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A frame-theoretic analysis of two rival conceptions of heat

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ABSTRACT

Under what circumstances, if any, are we warranted to assert that a theory is true or at least has some truth content? Scientific realists answer that such assertions are warranted only for those theories or theory-parts that enjoy explanatory and predictive success. A number of challenges to this answer have emerged, chief among them those arising from scientific theory change. For example, if, as scientific realists suggest, successive theories are to increasingly get closer to the truth, any theory changes must not undermine (i) the accumulation of explanatory and predictive success and (ii) the theoretical content responsible for that success. In this paper we employ frame theory to test to what extent certain theoretical claims made by the outdated caloric theory of heat and that, prima facie at least, were used to produce some of that theory's success have survived into the theory that superseded it, i.e. the kinetic theory of heat. Our findings lend credence to structural realism, the view that scientific theories at best reveal only structural features of the unobservable world.

1. Introduction

Under what circumstances, if any, are we warranted to assert that a theory is true, approximately true or at least has some truth content? Scientific realists answer that such assertions are warranted only for those theories that enjoy explanatory and predictive success. A number of challenges to this answer have emerged, chief amongst them those arising from scientific theory change. For example, if, as scientific realists suggest, successive theories are to increasingly get closer to the truth, any theory changes must not undermine (i) the accumulation of explanatory and predictive success and (ii) the theoretical content responsible for that success. In more detail, an outdated theory T which enjoyed some measure of success will, according to the realist, likely be: (i) partially true precisely when some of its theoretical claims help produce at least part of that success and (ii) superseded by a theory T^* that is closer to the truth (perhaps even strictly closer) and which preserves T's successful theoretical claims. In this paper we use the caloric theory of heat, which plays the role of the outdated theory T, and the modern kinetic theory of heat, which is the contemporarily accepted theory T^*, to test this consequence of scientific realism. We conduct our investigation by means of frame-theory because frame-theoretic reconstructions offer an intuitively simple way to illustrate similarities and differences between scientific theories, their concepts and their ontology.

The plan of the paper is as follows. We first present the problem of scientific theory change and situate it in the contemporary realism vs. anti-realism debate. We then give a basic account of Lawrence Barsalou's recursive frame theory, pointing out various salient features. This is followed by a short section that motivates our decision to model scientific theory change in terms of frame theory. Having prepared the ground, we then turn to an introduction of the caloric theory and its successor, the kinetic theory of heat. We give both theories a frame-theoretic treatment and identify some successes the caloric theory enjoyed. In the section that follows, we test how our own preferred version of realism, i.e. structural realism, fares with respect to two of the caloric theory's successes. Finally, we weigh our findings against a recent frame-theoretic analysis of incommensurability in scientific theory change.

2. Scientific theory change

In the realism debate there are two opposing camps: the realists and the anti-realists. Although the soldiers of these camps fight

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each other over a number of issues, e.g. semantic, ontological and axiological, it is the epistemic issue that draws the most attention. This is the issue that primarily (but not exclusively) interests us. Simply put, this issue concerns the conditions, if any, under which we are warranted to believe in the truth, in the approximate truth or at least in the partial truth of scientific claims—hereafter, and unless otherwise noted, this disjunction is expressed by the term ‘truthlikeness’—and the kind of knowledge, if any, that this yields. Scientific realists argue that predictively and explanatorily successful theories give rise to truthlike claims about the observable and the unobservable world. There are, of course, many kinds of scientific realists—more on this below. One widespread expectation amongst them is the following (or something very much like it): If successive successful scientific theories are to largely converge towards the truth about both the observable and unobservable worlds, then some theoretical claims must help produce at least part of the success and such claims must more often than not be preserved through theory change.[1] Anti-realists hold that it is not the case that, or at least we cannot know whether, any scientific theories produce truthlike claims about the world. Successive theories, anti-realists claim, are not converging towards the truth or at least we cannot know that they are. Theories, concepts and ontologies eventually end up in the scrapheap of discarded science. As with realism, there are many kinds of anti-realism. We are here more interested in the anti-realism of van Fraassen—see his (2006)—because it is one of the most plausible and best articulated kinds of anti-realism. Constructive empiricism, as he calls it, is the view that our theories aim and to some extent succeed at uncovering the truth only about the observable world. In other words, van Fraassen restricts his sceptical attitude towards claims about the unobservable world.

To support the claim that successive theories are not converging towards the truth, anti-realists often turn to the Pessimistic Meta-Induction argument (PMI). The argument questions the reliability of inductive inferences from explanatory and predictive success to truthlikeness by citing that the history of science is replete with successful theories that are now considered false. Indeed, the anti-realists who endorse this argument often take the historical record of science to inductively support the view that current successful theories will succumb to the same fate. In fact, the pessimism often runs deeper as it is claimed that even future theories are likewise destined to perish. The argument thus provides some prima facie reasons to suspend our belief in the truthlikeness of theories. In this respect it challenges the main realist argument or intuition, the so-called ‘no miracles argument’ (NMA), which holds that the only explanation that does not make the explanatory and predictive success of our theories an exceedingly lucky coincidence is that they have somehow latched on to the (observable and unobservable) world, i.e. that they are truth-like.

Realist reactions to the PMI vary. The main reaction questions the legitimacy of the meta-inductive inference. Advocates of this approach argue that upon closer scrutiny the historical record can be reconciled with scientific realism. When a successful theory is abandoned, not all of its theoretical parts are discarded but only those that are *inessential* or *idle* for the theory’s success. Their abandonment is thus inconsequential for the realist. What is important for the sustainability of scientific realism is that the theoretical parts ‘responsible for’ the success of the old theory survive into the new theory. After all, it is these parts that presumably granted their parent theory the designation ‘truthlike’ and it is with their help that we can claim that the new theory is closer to the truth. Stathis Psillos (1999) has called this the ‘divide-et-impera’ strategy.

One realist view along these lines is structural realism (SR). According to the epistemic form of SR, which we utilise here, we cannot know more than structural features of the unobservable world. More precisely, while our knowledge of observable aspects of the world is unrestricted, our knowledge of the unobservable aspects is at best structural. This view can be contrasted with run-of-the-mill scientific realism whose advocates insist that both observable and unobservable aspects of the world can be fully knowable. In other words, the relevant difference between the two views is the extent to which unobservable aspects of the world can be known. John Worrall (1989), who resuscitated SR and has been instrumental in its popularity, explains that although scientific revolutions lead to radical ontological change—in accordance with the PMI—any structural parts that help produce a predecessor theory’s success will be truthlike—in accordance with the NMA—and will survive into successor theories. In line with this approach, Schurz (2009) proves a theorem asserting that under certain conditions the preservation of an old theory’s empirical success into a new theory logically entails that at the theoretical level structure is preserved.

3. Frame theory

A frame is a hierarchical structure that represents ordinary and scientific concepts by a recursive system of attributes each of which takes a range of values (Barsalou, 1992). The recursiveness of the system becomes apparent when one realises that the nodes of a given frame may themselves be analysed into further frames. Consider the frame in Fig. 1 for the concept BIRD.[2] For the sake of simplicity only two attributes in the bird frame are included: BEAK which takes the values ROUND or POINTED, and FOOT which takes the values WEBBED or CLAWED. A complete specification of the frame requires additional attributes.

Note that in the frame-theoretic account, an attribute is not a property but a space of possible properties belonging to the same property dimension. The simplest property dimension is a yes-or-no-dimension which corresponds to a binary attribute (e.g. living entity: yes or no). Most fine-grained property dimensions are real-valued magnitudes, such as the attribute LENGTH-IN-METERS which takes real numbers as its possible values.

In frames which correspond to superordinate concepts typically none of the attributes is instantiated to a specific value. For example, all values of the attributes BEAK and FOOT are allowed in the frame BIRD. Subordinate concepts arise from the frame of the superordinate concept by fixing the values of certain attributes, or at least by restricting them to a subset of values. This is shown in Fig. 1 at the right-hand side where the values corresponding to the subordinate concepts LAND-BIRD and WATER-BIRD are specified.

In Fig. 1, FOOT is an attribute of the superordinate concept BIRD and of the subordinate concepts WATER BIRD and LAND BIRD. This attribute, however, is itself a concept that can be represented in terms of a frame (see Fig. 2).

The concept FOOT is here represented by three attributes, namely TARSUS, SKIN and NAIL. Each of these takes two values. The hierarchical nature of frame theory means that frames are nested, e.g. the frame for FOOT is lower in the hierarchy than the frame for BIRD. Moreover, it is important to understand that any attribute or value is itself a concept that may or may not be

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[1] Naturally, to guarantee strict convergence towards the truth, the preservation of successful theoretical claims must take place without exception. Since non-epistemic reasons, e.g. sociological ones, may prevent such exceptionless preservation, it is more prudent for the realist to drop the demand for strict convergence. For more on this see Votsis (2011).

[2] Hereafter, capitalised nouns denote concepts, attributes and their values.

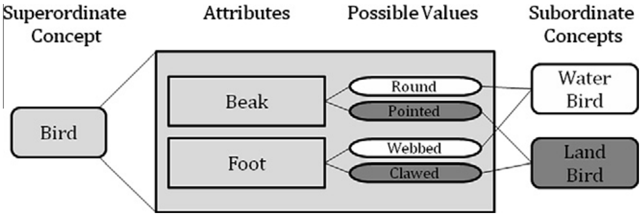

Fig. 1. *Partial Frame for Bird*. Adapted from Andersen et al. (2006, p. 70). The subordinate concepts are value-instantiations of the superordinate concept. Different shades indicate that the instantiated values correspond to different subordinate concepts.

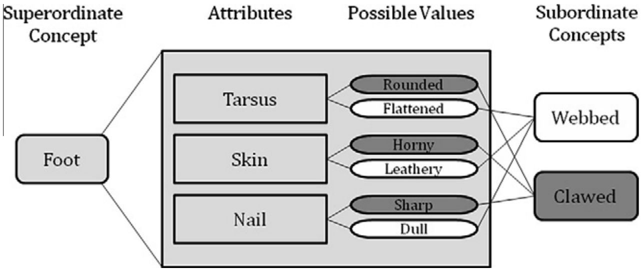

Fig. 2. *Partial Frame for Foot*. Adapted from Andersen et al. (2006, p. 58).

amenable to representation via a frame. Thus we may construct frames for the concepts TARSUS, SKIN, NAIL, ROUNDED, etc.

An array of additional characteristics of frames is worth considering. First of all, every frame is a classification system with an associated ontology. This should be obvious from our example where the category BIRD is subdivided into two subcategories, WATER BIRD and LAND BIRD, each of which identifies an ontological grouping. Whether this grouping is natural or artificial is of course a matter that is determined by how true-to-nature a given frame-theoretic representation is.

A second noteworthy feature is that frames need not be complete to convey information about a concept. Frames that are incomplete are called ‘partial frames’. For example, the aforementioned frame for BIRD is a partial frame because it is given in terms of two attributes FOOT and BEAK that do not exhaust all the relevant attributes and attribute-values of birds. The ways in which frames fall short of representing all the relevant features of a given ontological category are varied. It may be that the missing features are known to us but we intentionally omit them in order to represent a more abstract and simplified version of the given frame. The attribute PLUMAGE was omitted from the frame BIRD for precisely this reason. Another reason why a frame may fall short of representing all the relevant features is that we may not know which features are missing even though we know that our frame is incomplete. Most cases in science (especially science which is at an early stage of development) are of this kind. Since we very rarely have complete information in science it is useful to have a system like frame-theory that permits the construction of incomplete representations that we then have the option of modifying.

A third feature of frame theory is that subordinate concepts are defined in terms of the attributes of their respective superordinate concept but will sometimes introduce attributes that are specific to themselves, i.e. that cannot be found in the remaining subordinate concepts of the same level. Restrictions of attributes to specific subordinate concepts, or, in other words to specific value-instantiations of the given superordinate concept, are also called *value-attribute constraints*. For example, as can been see in Fig. 3, EGG SHELL TYPE is an attribute that is specific only to the subordinate concept MONOTREMES of the superordinate concept MAMMALS. The reason for this is that monotremes are the only mammals that lay eggs. Although EGG SHELL TYPE can in principle be listed as an attribute of MAMMALS, with MARSUPIALS and PLACENTALS taking the null value, this practice is best avoided for matters of simplicity and expediency.

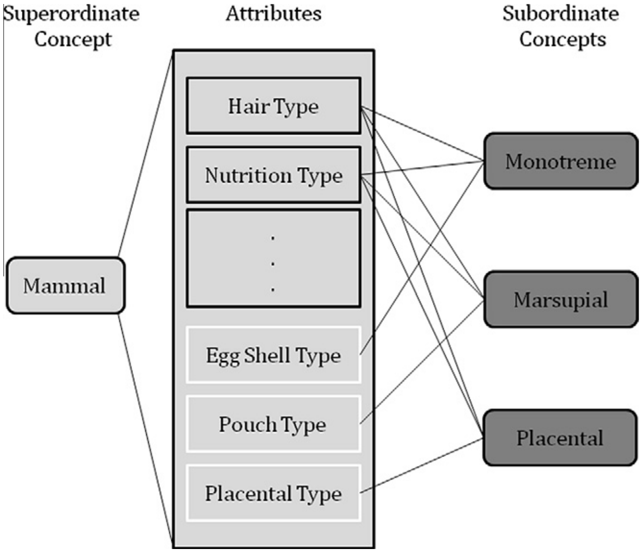

Fig. 3. *Partial Frame for Mammal*. Note the value-attribute constraint that holds between the value-instantiations of the superordinate concept (i.e. the subordinate concepts) and their respective attributes (shown here with a white outline).

A fourth interesting feature concerns the fixed values of certain attributes. We mentioned earlier that frames are hierarchical structures. That is, they consist of several levels that are ordered, e.g. in Fig. 3 the concept MAMMAL is at a higher level of the hierarchy than the concept MARSUPIAL. When the value of an attribute is fixed at a level n of the hierarchical structure, we may safely ignore that attribute at any level m where $m<n$. Thus, since the value CARTILAGINOUS is fixed for the attribute SHELL in the frame for TESTUDINES (this is the order which includes the turtles and tortoises), the frame-theoretic representation of any subordinate concepts like PLEURODIRA and CRYPTODIRA (these are suborders) need not include the said attribute.

A fifth noteworthy feature is that frame theory allows us to represent several sorts of *constraints* concerning values and attributes. Some constraints may be strict while others may just express an imperfect correlation. We have already introduced value-attribute constraints. A second type is *attribute-attribute constraints*. For example, the attribute BEAK *implies* the attribute NECK in the frame of the concept BIRD. A third type is *value-value-constraints*. For example, the value ROUND of the attribute BEAK *is correlated with* the value WEBBED of the attribute FOOT. One thing to note about constraints is that they allow us to express the idea that not all attributes and values are equally important. Some determine much of the hierarchical structure for a given concept while others are more peripheral. Another thing to note about constraints, indeed one that has been largely ignored in the literature, is that they may have wildly divergent characters. An analytic constraint primarily tells us something about the way meaning is distributed within a frame. For example, the value ABSOLUTE ZERO of the attribute TEMPERATURE is analytically constrained by the value ZERO of the attribute KINETIC ENERGY. That is, by definition, there cannot be a temperature lower than absolute zero, approximately minus 273.15 Celsius, since negative kinetic energies are not permissible in physics. A synthetic (i.e. empirical) constraint reflects a contingent relation between the categories involved and hence their corresponding concepts. For example, the foregoing correlation between the value ROUND of the attribute BEAK and the value WEBBED of the attribute FOOT is a synthetic constraint. Hereafter, we indicate constraints in frame diagrams by double-headed arrows.

4. Why frame theory?

One of frame theory's strengths is its ability to lay bare the inner structure of scientific concepts. This facilitates the task of comparing scientific theories because one can examine with relative ease whether frame-theoretically explicated concepts, their attributes and their values share structure. Such comparisons can reveal to what extent, if at all, two or more concepts are continuous and whether these concepts are incompatible and even radically incommensurable. As philosophers of science we find this ability very useful because one of the central aims of our discipline is to discover how scientific concepts of successive theories (and their respective ontologies) are related. As participants in the scientific realism debate we are particularly interested to find out whether the relations (or the lack of relations) between scientific concepts of successive theories uphold a realist or an anti-realist view of science.

Having motivated a reason to adopt frame theory for our investigation, we should also say something about the relation of frame-theory to some alternative accounts. Ultimately frame theory is just a representation tool and, of course, it is not the sole tool for reconstructing problems in the philosophy of science. Another tool, one that has been chosen by a large subsection of the philosophy of science community, is formal logic. Still another tool is the model-theoretic account of theories, according to which a theory is a family of models (see, for example, Sneed, 1971).[3] In our view, all three tools but also some others, e.g. category theory, provide representations of the contents of science that are adequate to at least a certain degree. A pragmatic advantage of frame theory is that its diagrammatic reconstructions of the contents of science are simpler and more intuitive than the reconstructions offered by its logical and model-theoretic counterparts in terms of sets of axioms or models-characterized-by-axioms respectively.[4]

One objection raised against frame theory is that it has the following limitation: it cannot be used to represent quantitative relations between concepts. For example, it has been argued that frame theory cannot be used to represent ratio scales.[5] Since the use of such scales is abundant in science this would present a rather serious problem to frame theory if it were true. As we already explained in the preceding section, frame theory allows a great variety of different kinds of attribute values. For example, the values of an attribute may be the structure of a vector space of real numbers (see also Chen, 2003). More generally, measurement scales are a natural refinement of the notion of a space of possible values that fits perfectly into frame theory. Hence, the claim that frame theory cannot represent quantitative concepts is incorrect. Frame theory is as general as general scale theory in that it allows values to be structured in terms of nominal, ordinal, interval, ratio or absolute scales. Indeed frame theory is even more general for it allows frames to have a recursive structure.

5. Two rival conceptions of heat

It was not until the eighteenth century that the study of heat begun to flourish. Antoine Lavoisier developed the first sophisticated theory of heat based on an idea whose roots go back to Antiquity, namely that heat is a special kind of substance.[6] Lavoisier called this substance 'caloric'. According to his theory, caloric is an elastic fluid that is virtually imperceptible, flowing from warmer to colder bodies. It is also a conserved quantity and its particles are subject to two forces. One is repulsive and holds between caloric particles. The other is attractive and holds between caloric particles and particles of ordinary matter.

The caloric theory enjoyed some measure of explanatory and predictive success in the sense of being able to deduce phenomena utilizing its theoretical machinery. Amongst its successes one may count the following: (i) an explanation for the fact that matter expands by heating and contracts by cooling, (ii) the postulation that a special kind of heat (i.e. latent heat) is involved in changes of state, (iii) the realisation that different substances with the same mass require different quantities of heat to raise their temperature by the same number of degrees—i.e. the concepts of *heat capacity and specific heat (capacity)*,[7] (iv) an explanation for the fact that the flow of heat from warm to cold bodies tends toward equilibrium, and (v) an explanation for the elasticity of gases.

Many different versions of the theory were available. We here focus on Lavoisier's version because it was the most influential and most articulated one. Recall that caloric was thought of as a special kind of substance, different from ordinary matter. This difference is reflected in Fig. 4 where HEAT AS CALORIC is an instantiation of a more general frame corresponding to the superordinate concept KIND OF SUBSTANCE.

One characteristic of Lavoisier's version of the theory was that caloric particles had absolutely no weight. This meant that they were not observable in any direct way. The only way caloric could be observed was indirectly, through its effects on temperature. The addition of caloric to a body would *typically* lead to a rise in that body's temperature while its subtraction would *typically* lead to a fall. This and other relationships are expressed as *constraints* (i.e. double-headed arrows) in Fig. 4. The dotted double-headed arrow line expresses a constraint that holds in alternative caloric theories which maintain that caloric particles have at least a little weight and are therefore in principle directly observable.[8]

As is well known, the caloric theory was dumped at around the middle of the nineteenth century. This was not merely a consequence of the numerous anomalies for which the theory had no convincing explanation. Rather, a more important factor seems to have been the rise in sophistication and success of the caloric theory's rival, namely the kinetic theory of heat. According to this theory, whose roots also go back to Antiquity, heat is a consequence of the *motion* of particles. Whether the theory survived through the centuries or was rediscovered is not a clear matter. What we do know is that it started gaining prominence again in the sixteenth century. Francis Bacon, for example, remarked that 'heat itself, its essence and its quiddity, is motion and nothing else'. At the height of the caloric theory's reign, i.e. the early part of the nineteenth

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[3] Certain elements of frames, for example the set of attributes and their possible values, are quite close to model-theoretic reconstructions, while other elements of frames, such as constraints, are closer to logical reconstructions. Concerning the relation to models, it should also be pointed out that since a frame does not specify all but only some values of its attributes, it corresponds not to a single model but to a set of models.

[4] Although it is not our aim to do so here, a thorough investigation of the relations between frame theoretical and model-theoretical theory reconstructions on the one hand, and of the possible use of frame-theoretical structures as a semantics of formal languages on the other, is a task that we hope to carry out at some point in the future.

[5] This claim is made by Frank Zenker (forthcoming).

[6] The Atomists and the Epicureans took the element fire to be a substance with weight.

[7] The concept of heat capacity encodes the idea that a certain amount of heat is needed to increase the temperature of a substance by one degree Celsius. The concept of specific heat relativises heat capacity to unit masses, i.e. it encodes the idea that a certain amount of heat is needed to raise the temperature of one gram of a substance by one degree Celsius.

[8] That the addition or subtraction of caloric has the aforesaid effect on temperature was a characteristic shared by all versions of the caloric theory.

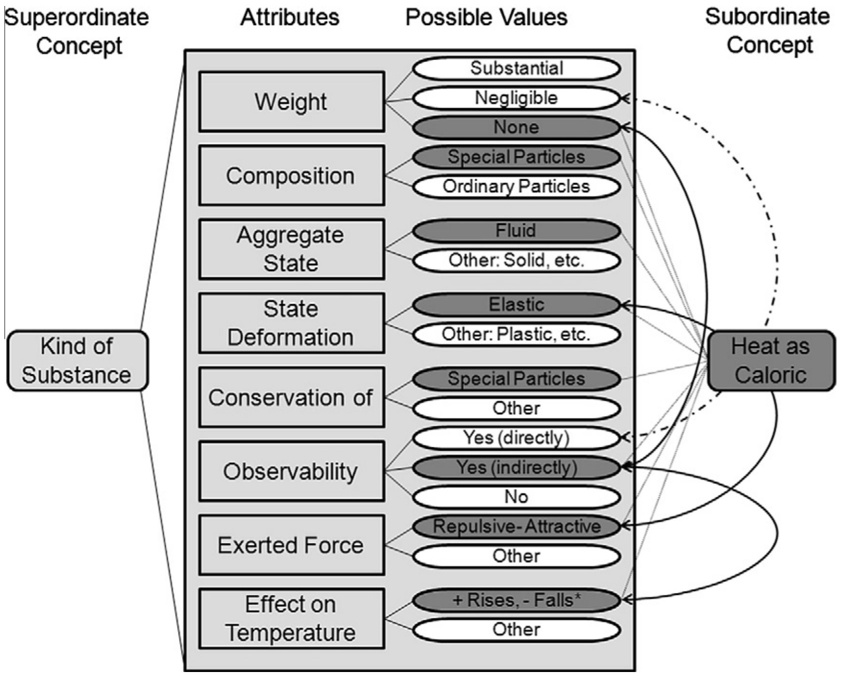

Fig. 4. *Partial Frame for Heat as Caloric*. This frame represents Lavoisier's notion of heat as caloric, shown here as an instantiation of the more general frame 'kind of substance'. Fields of instantiated values are shaded. The star in the instantiated value of the attribute EFFECT ON TEMPERATURE indicates that this relationship holds typically but not always. The conditions under which the addition (or subtraction) of caloric does not lead to a rise (or fall) in the temperature are explored below.

century, the kinetic theory remained largely undeveloped. Thus even though several experimental results posed problems for the caloric theory, e.g. Count Rumford's boring of cannons and Humphry Davy's rubbing of ice sheets, the kinetic theory could not at the time successfully compete with it (see, for example, Fox, 1971).

In what follows, we consider the frame for the modern version of the motion theory which takes heat to be an instance of kinetic energy. A proper contemplation of the notion of heat as an instance of kinetic energy requires a familiarisation with the general notion of energy. The modern notion of energy emerged in the early nineteenth century. Today we think of energy as a physical quantity that is conserved, scalar and comes in two forms, namely kinetic and potential. Potential energy is the type of energy that a physical system stores. It gets its name from the fact that in its stored state it has the potential to do work, i.e. it has the potential to displace an object with a given force. Kinetic energy, on the contrary, is the type of energy a body possesses precisely because that body is in motion. Thus when work is being performed potential energy is converted into kinetic energy because the displacement of a body puts it into motion.

The relationship between energy and kinetic energy can be seen in Fig. 5. KINETIC ENERGY is a subordinate concept, i.e. an instantiation of the more general frame for the superordinate concept ENERGY. Notice that at this level of description the subordinate concept KINETIC ENERGY does not instantiate the attribute KIND. The reason for this is that there are various forms of kinetic energy, among them electrical, sound and heat. We are, of course, interested in the last mentioned. To be precise, we are interested in the more specific concept of *heat flow*. According to the kinetic theory, heat flow is a process that takes place when energy is transferred from one object to another. Fig. 6 displays the frame for the concept HEAT AS (AN INSTANCE OF) KINETIC ENERGY. It results from instantiating the value HEAT in the attribute KIND of the frame for kinetic energy in Fig. 5. This instantiation introduces three new attributes, namely FORM, EFFECT ON TEMPERATURE and METHOD OF FLOW. It is thus another example of a value-attribute constraint at work. FORM and METHOD OF FLOW are left uninstantiated so as to allow for the possibility of dividing the concept of heat into further sub-concepts which are explained below.

A highly influential view of the relationship between the caloric and the kinetic theory is that of Kuhn. He regarded the two theories as competing paradigms or at least as competing parts of paradigms.[9] Given Kuhn's views, especially his early ones, on the incommensurability of paradigms, the question arises whether it is even possible to compare the two theories, frame-theoretically reconstructed or not. We return to this important issue in Section 7. For the time being we would like to make some relevant preliminary remarks. First, observe that the frame for HEAT AS (AN INSTANCE OF) KINETIC ENERGY in Fig. 6 is similar in some respects to the frame for HEAT AS CALORIC in Fig. 4. Both frames share the following attributes: CONSERVATION, OBSERVABILITY, and EFFECT ON TEMPERATURE. Thus, the frame-theoretic reconstruction has so far shown us that the two theory frames are not entirely incommensurable in that they share at least three attributes. Second, this similarity in and of itself is not sufficient to demonstrate the existence of robust correspondence relations between the two frames. Take the attribute CONSERVATION. Even though heat is considered to be a conserved quantity in both frames, what gets conserved differs radically. In the caloric frame, it is caloric that gets conserved since it was natural to assume that the universe consists of a fixed number of caloric particles. In the kinetic energy frame, what gets conserved is the total energy of a closed system. Even so, we may still say that *something or other* is conserved in both cases and that needn't have been the case. In other words, this kind of correspondence is not

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[9] Here are two corroborating quotations: (1) "... all these experiments arose from the caloric theory as *paradigm*" (1996 [1962], p. 29) [emphasis added] and (2) "Consider next a second type of component of the disciplinary matrix, one about which a good deal has been said in my original text under such rubrics as '*metaphysical paradigms*' or 'the *metaphysical parts of paradigms*.' I have in mind shared commitments to such beliefs as: heat is the kinetic energy of the constituent parts of bodies" (ibid., p. 184) [emphasis added].

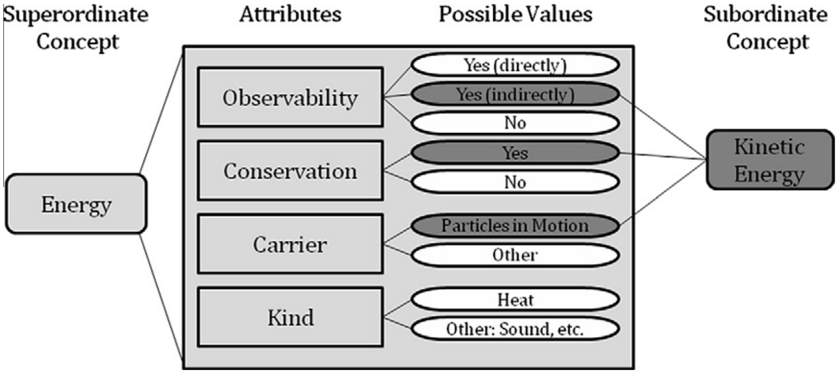

Fig. 5. *Partial Frame for Kinetic Energy*. The frame for kinetic energy is shown here as an instantiation of the frame for energy. Instantiated values are shaded. The attribute 'kind' is left uninstantiated.

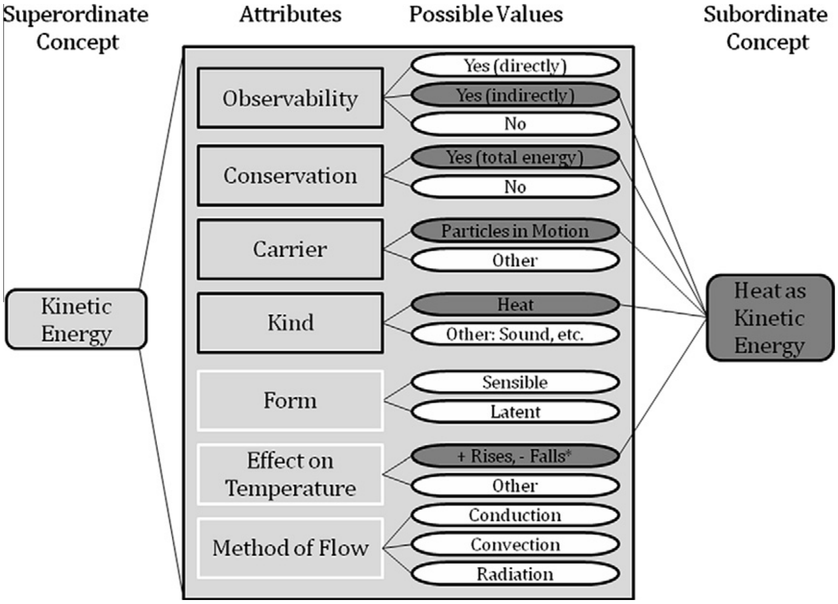

Fig. 6. *Partial Frame for Heat as Kinetic Energy*. Three attributes (shown here with a white outline) are added to this frame by way of value-attribute-constraints as in Fig. 3 above. As before, the star in the instantiated value of the attribute EFFECT ON TEMPERATURE indicates that this relationship holds typically but not always.

trivially satisfiable. In the section that follows, we argue that there are further correspondence relations between the two frames.

6. Structural realism under test

The fact that the caloric theory was a partially successful theory that was eventually abandoned makes it a prime candidate for the inductive basis of PMI. Unsurprisingly, Laudan (1981) includes the caloric theory in his list of once successful but ultimately false theories. If the anti-realists are right, it is unlikely that any theoretical parts of the caloric theory survived the thermodynamic revolution and even more unlikely that those parts had a hand in producing the theory's success. If on the contrary the realists are right, not only did certain theoretical parts of the caloric theory survive into our modern conception of heat, but also these same parts helped produce the success the caloric theory enjoyed. Of all the realist views, we take structural realism to be the most defensible one. If the structural realists are right the aforesaid successes must be encoded in at least some of the structures of the caloric theory and those structures will have been preserved in our modern conception of heat. Given limitations of space, we cannot discuss all five of the caloric theory's successes listed earlier. Instead we confine our discussion to the first two. To remind the reader, the caloric theory could potentially explain and/or predict the following: (i) that matter expands by heating and contracts by cooling and (ii) that a special kind of heat (i.e. latent heat) is involved in changes of state. Let us consider each of these in turn.

A small digression is necessary. Worrall (1989) does not really elaborate the notion of structure and hence the notion of structural continuity he employs. Instead he gives a few examples of structural continuity, all involving a sharing of equations between successive theories. Understandably some commentators, e.g. Psillos (1999), have drawn the conclusion that what Worrall understands by structure is nothing other than equations. In an elaboration of his views, Worrall (2007) asserts that the relevant notion of structure is given by a theory's Ramsey-sentence. Our approach here is similar. The content of a scientific theory can be captured in terms of the predicates of its language and the logico-mathematical relations that exist between them. Take the statement 'Positrons have the same charge as protons'. It consists of two terms 'positrons' and 'protons' that purport to denote specific kinds of unobservables, positrons and protons respectively, and a two-place predicate 'have the same charge as' that purports to denote a relation between the said classes. Structural realism, as we understand it, departs from the idea that nothing can be known about unobservables other than the relations they stand in with respect to the observables and with respect to themselves.[10] For this reason any unobservable concepts, i.e., any concepts whose corresponding terms purport to denote specific kinds of unobservables, are replaceable so long as the new concepts maintain the same relations (at least in the limit) between the denoted kinds of unobservables. If structural realism is correct, the replacement of successful concepts should take place without loss of predictive or explanatory success. Indeed, if the replacement is progressive it should be accompanied with added predictive and/or explanatory success. Frame-theoretically these moves can be translated into a replacement of frames, where relations between the unobservable concepts and attributes in the frame of a predecessor theory are preserved (at least in some limit form) in the frame of its successor, in spite of the fact that the latter theory introduces new unobservable concepts and attributes. This is what we mean by structural continuity in frame-theoretic terms.[11]

Consider first the caloric explanation for thermal expansion and contraction. The caloricists explained such phenomena by arguing that the first involves the addition of caloric to a body while the second involves its removal. The addition of caloric meant that caloric particles would push each other outwards because of the repulsive force that was thought to hold between them. The consequence was thus an increase in the volume of the body. The removal of caloric meant a decrease in volume since the body now contained less caloric particles and hence the repulsive force between them was weaker. Fig. 7 provides a frame-theoretic reconstruction of this explanation in terms of the nomological correlations between the values of the attributes of heat flow as a change in caloric and distinct subordinate concepts denoting different kinds of thermal effect.

The kinetic theory explanation of the same phenomena involves the increase and decrease of kinetic energy. When a body's kinetic energy is increased, its internal pressure is also increased since the collisions of the molecules with the body's boundaries are more intense and more frequent. That leads to an increase in the body's volume. Contraction involves the decrease of kinetic energy which leads to a decrease of internal pressure and therefore to less volume needed. Fig. 8 provides a frame-theoretic reconstruction of this explanation in terms of nomological correlations between the values of the attributes of heat flow as a change in kinetic energy and different kinds of thermal effect.

It should be painfully obvious that although the two explanations employ different conceptions of heat they still share the same structure.[12] As the amount of heat (caloric in the one case, kinetic energy in the other) in the substance under consideration is increased/decreased, the repulsive force or internal pressure within the substance is increased/decreased and that in turn leads to an increase/decrease in the volume needed. Thus, although the two theories offer a radically different conception of the metaphysical 'nature' of heat, the cited relation between the amount of caloric, repulsive force and volume is isomorphic to the relation between the magnitude of kinetic energy, internal pressure and volume. If we take the kinetic explanation of these phenomena to be true or at least truthlike we can give a reasonable account for the success enjoyed by the caloric explanation. The caloric explanation was successful because it had managed to get the structure of such processes right, even though the specifics of the unobservable ontology were wrong, i.e. the existence of caloric and its repulsive force. More carefully, the structural parts of the theory producing that success have been incorporated into the kinetic theory of heat.

This is precisely the kind of result that lends credence to structural realism as opposed to traditional scientific realism or empiricist anti-realism. Traditional scientific realists, you may recall, endorse the claim that we can know more about unobservables than the relations they stand in and hence they expect that more than merely structure gets preserved through scientific theory change. Anti-realists like van Fraassen endorse the claim that only observables can be known and hence they expect that only the structure of observables gets preserved through scientific theory change.[13] Our case study supports structural realism over these alternative views in a refreshingly unambiguous way. Against traditional scientific realism, it can be pointed out that the unobservable ontology posited by the caloric theory is replaced by the unobservable ontology posited by the kinetic theory and hence that no more than the structure of the unobservables gets preserved. Against empiricist anti-realism, it can be pointed out that more than the structure of the observables gets preserved.

Consider next the explanation that a special kind of heat is involved in changes of aggregate state or 'phase transitions', as they are now called. Phase transitions, e.g. evaporation, freezing and melting, had been known for centuries. Joseph Black, a leading caloricist of the eighteenth century, seems to have been the first to notice a rather unexpected feature of phase transitions in two famous experiments: one involving the vaporisation of boiling water and the other the melting of ice (see his posthumously published accounts 1803). We only need consider the melting ice experiment here. In that experiment Black applied heat to a block of ice and then measured the temperature of the ice and of the resulting water. Much to his disbelief he noticed that the temperature of neither the ice nor the water had risen. This result was unexpected because it was universally supposed that the addition of heat to a body would automatically result in an increase of that body's temperature.[14] To explain this phenomenon, Black distinguished between *latent* and *sensible* forms of caloric (see Fig. 9). When ice melts, Black claimed, the added caloric is converted into a latent form by combining with the particles of water in a way that it is no longer able to affect a thermometer. Since caloric was assumed to be a conserved quantity this heat could not have been lost. Indeed, Black realised that latent heat can be retrieved (i.e. it can be made sensible again) when the process is reversed.[15] Non-latent heat was called 'sensible' for obvious reasons.

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[10] Even the relations cannot be fully known but only up-to-isomorphism.

[11] Successor theories typically make modifications (not just additions) to some parts of the structure of their predecessors. This is the reason why we added the clause 'at least in some limit form' to the continuity claim. We clearly allude to the correspondence principle here. For more on this see Votsis (2011) as well as Section 7 below.

[12] It is not our intention here to develop a full account of scientific explanation within the theory of frames. Rather we want to point out that to the extent that the explanations cite certain nomological relations these can be captured in frame-theoretic terms as correlations between the values of different attributes.

[13] Chang (2003) argues that to the extent that there is some preservation from the caloric theory to the kinetic theory it is only at the phenomenological level and hence it cannot help the realist because such preservation is compatible with constructive empiricism. Alas, Chang does not discuss the cases of success cited here. Needless to say that even if the cases he discusses support preservation only at the phenomenological level, this does not automatically rule out realism (structural or other) because the latter is compatible with some such preservation. Another issue worth discussing here, if only briefly, concerns the possibility that convergence towards some unobservable structure need not signify convergence towards the truth. We are aware of this possibility and for this reason insist that the prime motivation for any form of realism cannot be mere historical convergence. This issue is explored in Votsis (2011).

[14] As explained earlier, the star in the value "+Rises, -Falls*" for the attribute EFFECT ON TEMPERATURE in Figs. 4 and 6 is meant to remind us of this exception, i.e. that the temperature typically rises when heat is added and it typically falls when it is removed.

[15] See Home (2003, p. 367). That we can retrieve this heat is nowadays demonstrated by refrigerators which essentially pump heat from the inside of the refrigerator to the outside.

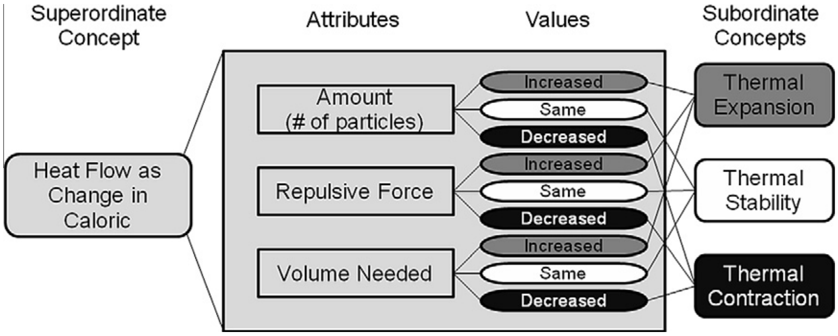

Fig. 7. *Partial Frame for Heat Flow as Change in Caloric*. This frame depicts the caloric explanation of the thermal expansion and contraction of a substance in terms of changes in the amount of caloric. Different shades indicate that the instantiated values correspond to different subordinate concepts.

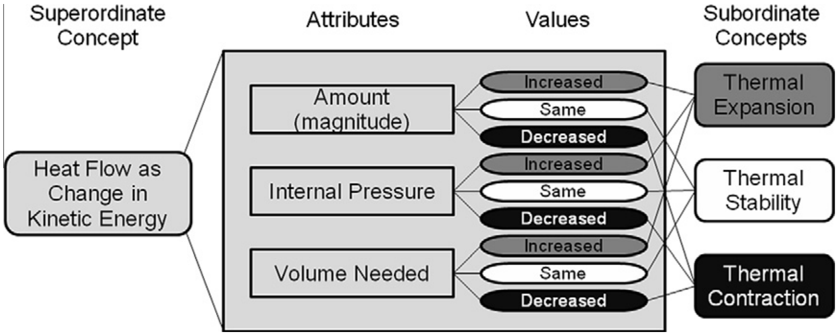

Fig. 8. *Partial Frame for Heat Flow as Change in Kinetic Energy*. This frame depicts the kinetic explanation of the thermal expansion and contraction of a substance in terms of changes in the amount of kinetic energy. Different shades indicate that the instantiated values correspond to different subordinate concepts.

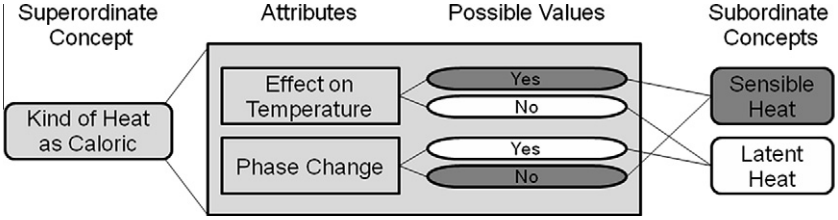

Fig. 9. *Partial Frame for Kind of Heat as Caloric*. This frame represents the caloric 'explanation' of phase change. Different shades indicate how the instantiated values correspond to the two subordinate concepts.

The distinction between latent and sensible forms of heat survived the thermodynamic revolution and continues to be part of our conception of heat to this day. In modern terms, latent heat is the quantity of energy released or absorbed by a given substance when undergoing a phase change and, of course, without an accompanying temperature change. During the melting of ice, the kinetic energy of the applied heat is used to break up the molecular bonds of the ice instead of increasing the average kinetic energy of its molecules, i.e. their temperature. This kinetic energy is not lost but converted into potential energy that is stored in the water (see Fig. 10).[16]

Unlike the expansion-contraction case, the correspondence between the two theories' explanations of phase change is a bit more involved. Black's achievement was to discover an empirical regularity, namely that during a phase change the temperature of the body undergoing the change remains constant. His theoretical explanation of the mechanism behind the phenomenon, however, was no more than an exercise in ad-hockery. He simply postulated that the caloric particles combine with the body's own particles in such a way so as to not have any effect on a thermometer. No details concerning this mechanism and no independent evidence for its existence were given. The modern explanation, by contrast, cites well understood and independently confirmed mechanisms. For example, we now know that various properties of objects including their (aggregate) state are determined by the bonds between their molecules. Moreover, we know that a certain amount of energy is required to break the molecular bonds of a particular kind of substance and is 'consumed' (viz. turned into potential energy) during this process so that it cannot be used to increase the average kinetic energy of the given substance. There is thus a well-confirmed theoretical underpinning to the empirical regularity discovered by Black.

Where does all of this leave the structural realist? The two explanations have an identical structure insofar as their empirical substructures are concerned. That is, they both incorporate the empirical regularity that during phase changes the temperature of the given substance remains constant. This fact on its own is not sufficient to support a structural realist view of science.

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[16] Modern physics identifies three types of latent heat: (i) latent heat of fusion, (ii) latent heat of vaporisation and (iii) latent heat of sublimation.

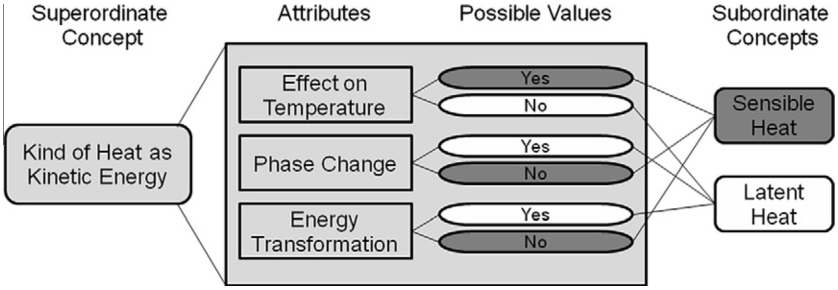

Fig. 10. *Partial Frame for Kind of Heat as Kinetic Energy*. This frame represents the modern explanation of phase change. Different shades indicate how the instantiated values correspond to the two subordinate concepts.

Someone like van Fraassen (ibid.) would happily point out that the preservation of empirical structures through theory change is evidence only for anti-realist empiricism. Notice, however, that the caloricists did get something right at the theoretical level. They realised that the said empirical regularity needed the postulation of a new cause and labelled this cause ‘latent heat’ or ‘latent caloric’. Thus the caloric and the kinetic explanation share at least some theoretical structure, namely that there exists an unobservable cause for the phenomenon of temperature invariance during phase transitions. As was explained earlier, the kinetic explanation takes this cause to be the kinetic energy being used—more precisely being converted into potential energy—to break up the molecular bonds of the substance undergoing a phase transition. Since no more than a structural claim about the unobservable ontology is preserved the traditional scientific realist cannot gain any benefit from this case either. In sum and once more, we can assert that the structural parts that produced the success of the caloric explanation for phase transitions have been incorporated into the kinetic theory of heat.

7. Incommensurability

At this point it is worth considering how our results compare to those found in other frame-theoretic analyses of scientific theory change. Andersen, Barker, and Chen (2006) take a Kuhnian approach to scientific theory change, arguing that often two theories, paradigms or conceptual structures are incommensurable. Here’s what they say:

> In its simplest terms incommensurability is a mismatch between the nodes of two frames that represent what appear to be the same superordinate concepts…The addition or deletion of an attribute will create incommensurability only if the new attribute-value sets violate the no-overlap principle (or another of the hierarchical principles introduced in Section 4.2) (ibid., p. 116–128).

Are the caloric and kinetic frames discussed above incommensurable in Andersen et al.’s sense? To answer this question we need not explicate all of their principles. After all, the violation of one principle is sufficient to establish incommensurability. Take the no-overlap principle. It asserts that “no concepts in a contrast set formed by division of a superordinate are allowed to overlap” (p. 67). In cases of scientific theory change, Andersen et al. argue that this principle is violated when a concept in a new classification scheme classifies entities together that under the old classification scheme were classified apart. In other words, the principle is violated when one applies this principle to the union of the old and the new classification schemes. Andersen et al. offer the following example from the history of astronomy to illustrate their point. Take the superordinate concepts of CELESTIAL and TERRESTRIAL objects in pre-Copernican astronomy. The two concepts form a contrast set because no object can be both celestial and terrestrial. For example, planets are celestial objects but Earth is “by definition terrestrial” (p. 69). The pre-Copernican concept PLANET is subordinate to the superordinate concept CELESTIAL. As we all know, one of the great innovations of Copernican astronomy was the realisation that Earth is a planet. The Copernican concept PLANET thus classifies objects together, e.g. Earth and Venus, which under the pre-Copernican classification scheme were classified apart. Hence, according to Andersen et al., there is a violation of the no-overlap principle and, as a consequence, incommensurability ensues. Returning to the question at the beginning of this paragraph, it seems that the caloric and kinetic frames do indeed qualify as incommensurable in Andersen et al.’s sense. For example, as we move from the caloric explanation of expansion and contraction to the kinetic one (Figs. 7 and 8) we lose the attribute AMOUNT (# OF CALORIC PARTICLES) and gain the attribute AMOUNT (MAGNITUDE OF KINETIC ENERGY). Moreover, the general concept of kinetic energy subdivides into concepts that were taken to be separate under the old paradigm, e.g. HEAT and ELECTRICITY.

Andersen et al.’s analysis of the notion of incommensurability is inadequate for two reasons. First, on the most widely accepted understanding of incommensurability and despite Andersen et al.’s explicit (yet without motivation) dismissal of it, two paradigms are incommensurable if they cannot be compared on semantic, methodological or observational grounds.[17] On this conception the caloric and kinetic frames considered above come out perfectly commensurable. Throughout the eighteenth and nineteenth centuries scientists supporting one theory of heat understood the other theory, what it meant and what its consequences were. Among other things, this allowed them to devise experiments to test both theories. The methodology employed was for the most part common to both parties, e.g. temperature and weight measurements. Moreover, any observations made were generally agreed upon. Psillos (ibid., ch. 6) illustrates this commensurability with a nice set of quotations from leading figures in the debate in the eighteenth and nineteenth centuries. Here’s a telling quote from Laplace and Lavoisier’s *Mémoire sur la chaleur* (as translated by Psillos) who, despite being supporters of the caloric theory, were aware of what one theory could explain better than the other but also of what the two theories had in common:

> We will not decide at all between the two foregoing hypotheses [i.e. the two theories of heat]. Several phenomena seem favourable to the second [i.e. the motion theory], such as the heat produced by the friction of two solid bodies, for example; but there are others which are explained more simply by the other [i.e. the caloric theory]—perhaps they both hold at the same time. So, one must admit their common principles: that is to say, in

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[17] For a clear explication of the notion of incommensurability see Bird (2000).

> either of those, *the quantity of free heat remains always the same in simple mixtures of bodies*…The conservation of the free heat, in simple mixtures of bodies, is, then, independent of those hypotheses about the nature of heat; this is generally admitted by the physicists, and we shall adopt it in the following researches (ibid., p. 118).

Even when observations contradicted one's own theory, the result was not a lapse into denial but rather an attempt to find out which assumption was the culprit. Typically this meant questioning some peripheral assumption rather than the central theory itself. Be that as it may, the central theory was not beyond reproach. Hence the fact that the weight of bodies did not increase when they were heated was a problem for the caloric theory that caloricists could only address by postulating that caloric particles were weightless or had negligible weight.[18]

Second, branding the above frames 'incommensurable' is at best unhelpful for it eschews important relations that exist between them. As we have just demonstrated, in spite of all their differences the caloric and the kinetic frames have structural similarities. Saying that the relevant frames are incomparable merely invites turning one's back on a more sensitive analysis of the degree to which two frames are continuous. In Andersen et al.'s defence, it may be argued that their own notion of incommensurability is not intended to mean incomparability but something more akin to inconsistency. You may recall that the violation of the no-overlap principle implies the existence of an inconsistency between two frames. But, if that's the correct reading of their notion, one wonders why they make use of the term 'incommensurability', which literally means 'lacking a common measure'. As Achinstein (1964) and others have pointed out two theories that are incommensurable cannot be inconsistent and vice-versa. Andersen et al. ignore this point and happily describe cases of inconsistent frames as involving communication and translation failures.[19]

The punchline of this section is that the caloric and kinetic frames considered earlier are not incommensurable. Strictly speaking the two theories are, however, inconsistent. An obvious inconsistency is that heat is taken to be a substance in the caloric theory and a process in the kinetic one. The existence of structural similarities is unaffected by such inconsistencies. Indeed, two genuinely rival theories that share structure but differ in their unobservable posits are bound to be inconsistent. All that matters to the structural realist is that to the extent that the predecessor theory was successful any structural parts responsible for that success are retained (at least in some limit form) in the successor theory. Paradoxical as it may sound inconsistencies explain why a predecessor theory is not as successful as its successor. After all, a successor which allows more precise calculations of a given quantity necessarily conflicts with the calculations of its predecessor.[20]

8. Conclusion

We hope to have provided compelling evidence that at least in the two cases considered the structural parts that helped produce that success were preserved through theory change. Needless to say, more investigation is required to ascertain whether the rest of the caloric theory's successes, if any, were similarly preserved. We are cautiously optimistic that this is indeed the case. The same optimism underwrites our attitude towards other scientific theories that have successful predecessors. However, the proof, as they say, is in the pudding.

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[18] Black acknowledges the severity of the problem by saying: "It must be confessed that the aforementioned fact [i.e. that heating does not bring about a measurable increase in weight] may be stated as a strong objection against this supposition [i.e. the caloric theory]" (ibid., p.45).

[19] It must be noted that Andersen, Barker and Chen distinguish two types of incommensurability, (i) that which involves at least partial communication and translation failures (§4.5.2) and (ii) that which does not (§4.5.1).

[20] A good example of this is the classical concept of momentum which is less predictively successful than (and also inconsistent to) the corresponding concept in special relativity. The latter's introduction of the so-called Lorentz term γ makes all the difference. Yet one must not forget that the two concepts still share structural features, for they both define momentum as a function of mass and velocity.