to this character of the system, might appear anomalous and incomprehensible.

Fitting parts and wholes, or ends and means, together expresses an aesthetic:

> The contemplation of ends without means would add nothing to the value or lustre of human wisdom, and far less would the knowledge of means without ends. It must not appear idle speculation to discover the connection of efficient and final causes.[49]

Thus, Hutton had an intellectual framework that, given his other views, called on him to address mechanisms or efficient causes of heat.

But even further, the geological context introduced touchstones for what would constitute an adequate solution to the more general problem of heat. For Hutton, the answer to the problem of geological heat was simple: subterranean coal burned and produced heat for uplift. But one then needed to explain further how coal could burn where there was no atmosphere (what critics had focused on). It was essential for Hutton to seek alternatives to Lavoisier's claim that oxygen was absolutely necessary for combustion. When Hutton discussed how oxygen alone is not the cause of the light and heat emitted by burning coal, he was clearly constructing a model for the subterranean environment.[50] His attention to the sulphurating of metals, as well, highlighted his need to exclude oxygen from a theory of combustion. The basic form of Hutton's concept of phlogiston was thus shaped by the particular phenomena his theory of heat was called upon to explain.

All these concerns, however, were further shaped by Hutton's theology. For Hutton, the perpetual habitability of planet (for man's benefit) was a given end. But it was also an end whose means could be understood--or more appropriately, appreciated. Thus, Hutton's great geological cycles fundamentally explained the renewal of soil for planting crops. Likewise, Hutton was interested how, in `the wisdom of nature', food is replenished. In order for organisms to produce animal heat, their source of fuel, along with the means to burn it, must be renewed rather than merely be exhausted. Hutton therefore inquires as to how two substances, phlogiston and vital air, are conserved in the economy of the earth.

Hutton highlights the role of plants in this global cycle. He notes how the system of the earth is designed for plants, from the provision of soil to the falling of rain. Vegetation contributes to the life of man and other animals (as a final cause) by replenishing the deficits they leave. `Thus we are led to look for the source of phlogistic composition in the constitution of plants, for the growth of which the surface of this earth is so admirably contrived'. When plants transform foul air into vital air and compose phlogistic matter, therefore, they are serving a larger, more important function in balancing the action of animals and establishing a self-sustaining cycle.[51] Hutton, in fact, presents this context as a further argument for preserving the concept of phlogiston.

For Hutton, the theory of plant fuel is even more deeply entrenched in the economy of the earth. That is, the geological cycles, as well, must be fueled. The waste and replenishment of phlogiston, which poses a problem on the surface of the globe, poses an equivalent problem under the oceans, where heat is used continually to fuse, consolidate and lift rock. Hutton claims that this heat is also provided by plants, but indirectly in the form of coal:

> With regard to the composition of mineral coal, the theory is this. That inflammable, vegetable, and animal substances, in a subtilised state, had subsided in the sea, being mixed more or less with agrillaceous, calcareous, and other earthy substances in an impalpable state. Now the chymical analysis of fossil coal justifies that theory.[52]

Hutton's thinking thus leads him to a theory of `the production of coal from vegetable bodies, in which that phlogistic substance is originally produced'. The vegetable theory of coal is, once again, crucial, in understanding how the planet is sustained:

> According to my theory, the strata of this earth are composed of the materials which came from a former earth; particularly these combustible strata that contain plants which must have grown upon the land. Let us then suppose the subterraneous fire supplied with its combustible materials from this source, the vegetable bodies growing upon the surface of the land. Here is a source provided for the supplying of mineral fire, a source which is inexhaustible or unlimited, unless we are to circumscribe it with regard to time, and the necessary ingredients; such as the matter of light, carbonic matter, and the hydrogenous principle.[53]

In other words, coal will be produced so long as the geological cycles themselves operate, and so long as plants have sunlight, fixed air and water. One can see that the "coal cycle" is as important as the soil, rain or food/oxygen cycles in nature, especially in terms of Hutton's philosophy:

> Thus the wonderful constitution of light and heat, . . . may be traced through many

> processes in the wise oeconomy of nature, or in the system of this world, where ends and means are the proper subjects of our science.[54]

Indirectly, then, a theory of heat and combustion for Hutton had to be also simultaneously a theory of coal. Once again, the cognitive context for a theory of heat helped to shape what observational content would be considered relevant.

Finally, one may note Hutton's attitudes towards light and heat themselves. Hutton expresses his admiration and wonder:

> Among all the sensible qualities of bodies, there is none more wonderful than the production of light by inflammation, of the power of bodies to give light. This operation, however, by having always been familiar, seems not to raise in our minds that admiration which the subject merits, and which upon reflection, it cannot fail to excite. . . . [Our] curiosity is excited . . . [and] the intellect gratified to enquire [into] . . . this wonderful substance, which in a manner animates all sublunary things.

Thus:

> No subject is more interesting to the natural philosopher than is that of fire.[55]

In his M.D. dissertation, Hutton commented that the principle of sulfur, `the matter of fire and light which pervades everything' (XXXI), `enjoys a nature and properties which are more distinctive than the others' (the principles of earth, salt, spirit, and water or phlegm; XXX). His judgement is based on the dual role of heat in animal life (the flammable matter `serves the blood to advantage'; XXXIV) and also in the planet's habitability:

> Here we have more in view, besides the establishing of a simple fact, or a scientific truth; we have a desire to contemplate the oeconomy of nature, and to observe the admirable contrivance of the system in which we are placed. This is most evidently displayed in the various uses of light and heat, of vital air and water, the study of which will give ample range, and the highest satisfaction, to those who take pleasure in enlarging and improving our knowledge of nature.

`Next after the life of animals and growth of plants, the most wonderful and the most important operation of this earth, is the burning of fire, and the production of light'. Therefore (recalling, once again, his philosophy), Hutton prefaces the 1792 work, extolling the interconnected virtues of light and science:

> What an object then for science, to perceive the means employed by nature in procuring fire, the source of sublunary light and heat! What an object for natural philosophy to understand the intention of nature, in giving an atmosphere to the earth! If rain, which is so necessary to vegetable productions, and if fire, which is so necessary to animal life and the internal constitution of this earth, have such an intimate connection with the atmosphere of the globe, it is surely an object for the philosopher, to trace the chymical process of nature by which so many important operations are performed.[56]

For Hutton, light and heat drive the natural economy and life itself and thus they form the proper focal point of any scientific investigation or philosophy.

Hutton, as a chemist, geologist, meteorologist, farmer, philosopher of knowledge, theologian, and natural philosopher, had reasons for addressing issues of heat and light in his dissertations on phlogiston. His cognitive resources, shaped biographically, of course, do not explain directly why Hutton would have held any one position on phlogiston. But they do explain what categories of phenomena were conceptually significant or relevant and thereby determined what a complete theory of heat must ultimately have explained. The cognitive and observational contexts coupled together, then, jointly explain the defense of phlogiston from the perspective of Hutton as an individual.

IV. Disciplinary Context

Of course, Hutton's position must also be considered in the context of other contemporary chemists. Was Hutton unique for the time or did he reflect more widespread patterns of thinking? Hutton's cognitive context certainly suggests how some observations could be selected as key from among all those publicly available. But this by itself does not guarantee that others with different intellectual orientations or cognitive resources would have focused on or perceived these same phenomena in a similar way. Indeed, Hutton's own criticisms of those philosophers `who, with the balance in their hands' became preoccupied with weight, certainly suggests diverging aims. Here, one may use Hutton as a focal point or `type specimen' for analyzing the discipline, construed as the community of contemporary thinkers addressing the same topic.[57] By searching for resonances with Hutton, we can understand what his particular arguments reveal about the period. In fact, Hutton was not an isolated case.[58]

The most provocative aspect of Hutton's position, perhaps, was how he accepted both the new discoveries and existing doctrines. Lavoisier claimed to have brought about a revolution in chemistry, to have completely replaced one system by another.[59] Many participants in the debate also polarized the theoretical positions, exemplified, for instance, in the recurring "antiphlogistic" label. Chemists clearly argued for, and sometimes renounced, one stance in direct contrast to the other (e.g., Van Marum, Fourcroy). Nonetheless, others--Crell and Trommsdorf, for example--found the two systems compatible.[60] Some felt that they had satisfactorily reconciled or, like Hutton, split the explanatory roles of the "competing" systems. Jean Senebier, for example, urged in 1787 that both the old and new theories be preserved as complementary:

> La nouvelle doctrine me paroit l'appui & le complément de l'ancienne.[61]

More specifically, there were those who admitted the existence of oxygen as a distinct gaseous element and, like Hutton, used its name along with `phlogiston'.[62] In a parallel way, some borrowed the new system's concept of caloric while also using some variation of the phlogiston concept.[63] Though we tend to simplify the issue to one dimension (as many of the time did), the "opposing" views did not necessarily represent an "either-or" dichotomy. Senebier's comment, in particular, reinforces Hutton's interpretation that despite disagreements on certain issues, the two positions could coexist. Attention to the disciplinary context of Hutton's ideas thrusts these shared views into the foreground and casts doubt on at least Lavoisier's assertion that the new theory conceptually replaced an older chemistry.

Traditionally, discussions of the role of phlogiston in the Chemical Revolution focus on the problem of negative weight or on the composition of water.[64] Indeed, such issues were critical--at least for advocates of the new nomenclature. But while these elements of the controversy were important, as Hutton admits, they were not the only ones. For some, the new claims about oxygen or the weight of reactants and products were not controversial at all. Rather, many of Lavoisier critic's shared Hutton's concern that heat, light, or both were not well explained in the new system. This is particularly well documented by Partington and McKie, who cite a variety of critics ranging from 1775 to 1802 and working in the English, French and German communities.[65] Gadolin, in particular, echoed Hutton's sentiments well:

> Phlogiston, which is without weight, is the same as the matter of light. . . . I am true to the old theory of phlogiston or the combustible principle.[66]

Black's thoughts are particularly noteworthy, because he is regarded as one of the early converts to the new nomenclature, and because he and Hutton frequently shared thoughts. Black wrote to a former student in 1791 about his initial reluctance and his later acceptance of the French theory, then qualified his support, noting that `it must be confessed that it takes almost no notice of light'. Black's position was also recorded in lecture notes: `Mr. Lavoisier's system did not explain the light which is so characteristic of combustion'.[67] Black's "acceptance" was clearly limited, and ended precisely where light was concerned. Again, Hutton's position helps highlight how light and heat were significant for other chemists in the same period who advocated the existence of phlogiston.

Among the issues left outstanding was the relationship of phlogiston to electricity. Hutton viewed electricity, like phlogiston, as a `modification of the solar substance'. He considered its close relationship with light, heat, and fire in 1794:

> In electricity we perceive a moving cause for matter of the same kind as that which moves in light.
>
> In the violent exertions of this fluid to restore an equilibrium which had been greatly violated, we find appearances which may be generalized with those of fire. . . . In the case of being conducted through an opake body, it exhibits the appearance of heating the body from the lowest to the highest degree of incandescence. . . . When electricity is made to leap from one conducting body to another, through the rarest space . . . incapable of being heated, . . . electricity is immediately converted into light. . . . Consequently, there is reason to conclude, that the conversion of electricity, into the appearances of fire, is made upon the same principle as that by which bodies are burned.[68]

That is, electricity could be converted into heat or light, just as the decomposition of phlogiston produced fire. Explanations of light or heat and electricity were essentially linked. Hutton was not alone in postulating such relationships. The electric fluid was equated with phlogiston by Senebier, Leslie, Drew, Elliott and others. For Gren, phlogiston was only present <u>in</u> electric matter. Peart classified light, fire and electricity as similar, being combinations of phlogiston and aether. Weber, on the other hand, considered phlogiston a combination of electrical matter and earth. Marchand claimed a negatively electrified body contained phlogiston, while the positively electrified body contained fire (not to be confused with light!). When electrolysis and the Voltaic pile appeared, they provided additional material for consideration. Gibbes suggested that `the principle of the negative side of the galvanic apparatus' was phlogiston, and when joined with water (as in electrolysis), it would form inflammable air.[69] No single model of electricity, light and heat held consensus, but many drew on the existing concept of phlogiston. Clearly, Lavoisier had not resolved concerns about problems of energy, or of electricity in particular, problems that seemed better suited by many to the phlogistic schema.

Hutton was also unlike his contemporaries in several respects. First, Hutton seems unusual in stressing the role of phlogiston in the natural economy (and what we would call energy flow through the ecosystem). His unique theological concerns thus broadened his awareness to the wider contexts of combustion (not merely its mechanisms) and, especially, to the reverse reactions involving the `composition' of phlogiston. Similarly, Hutton focused on the source of coal's combustibility. Hutton was not the first to suggest the vegetable nature of buried fuels (e.g., Bergman prior to 1783), or the sun as a source of phlogiston (e.g., Leslie in 1778) but he seems to be original in viewing coal as containing a direct transformation of sunlight (phlogiston as the `solar substance'). Finally, Hutton seems to have anticipated the discipline in fully appreciating the alternative role of sulfur in combustion, not recognized more generally until after the turn of the century.[70] The distinguishing features of Hutton's arguments, though congruent with the more common mentions of light, heat and electricity, indicate more fully how the concept of phlogiston might have developed further. Any complete account of the dynamics of the Chemical Revolution must consider the potential of these alternative lineages.

Some chemists, of course, supported phlogiston for other reasons. Those like Priestley, Cavendish and Kirwan, however, who equated phlogiston with some form of gas, were inevitably led into awkward (if not locally inconsistent) theoretical constructions. Yet while they were prominent in debate, theirs was not the exclusive view of phlogiston, nor one as much in accord with the Stahlian roots of the concept linking calcination and reduction. Those who pursued the concept of phlogiston as relating chemical reactions to light, heat, electricity and phosphoresence, by contrast, did not encounter the problematic configurations generated by the identity of oxygen. Hutton's defense, though not influential as far as we can tell, nevertheless serves as an important historical benchmark, neatly capturing this second set of arguments.

How, then, are we to interpret Lavoisier's achievement and the controversy that surrounded it? From an epistemic perspective, the question is not whether one doctrine was "right" and the other "wrong," but how (or where or when) each could be construed as well-founded. We need, in particular, to articulate how thinking via either phlogiston or oxygen was appropriately associated with certain empirical domains, or applied within certain boundaries or ranges of phenomena. Combustion, of course, was explained by both conceptual schemes and became a locus of contention. But combustion was also not the only phenomenon explained by each. Lavoisier, through the concept of oxygen, related buring to acidification and weight relationships. Others, as just noted, related it to electricity, light, coal or phosphorescence. Debate arose specifically where the two systems of interpretation overlapped or converged. Neither theory could simultaneously accomodate the concerns of the other adequately. For Hutton, remember, the gravitating matter was a thing `of little importance' compared with the `wonderful' production of light and heat: weight reveal nothing interesting about the appearance of flames. Lavoisier and his followers, on the other hand, were impressed by the conservation of mass in chemical processes, especially involving gases. All imponderables, such as heat and light, were eclipsed from their realm of consideration.[71] More clearly discerned, then, combustion did not receive two conflicting explanations, but rather two types of explanations, or solutions to two different sets of problems. As Hutton noted, one was based on weight, the other basically on light (or, for us, energy). This distinction, though crude (it disregards, for example, questions of acidification, nomenclature and calorimetry[72]), focuses historical attention on the divisions of theoretical knowledge, or how Lavoisier reorganized `discursive formations'.[73] Lavoisier, again, may not have replaced an old system, as implied by Herschel and his successors, so much as provided an additional--and ultimately quite productive--way of looking at an otherwise familiar phenomena. The view suggested here is that the change in the discipline may best be framed, not as linear replacement, but as the differentation or partitioning of separate, overlapping lineages that had converged unexpectedly.

V. Synthesis of Contexts and Conclusions

Hutton's observational, cognitive, and disciplinary contexts jointly explain why Hutton defended phlogiston. First, Hutton's claims were grounded in observations. Despite his personal motivations or theological goals, Hutton appealed to empirical phenomena. Hutton could appeal to numerous observations not adequately explained by the "antiphlogistonists": ignition, the generation of light and heat, combustion with sulfur, the origin of combustible material in plants and coal, and, more generally, the storing of energy in material (chemical) form. Why did Hutton defend the doctrine of phlogiston? Observationally, for good reasons. Hutton identified systematic deficiencies in the new theory viewed as an alternative or substitute to phlogiston.

What gives depth to Hutton's story is the context or reasons in which his perspective makes sense. Hutton's position grew out of his personal intellectual history or cognitive orientation. He attended to the role of circulation and cycles (his M.D. work) and later was concerned (largely theologically) with the global equilibrium (producing rain, soil, food, and coal). He had a background in chemistry, enhanced by his relationship with Black, from whom he gained familiarity with the concept of latent heat. His interests in geological uplift, rain, and farming, each gave heat a prominent role, while his philosophical orientation dictated that he understand the mechanism or means of its production more fully. Heat and light were central, and his strong motivation to explain them reflects that. Why did Hutton defend the doctrine of phlogiston? Cognitively (biographically, psychologically) because his individual intellectual resources (including but extending well beyond his geology) circumscribed what observations he considered relevant. The context in which he addressed the issue of heat framed the problems in specific ways and gave certain aspects central significance. Hutton's particular constellation of experiences established the basis for a complementary theoretic position.

One may appreciate especially how understanding Hutton's position on phlogiston brings with it a deeper understanding of Hutton more generally. Exploring the foundations of his defenses sometimes takes one far afield from chemistry, into geology, meteorology, agriculture, and philosophy--and shows how for Hutton they were all interconnected. In particular, we can see more clearly how his renowned geological work and theory of the earth fit as merely one element among many, all part of the natural economy, with its theological significance. The central role of light and heat, and Hutton's near obsession with explaining them, highlights the basic motivations that seem to permeate Hutton's thinking. Thus, while the pair of dissertations on phlogiston may seem peripheral in a casual glance of Hutton's work, in fact, they serve as valuable focal points for integrating his life and overall thinking.

Finally, Hutton's position was related conceptually to his contemporaries. Both Hutton and Lavoisier, for instance, were concerned with combustion. Lavoisier (as Hutton pointed out) was concerned with the gravitating matter of bodies. Hutton, on the other hand--like Black, Gren, Gadolin, Gibbes, and others in the discipline--focused on light, heat, and even electricity, or what Hutton collectively called the `solar substance'. Hutton could thus accept the concept of oxygen, while simultaneously dismissing it as insignificant. Though proponents of the new system and their critics shared some common concerns, they also diverged on what observations they deemed relevant. Why did Hutton (and others) support phlogiston? Disciplinarily, because it addressed a set of problems that Lavoisier's theory did not. Hutton epitomized those chemists who wanted primarily to explain energy-related phenomena.

Understanding Hutton's works on phlogiston thus leads, more broadly, to an historical approach to phlogiston after Lavoisier. Brown, for example, considered (in 1864) that phlogiston anticipated the concept of potential energy: `there can be no doubt that this is what the chemists of the seventeenth [sic] century meant when they spoke of phlogiston'.[74] His tone was decidedly Whiggish, but still suggestive. Odling extended Brown's argument in evaluating Lavoisier and the events of the previous century:

> . . . the truth which he established, alike with that he subverted, is now recognizable as partial truth only; and the merit of his generalization is now perceived to consist in its addition to--its demerit to consist in its suppression of--the not less grand generalization established by his scarcely remembered predecessors. . . . Accordingly, the phlogistic theory and antiphlogistic theory are in reality complementary and not, as suggested by their names and usually maintained, antagonistic to one another.[75]

Hutton's defense of phlogiston richly articulates this view and thus strengthens Odling's implicit invitation to acknowledge the positive role of phlogistic theory even through the Chemical Revolution.

Appendix: Historiographic Methods

It is conventional among scientists, though not yet among historians, to document their `Materials and Methods' when presenting the results of their research. Recent debates among historians, as well as philosophers and sociologists of science, however, suggest the critical importance of one's interpretive models.[76] Here, in a more reflexive mode (advocated by some sociologists[77]), I strive to acknowledge the types of concerns that characterized my orientation, guided this study, and shaped its findings.

As stated in the introduction, I use several contexts of analysis--observational, cognitive and disciplinary. These interpretive contexts complement one another (and, I would contend, all are necessary and equally important in a complete and informative interpretation). One may note, in fact, how the conclusions here emerge only through the use of multiple frames of analysis. If one were to focus on the empirical alone, one would understand how evidence for phlogiston was assembled, but not why individual problem frames differed or why there was disagreement and controversy. If one were to focus on the cognitive alone, one could trace how Hutton's conceptual position developed, but one would miss the disciplinary scope of his objections and how they were based on more than mere personal contigency. If one were, finally, to concentrate on the disciplinary (social) context alone, one would see the diversity of views, but might omit the empirical support for individual variants and fail to appreciate why certain persons dissented and what that implies epistemically. Collectively, however, the interlocking contexts imply a penetrating, cohesive view in which Hutton defended phlogiston for good empirical reasons, reasons also shaped by his personal experience. Further, he shared concerns with others, indicating a thread of dissent about the extent of Lavoisier's achievements. This fuller, richer historical understanding emerges only through integrating interpretive contexts.

The notion of `cognitive resorces', introduced by Giere (see footnote 36), is particularly important here. Hutton's case nicely illustrates how a layer of selective interpretation functions between publicly available observations and the equally public debate. Each individual position, even in social discourse, is mediated and shaped by personal experience. The cognitive framework allows one to articulate how an individual becomes aware of, accesses, and interprets--all in a particular style--what is otherwise "objective." While a biographical or intellectual perspective is hardly novel historiographically, the concept of cognitive resources emphasizes more clearly the important epistemic link between the empirical and the disciplinary.[78] As a bridge, the framework of cognitive resources facilitates how we integrate alternative interpretive contexts.

More deeply, this study has been guided by a principle of empirical symmetry. Barnes, Bloor and others in the Strong Programme in the sociology of science have claimed that we must explain beliefs `symmetrically': that is, both "true" and "false" beliefs must be explained according the same set of principles.[79] They challenge those who, traditionally, give empirical reasons for beliefs in ideas now accepted as correct, and sociological (or psychological) reasons for beliefs we regard as erroneous. Sociologists, of course, claim that both true and false beliefs must be explained sociologically (sociological symmetry). While not disagreeing with their claim, I hold that one must also follow a principle of empirical symmetry: we must search for the empirical reasons supporting both true and false ideas. That is, we must show how false ideas may be warranted *empirically*. Thus, though we typically regard the concept of phlogiston as mistaken, a complete historical account must articulate the empirical evidence given in its support and the context in which this evidence made sense.

The principle of empirical symmetry parallels a further notion one may call `reverse whiggism'. If whiggism, normally construed, is a linear account of the past biased by the present status of knowledge, then `reverse whiggism' is an account of a future lineage (or subsequent events) biased by a former status of knowledge. That is, in this view one is encouraged to look at the outcome of the Chemical Revolution from the perspective of those earlier in the century, particularly by tracing the fate of the now discredited concept of phlogiston. How do mid-18th-century conceptual commitments bias the story or, alternatively, reveal something that might be suppressed by the backwards-looking approach? If one must unavoidably compose a narrative from some temporal perspective, then an antedated viewpoint is surely as legitimate and potentially informative as any other. The historiographic task of being sympathetic or sensitive to one's given period and using one's historical imagination to reconstruct contemporary views, is expanded to include constructing dated interpretations of history that followed. In this study, phlogiston is not merely justified in the context of the time frame during which we know it was widely accepted, but is considered in a context of later alternative beliefs. Reverse whiggism as an interpretive tool not only highlighted Hutton's dissertations on phlogiston as a potentially fruitful locus of research, but also guided an interpretation that, in this case, enriches our view of the epistemic role of phlogiston through the Chemical Revolution.

Notes

1. James Hutton, `A Chymical Dissertation concerning Phlogiston, or the Principle of Fire', in Dissertations on Different Subjects in Natural Philosophy (Edinburgh, 1792), Part II; Dissertation on the Philosophy of Light, Heat, and Fire (Edinburgh, 1794). The 1794 work is abstracted in Transactions of the Royal Society, Edinburgh, 3(1796, History), 7-16.

   I am primarily concerned here with the content of the publications, but one may briefly note the occasions for their publication. Indeed, the two works occupy significant positions in Hutton's publication history. The 1792 dissertation was his first treatise following his 1788 "Theory of the Earth" (presented to the Royal Society of Edinburgh in 1785). The 1794 volume, adding to his argument only two years later, reaffirms the prominence of phlogiston for Hutton.

   Hutton first presented most of the content of the 1792 work in two sessions before the Royal Society of Edinburgh, May 5 and 12, 1788, though Playfair (see footnote 37) believed the dissertation was in manuscript `probably by 1781' (p. 74 fn.). Hutton was responding to Sir James Hall, who had presented `A View of M. Lavoisier's new Theory of Chemistry' to the Society (February-April, 1788), Hall having been converted to the new system in a recent visit to Paris. Hutton later presented an additional segment on March 7, 1791.

   One may note that the first dissertation was not published separately, but rather in a volume with his `Meteorological Dissertation on Rain and Wind' (presented to the Royal Society, Edin., in 1784) and `Physical Dissertations on the Powers of Matter and Appearance of Bodies'. The concept of latent heat was significant to Hutton's arguments in all three dissertations--and, indeed, we find the volume dedicated to Joseph Black, in public acknowledgement of his discovery of latent heat (see also `Cognitive Context' below). Accounts by Robison, Black's friend and successor at Edinburgh University, suggest that both Black and Hutton were concerned over credit and priority for Black's discovery, especially at this time, when Black's letter on supporting the new nomenclature had been solicited and published in the Annales de Chimie (see William Ramsay, Life and Letters of Joseph Black, M.D. (London, 1918), pp. 94-96; and Eric Robinson and Douglas McKie, Partners in Science: Letters of James Watt and Joseph Black (London, 1970), p. 337).

The 1794 work was prompted, Hutton tells us, by experiments by Saussure on transmission of heat by reflection and by Pictet on the apparent reflection of cold. Each raised further questions about the relationship of light and heat in how phlogiston was emitted from bodies.

2. For some current assessments, see Arthur Donovan, ed., The Chemical Revolution: Essays in Reinterpretation, Osiris 4(1988); Bulletin for the History of Chemistry, 5(1989); and C. E. Perrin, "The Chemical Revolution: Shifts in Guiding Assumptions," in Scrutinizing Science: Empirical Studies of Scientific Change, edited by Arthur Donovan, Larry Laudan and Rachel Laudan (Dordrecht, 1988), pp. 105-124.
3. e.g., Archibald Giekie, Founders of Geology (London, 1897, 1905); E.B. Bailey, James Hutton: The Founder of Modern Geology (Amsterdam, 1967).
4. e.g., Arthur Donovan, `James Hutton, Joseph Black and the Chemical Theory of Heat', Ambix, 25(1978), 176-190; and Patsy A. Gerstner, `James Hutton's Theory of the Earth and His Theory of Matter', Isis, 59(1968), 26-31.
5. Arthur Donovan and Joseph Prentiss, `James Hutton's Medical Dissertation', Transactions of the American Philosophical Society, 70, No. 6 (1980).
6. Hutton's biographers (see footnote 3) give these works little notice. Bailey devotes a modest page and a half to summarizing them. Giekie, as if to avoid embarassment by association with phlogiston, excludes mention of them entirely.
7. The signigicance of cycles have been previously noted by Bailey (footnote 3, pp.61-62), who called them `physiological cycles'; Donovan and Prentiss, "M.D. Dissertation" (footnote 5); and Stephen Jay Gould, Time's Arrow, Time's Cycle (Cambridge, Mass., 1987).
8. J. R. Partington and Douglas McKie, `Historical Studies on the Phlogiston Theory. I-IV'. Annals of Science 2(1937), 361-404; 3(1938), 1-38, 336-371; 4(1939), 113-149. Discussion of Hutton appears in Part III, pp. 366-370.
9. Hutton, 1794 Abstract (footnote 1), p. 12; `Phlogiston', p. 193.
10. Alexander Crum Brown, `Note on phlogistic theory', Proceedings of the Royal Society of Edinburgh, 5, Part V (1866), 328-330. John F. W. Herschel, `A Preliminary Discourse on the Study of Natural Philosophy' (1830), reprinted with a foreword by Arthur Fine (Chicago, 1987), pp. 300-301. For similar views on replacement, see James Bryant Conant, `The Overthrow of the Phlogiston Theory: The Chemical Revolution of 1775-1789', in Harvard Case Histories in Experimental Science, 2 vols (Cambridge, Mass., 1957), I, 65-115; H. Gilman McCann, Chemistry Transformed (Norwood, New Jersey, 1978); Colin A. Ronan, Science: Its History and Development Among the World Cultures (New York, 1982), p. 389; I. Bernard Cohen, Revolutions in Science (Cambridge, Mass., 1985), p. 231; Leonard C. Bruno, The Tradition of Science (Washington, D.C., 1987), p. 185; Robert Siegfried, `Lavoisier and the Phlogistic Connection', Ambix, 36(1989), 31-40; F. L. Holmes, Eighteenth Century Chemistry as an Investigative Enterprise (Berkeley: Univ. of California Office for History of Science and Technology, 1989), on pp. 108, 110, 111; E. M. Melhado, `Toward an Understanding of the Chemical Revolution', Knowledge in Society, 8(1989), 123-27; William A. Smeaton, `The Legacy of Lavoisier', Bulletin for the History of Chemistry, 5(1989), 4-10, (p. 5); Robert Siegfried, `Lavoisier and the Conservation of Weight Principle', Bulletin for the History of Chemistry, 5(1989), 18-24, (p. 18); Arthur Donovan, `Lavoisier as Chemist

and Experimental Physicist: A Reply to Perrin', Isis, 81(1990), 270-72, (p. 272); Paul Thagard, `The Conceptual Structure of the Chemical Revolution', Philosophy of Science, 57(1990), 183-209, (pp. 184, 201).

11. Hutton's concept of phlogiston is standard. He characterizes it as the principle of combustibility, which is used non-renewably in burning and can be transferred from one body to another (`Phlogiston', §§1.10, 4.11). But see also below for Hutton's more sophisticated theory of matter.
12. One may note the obvious parallels in the structure of the argument with Hutton's 1788 `Theory of the Earth', in which the `composition' and `dissolution' of rocks are considered in turn. To someone like Hutton who valued deep analogies, this correspondence cannot be accidental.
13. Hutton, `Phlogiston', p. 173.
14. Hutton, Light, Heat, and Fire, p. 326. It should be noted that Hutton's concerns included language. This is exemplified in his `Dissertation on Written Language as a Sign of Speech', read before the Royal Society of Edinburgh in June, July and November, 1786 (Trans. Roy. Soc. Edin. 2(1788), 5-15).
15. Hutton, Light, Heat, and Fire, pp. 153-154. Hutton's use of terms from the new nomenclature obviously complements the specificity of his criticism in this passage.
16. Hutton, `Phlogiston', §2.6.
17. Donovan (footnote 4, p. 187) notes that all Scottish chemists tended to interpret caloric as latent heat. See also Arthur Donovan, `Scottish Responses to the New Chemistry of Lavoisier', Studies in Eighteenth-Century Culture 9(1979), 237-249.
18. Hutton, `Phlogiston', §§1.4., 2.5.; Hutton, Light, Heat, and Fire, p. xvii.
19. Hutton, `Phlogiston', §§2.10-13.
20. Hutton, `Phlogiston', §§2.8-2.9.; Light, Heat, and Fire, pp. 198, 232.
21. Partington and McKie (footnote 8), Part IV (p. 135). Hutton, `Phlogiston', §2.10; idem, "An Examination of a New Phenomenon which occurs in the sulpherating of Metals," read before the Royal Society of Edinburgh, May 9, 1796. An abstract appears in Trans. Roy. Soc. Edin., 4(1798, History), 27-36 (excerpt is from p. 33).
22. Hutton, Light, Heat, and Fire, p. 133.
23. Hutton, `Phlogiston', §§2.16, 2.18, 2.21.
24. Hutton, `Physical Dissertations on the Powers of Matter and Appearances of Bodies', Subjs. Nat. Phil. (footnote 1), Part III. Hutton followed a tradition of Newtonian theories of matter in the eighteenth century. See Marie Boas, Critical Problems in the History of Science (History of Science Society, 1957); and Gerstner (footnote 4).
25. `Whilst heat has a sensible effect upon the weight of bodies, the solar substance, or matter of light, which is in the modification of phlogiston, would appear to have no such effect' (Light, Heat, and Fire, p. 254). `Fixed light, or a peculiar modification of the solar substance, . . . then is a distinct modification, different from those of heat, or light, or electricity. Hence we obtain a theory of burning bodies, or a principle of fire, distinctly different from that of heat' (p. 229).
26. Hutton, `Phlogiston', §2.16.
27. Ibid., §2.21; Hutton, `Powers of Matter' (footnote 24), pp. 516-521, 614-621.
28. Hutton, `Phlogiston', p. 240.

29. This characterization, though hinting of Whiggish charity, gains even more depth when one considers how Hutton and many of his contemporaries viewed the relationship between phlogiston and electricity (see `Disciplinary Context' below).
30. Hutton, `Phlogiston', pp. 180, 204-205, 207.
31. Ibid., §§3.16, 4.14, 4.16.
32. Ibid., §§4.16-17. See also Hutton, Theory of the Earth, 2 vols (Edinburgh, 1795), I, 607-608, 612.
33. Hutton, Light, Heat, and Fire, p. 322; `Phlogiston', §§3.18-23. See also John Ingen-Housz, Experiments upon Vegetables (London, 1779).
34. e.g., Hutton, `Phlogiston', p. 215. One may briefly note Hutton's view of the relationship between light and heat here. Heat, for Hutton, cannot be converted into light. Thus he criticizes views that calorique, understood as a form of heat, can explain the generation of light. Light, however, can be converted into heat, as frequently occurs when the `solar substance' is burned. He identifies the radiant heat in the reflecting experiments of Saussure and Pictet, for example, as a form of light. The 1794 dissertation is structured to argue this point. See also Masao Watanabe, `James Hutton's Obscure Light', Japanese Studies in the History of Science, 17(1978), 97-104.
35. Hutton, `Phlogiston', pp. 182, 246, 210-211, 178-179.
36. Ron Giere, Explaining Science: A Cognitive Approach (Chicago, 1988), esp. pp. 213-14, 240-41.
37. See footnote 4. In addition, one may note that John Playfair commented in his biography that Hutton was the first to find mineral alkali: `On boiling the gelatinous substance obtained from combining [zeolite] with muriatic acid, he found that, after evaporation, sea salt was formed' (`Biographical Account of the late Dr. James Hutton, F. R. S. Edin.', Trans. Roy. Soc. Edin., 5(1802, Part 3), 39-99 (p. 47). Also, Hutton's theory of rain, though today only able to explain the condensation of breath and certain types of fog, was firmly based on principles of vapor pressures at different temperatures (William Middleton, History of the Theories of Rain, New York, 1966).
38. Donovan and Prentiss (footnote 5); Playfair (footnote 37).
39. Hutton's introduction to science was through chemistry at Edinburgh University. At his first job (in 1743), according to Playfair (n. 37), he `was often found amusing himself and his fellow apprentices with chemical experiments, when he should have been copying papers, or studying the forms of legal proceedings'. Hutton's geological interests developed later, against this background early in his agricultural career, around 1753. Donovan (footnote 4) further presents the case that Hutton's notions about the consolidation of strata grew out of an interest in the chemical puzzle of fusing limestone.
40. One may return, once again, to Hutton's M.D. dissertation (footnote 5) for a hint of his early interests in this problem. There he confronted the problem of the elasticity of the air and how it became fixed in the blood (Sect. XXXVIII).
41. Playfair (footnote 37), p. 67fn. (The hygrometer was later also developed by Leslie).
42. Hutton, `Sulpherating' (footnote 21), 33-34.
43. The alternative theory on the formation of rock at the time was the Wernerian, or `Neptunian', doctrine. It claimed that rocks were the chemical or particulate precipitate from a solution, the ocean, which at one point covered the globe. Any theory needed to explain how rocks in an original fluid state flowed, say, in the formation of mineral veins.

The debate, here, was largely between water and heat as sources of this fluidity.

44. Hutton, Light, Heat, and Fire, pp. 320-321.
45. John Murray, A Comparative View of the Huttonian and Neptunian Systems of Geology (Edinburgh, 1802). For accounts of Thomson, Kirwan and Deluc, see Patsy A. Gerstner, `The Reaction to James Hutton's Use of Heat as a Geological Agent', British Jounral of the History of Science, 5(1971), 353-362.
46. See Gould (footnote 7).
47. James Hutton, `The Theory of Rain', Trans. Roy. Soc. Edin., 1(1788), 41-86, reprinted and expanded with the dissertation on phlogiston in Hutton, Subjs. Nat. Phil. (footnote 1), Part I, pp. 1-168.
48. Playfair (footnote 37), p. 87; Edward B. Bailey, "James Hutton, Founder of Modern Geology," Proc. Roy. Soc. Edin. 63(B), 357-68 (p. 360).
49. Hutton, `Phlogiston', p. 261; `Theory of the Earth', Trans. Roy. Soc. Edin. 1(1788), Section 1 (Physical Sciences), 209-304 (p. 210).
50. Hutton, Light, Heat, and Fire, pp. 156-70.
51. Hutton, Light, Heat, and Fire, p. 322; `Phlogiston', §§3.8, 3.12-15.
52. Hutton, Theory of the Earth (footnote 32), I, 586. Hutton uses other observations as well to argue for the vegetable origin of coal, including the impression of plants in related strata and in English clod coal, and an analogy with fossil wood and peat mosses under compression (pp. 588-589). For Hutton's argument on the role of coal in uplift, see pp. 599-600.
53. Ibid., pp. 612, 243.
54. Hutton, Light, Heat, and Fire, pp. 305-306.
55. Hutton, `Phlogiston', p. 174; Light, Heat and Fire, p. 143.
56. Hutton, `Phlogiston', pp. 233, vi-vii.
57. See David Hull, `Darwinism as a Historical Entity: A Historiogrpahic Proposal', in The Darwinian Heritage, edited by David Kohn (Princeton, 1985), 773-812, (pp. 781-84); James Griesemer and William C. Wimsatt, `Picturing Wiesmannism: A Case Study of Conceptual Evolution', in What the Philosophy of Biology Is, edited by Michael Ruse (Boston, 1989), 75-137; Douglas Allchin, `Resolving Disagreement in Science: The Ox-Phos Controversy, 1961-1977', unpublished Ph.D. dissertation, Univeristy of Chicago, 1991), pp. 44-45, 59-63.
58. The status of the discipline is elaborated more fully in Douglas Allchin, `Phlogiston After Oxygen', Ambix 39(1992), 110-116.
59. Few historians have challenged the image of the change as conceptual replacement (see footnote 10), though many now doubt the suddenness of that change (e.g., J.B. Gough, `Lavoisier and the Fulfillment of the Stahlian Revolution', Osiris 4(1988), 15-33; C.E. Perrin, `Research Traditions, Lavoisier, and the Chemical Revolution', Osiris, 4(1988), 53-81; John G. McEvoy, `Continuity and Discontinuity in the Chemical Revolution', Osiris, 4(1988), 195-213).
60. See Partington and McKie (footnote 8), Part II, 3; and Part IV. For Crell, see pp. 144-145; Trommsdorf, pp. 135-136.
61. Ibid., Part III, p. 123, n. 89.
62. Ibid., Part IV. These include: Johann Gadolin, (see pp. 125-126; see also Part II, p. 56); Carl Gren (pp. 136-139); Richter (pp. 131-135); Crell (p. 145); and Zauschner (p. 146).

63. Ibid. These include: Guyton de Morveau (see Part III, p. 354); J. H. Voigt and George Smith Gibbes (Part IV, p. 119); and Gren and Richter (Part IV, p. 137). See also S.L. Mitchell, `An Attempt to Accomodate the Disputes among the Chemists Concerning Phlogiston', Medical Repository, 1(1796), no. 4: #9.
64. e.g., Ibid., Parts I and II. See also Howard Margolis, Paradigms and Barriers (Chicago, 1993), Chap. 4.
65. Op. cit. (n. 8), Parts II-IV. Individuals include: Bryan Higgins (1775, Eng.), Pierre Macquer (1778, Fr.), Patrick Leslie (1778, Eng.), Adair Crawford (1779-1788, Eng.), John Elliott (1780, 1782, Eng.), C. R. Hopson (1781, 1789, Eng.), Senebier (1782, 1788), Christian Gottlieb Selle (1782-1786, Ger.), Jean Claude de la Metherie (1786, Fr.), James St. John (1788, Eng.), Trommsdorf, Gren, Wiegleb (1795, 1796, Ger.), Zauschner, and Thomas Thomson (1802, Eng.). Again, see Allchin (footnote 58).
66. Crell's Annalen, 1788, I, 15, 417, cited in Ibid., Part IV, p. 126.
67. Letter to Dr. Henry Menish in William Ramsay, Life and Letters of Joseph Black, M.D. (London: Constable, 1912), pp. 97-98; Black, Lectures on the Elements of Chemistry, (Robison, ed.), Vol. 1 (Edinburgh, 1803), p. 550. See also C. E. Perrin, `A Reluctant Catalyst: Joseph Black and the Edinburgh Reception of Lavoisier's Chemistry', Ambix 29(1982), 141-176, (p. 164).
68. e.g., Hutton, Light, Heat, and Fire, pp. 48, 143, 225-26; `Powers of Matter' (footnote 24), 516.
69. Partington and McKie, `Phlogiston', Part III, pp. 345, 119; IV, pp. 123, 137, 125, 119. William Drew, The Art of Making Coloured Crystals . . . Also a New Theory of Phlogiston, Electric Fluid (etc.), 1787. See also William M. Sudduth, `Eighteenth-Century Identifications of Electricity with Phlogiston', Ambix 25(1978), 131-47; H. A. M. Smelders, `The New Chemistry in the Netherlands', Osiris 4(1988), 121-45.
70. Partington and McKie, `Phlogiston', Part IV, p. 135, n. 65. Hutton's views perhaps most closely resemble those of Crawford, who also considered the cycling of the element of fire in a natural theological context, and saw subterranean fires as reactions of iron, sulphur and water. Crawford, however, claimed that heat was derived from the air. See Adair Crawford, Experiments and Observations on Animal Heat, and the Inflammation of Combustible Bodies, 2nd ed. (London: J. Johnson, 1788), pp. 423-28.
71. Robert Siegfried and Betty Jo Dobbs, `Composition: A Neglected Aspect of the Chemical Revolution', Annals of Science 24(1968), 275-293; J.B. Gough (footnote 59), 17-18.; Robert Siegfried, `The Chemical Revolution in the History of Chemistry', Osiris 4(1988), 34-52.
72. Ramon Gago notes, for instance, that the French theory of acidification was received skeptically in Spain (see Osiris, footnote 2). On nomenclature, see Siegfried (footnote 71).
73. See Michel Foucault, The Archaeology of Knowledge, trans. by A. M. Sheridan Smith, (New York, 1972), esp. pp. 106-7. One may contrast this view of reorganization with the simpler model of wholesale substitution of paradigms in Thomas S. Kuhn, The Structure of Scientific Revolutions (Chicago, 1962).
74. Brown (footnote 10).
75. William Odling, `On the Revived Theory of Phlogiston', Proceedings, Royal Society of Great Britain, 6(1871), 315-325, (pp.322-323); also Pharmaceutical Journal (3rd series),

1, 977-981.

76. Stewart Richards, Philosophy and Sociology of Science: An Introduction, 2nd ed. (Oxford, 1987); Robert J. Richards, Darwin and the Emergence of Evolutionary Theories of Mind and Behavior (Chicago, 1987), 14-17, 559-93; Alan Chalmers, Science and its Fabrication, (Minneapolis, 1990); Steve Fuller, `Is the History and Philosophy of Science Withering on the Vine?', Philosophy of Social Science, 21(1991), 149-74.

77. Steve Woolgar, ed., Knowledge and Reflexivity: New Frontiers in the Sociology of Knowledge, (London, 1988); see also Donna Haraway, Primate Visions, (New York, 1989), esp. pp. 1-15.

78. See also e.g., Nancy Nersessian, `The Cognitive Sciences and the History of Science', Critical Problems and Research Frontiers in the History of Science and the History of Technology (Madison, Wisconsin: History of Science Society, 1991), 92-115.

79. David Bloor, Knowledge and Social Imagery, (London, 1976), esp. pp. 1-19.