The Caloric Concept under a Frame-Theoretic Spotlight

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Abstract. Under what circumstances, if any, are we warranted to assert that a theory is true or at least approximately true? 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 among them those arising from scientific theory change. For example, if, as scientific realists suggest, successive theories are to increasingly approximate truth, any theory changes must not significantly undermine the historical accumulation of explanatory and predictive successes. In more detail, an outdated theory T which enjoyed some measure of success must, according to the realist, be: (i) partially true precisely because some of its theoretical claims are responsible for its success and (ii) superseded by a (strictly) more approximately true theory T* which, of course, preserves T's successful theoretical claims. In this paper we use the caloric theory of heat, which plays the role of the outdated theory T, and the modern kinetic theory of heat, which is the contemporarily accepted theory T*, to confirm this consequence of scientific realism. We conduct our investigation by means of frame-theory because the frame-theoretic structure of these two theories is especially apt for revealing how the caloric theory's truth-bearing parts have survived into the kinetic theory.

Keywords: frame theory, caloric theory, kinetic theory, scientific realism, structural realism, incommensurability.

1. Introduction

Under what circumstances, if any, are we warranted to assert that a theory is true or at least approximately true? 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 approximate truth, any theory changes must not undermine the historical accumulation of explanatory and predictive successes. In more detail, an outdated theory T which enjoyed some measure of success must, according to the realist, be: (i) partially true precisely because some of its theoretical claims are responsible for its success and (ii) superseded by a (strictly) more approximately true theory T* which, of course, preserves T's successful theoretical claims.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 confirm this consequence of scientific realism. We conduct our investigation by means of frame-theory because the frame-theoretic structure of these two theories is especially apt for revealing how the caloric theory's truth-bearing parts have survived into the kinetic theory.[1]

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

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[1] Schurz and Votsis (2010) provide a frame-theoretic illustration of the structural correspondence between the phlogiston and oxygen theories of combustion (which is the written version of a paper presented at the CFT07 conference). The paper confirms that frame-theory is a fruitful tool for reconstructing scientific theories and their interrelations.

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 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, what kind of knowledge, if any, does science yield? The realist answer is that predictively and explanatorily successful theories give rise to true, or at least approximately true, statements about the observable and unobservable world.[2] To guarantee that successive theories are strictly converging towards the truth, a predecessor theory's success and any theoretical principles responsible for that success need to be preserved in that theory's successors. The anti-realist answer rejects one or more of the aforementioned claims. Anti-realists hold that it is not the case that, or at least we cannot know whether, any scientific theories produce true or approximately true statements about the world. Some anti-realists, famously van Fraassen, restrict this scepticism to claims about the unobservable world. Successive theories, anti-realists claim, are not converging towards the truth or at least we cannot know that they are. Scientific knowledge is therefore unlikely to be cumulative. All theories, concepts and ontologies eventually end up in the scrapheap of discarded science.

To support this last point, anti-realists often turn to the Pessimistic Meta-Induction argument (PMI). According to Larry Laudan's (1977) formulation, the history of science supplies ample evidence against realism in the form of successful theories that are now considered false. In other words, he questions the reliability of inductive inferences from explanatory and predictive success to (approximate) truth. Assuming Laudan is right, anti-realists 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 runs even deeper as future theories are also destined to failure. The argument thus provides some prima facie reasons to suspend our belief in the (approximate) truth of our theories and the referential success of their theoretical terms. In this respect it challenges the main realist argument or intuition, the so-called 'no miracles argument' (NMA). According to the NMA, 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 world, i.e. that they are (approximately) true.

Realists have reacted in various ways to the PMI. 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 components are discarded but only those that are *inessential* or *idle* for the theory's success. Their abandonment is thus inconsequential for the realist. So long as the essential components survive into the new theory there is no cause for alarm. After all, it is these components that presumably granted their parent theory the designation 'approximately true' 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' approach.

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[2] Hereafter this disjunction is expressed by the phrase '(approximate) truth'.

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 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 and helped put this view on the philosophical map, explains that although scientific revolutions lead to radical ontological change – pace PMI – the structural parts of a predecessor theory responsible for its success are still considered approximately true for they survive into the new theory – pace NMA.

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 Figure 1 for the concept BIRD.[3] For sake of simplicity only two attributes in the bird-frame are included: BEAK which takes the values ROUND and POINTED, and FOOT which takes the values WEBBED and CLAWED. A complete specification of the frame requires additional attributes.

Note that in the frame-theoretic terminology, 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 (such as living thing: 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 Figure 1 at the right side where the values corresponding to the subordinate concepts LAND-BIRD and WATER-BIRD are specified.

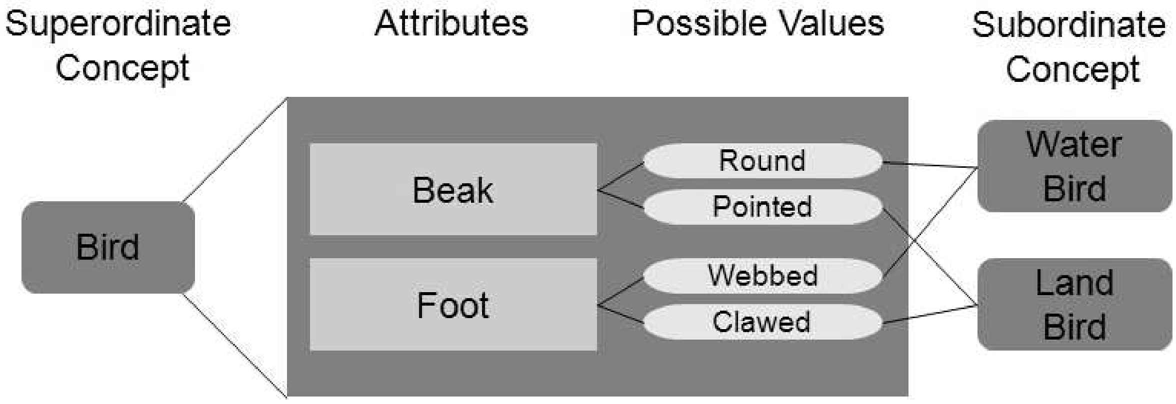

Figure 1. Adapted from Andersen, Barker and Chen (2006, p. 70). The subordinate concepts are value-instantiations of the superordinate concept.

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

In Figure 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 Figure 2).

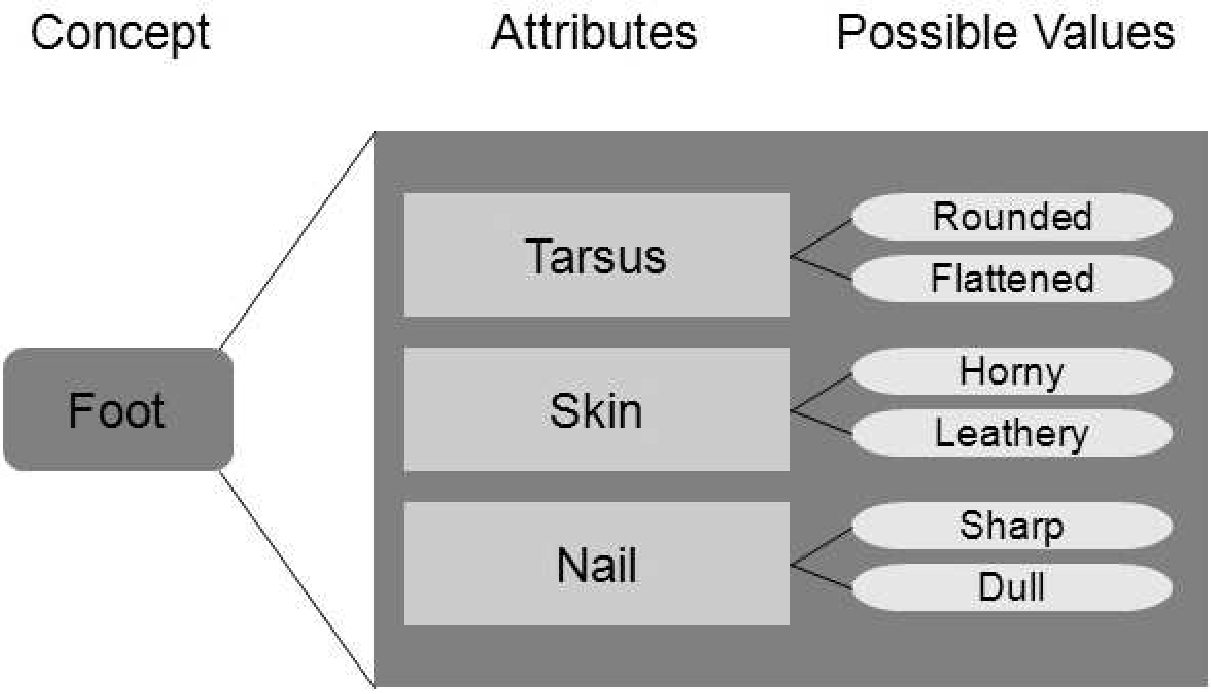

Figure 2. Adapted from Andersen, Barker and Chen (2006, p.58).

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 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 are 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 because our ability to construct a complete frame is limited by our knowledge of the ontological category at issue. Since we very rarely have complete information in science it is useful to have a system 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 Figure 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.

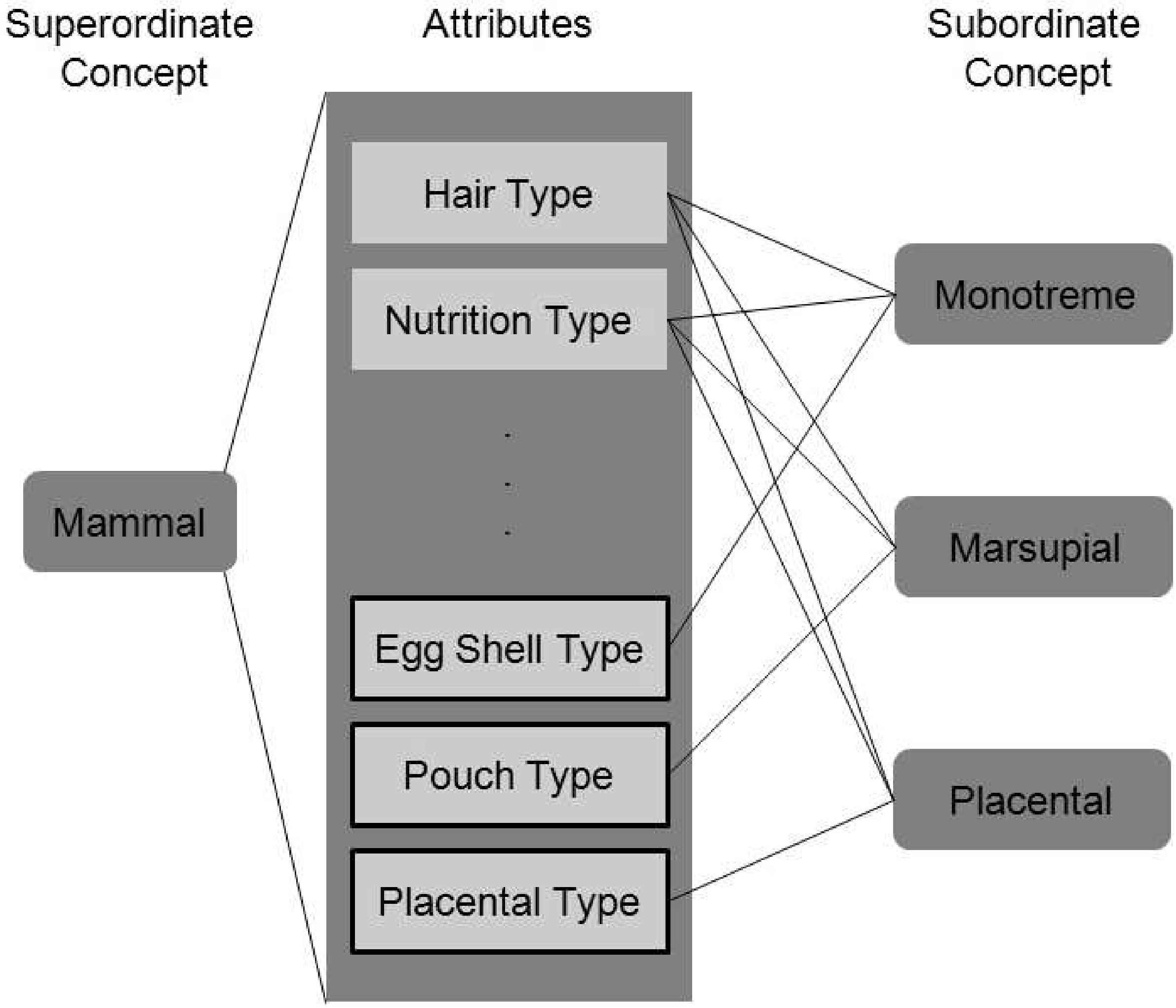

Figure 3. Partial frame for mammal. Note the value-attribute constraint that holds between the value-instantiations of the superordinate concept (i.e. the subordinate concepts) and their respective attributes (shown here with a black outline).

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 Figure 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 feature that is important to mention is that frame theory allow us to represent several sorts of *constraints* concerning values and attributes. Some constraints may be strict while others may just express an imperfect correlation. The first type of constraints is value-attribute constraints which have been already explained above. For example, the value OVIPAROUS (i.e. egg-laying) of the attribute REPRODUCTION *implies* the introduction of additional attributes like EGG SHELL TYPE. A second type of constraints is *attribute-attribute constraints*. For example, the attribute BEAK *implies* the attribute NECK in the frame of the concept BIRD. The third and maybe most important kind of constraints are *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 will indicate constraints in frame diagrams by double-headed arrows.

4. Why Frame Theory?

Frame theory lays bare all sorts of relations between scientific concepts, theories and ontologies. By making explicit the inner structure of a scientific concept, frame theory in fact allows one to compare scientific concepts on the basis of shared or distinct attributes and values. 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 the 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 theories. 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 such tool that has been the choice of a large subsection of the philosophy of science community is formal reconstruction within a logical language. 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). The main advantage of frame theory over logical or model-theoretic reconstructions is that a frame provides an economic and cognitively very intuitive representation of a structure whose logical or model-theoretic reconstruction would be a rather complicated set of axioms or models-characterized-by-axioms. Certain elements of frames, for example the set of attributes and their possible values, are quite close to model-theoretic representations, while other elements of frames, such as constraints, are closer to logical reconstructions.[4]

Some authors have argued that frame theory 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. But as we have already explained in the beginning of this paper, the values of an attribute may, of course, also be the structure of a vector space of real numbers. 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. The situation is rather the opposite: frame theory is more general than measurement theory because it does not presuppose that the values of concepts are given by metric scales, though it of course allows for that possibility.

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.

It is generally agreed that the caloric theory enjoyed some measure of success in explaining and/or predicting phenomena. Amongst its successes one can 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 will here focus on Lavoisier’s version because it was the most influential and most articulated one. It will become obvious from the discussion below that this choice has no effect on the validity of our main points.

Recall that caloric was thought of as a special kind of substance, different from ordinary matter. This difference is reflected in Figure 4 where HEAT AS CALORIC is an instantiation of a more general frame corresponding to the superordinate concept KIND OF SUBSTANCE.

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[4] 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.

[5] This claim was made by Frank Zenker in his presentation at the CTF09 conference.

[6] For example, the Atomists and the Epicureans conceived of the element fire as 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.

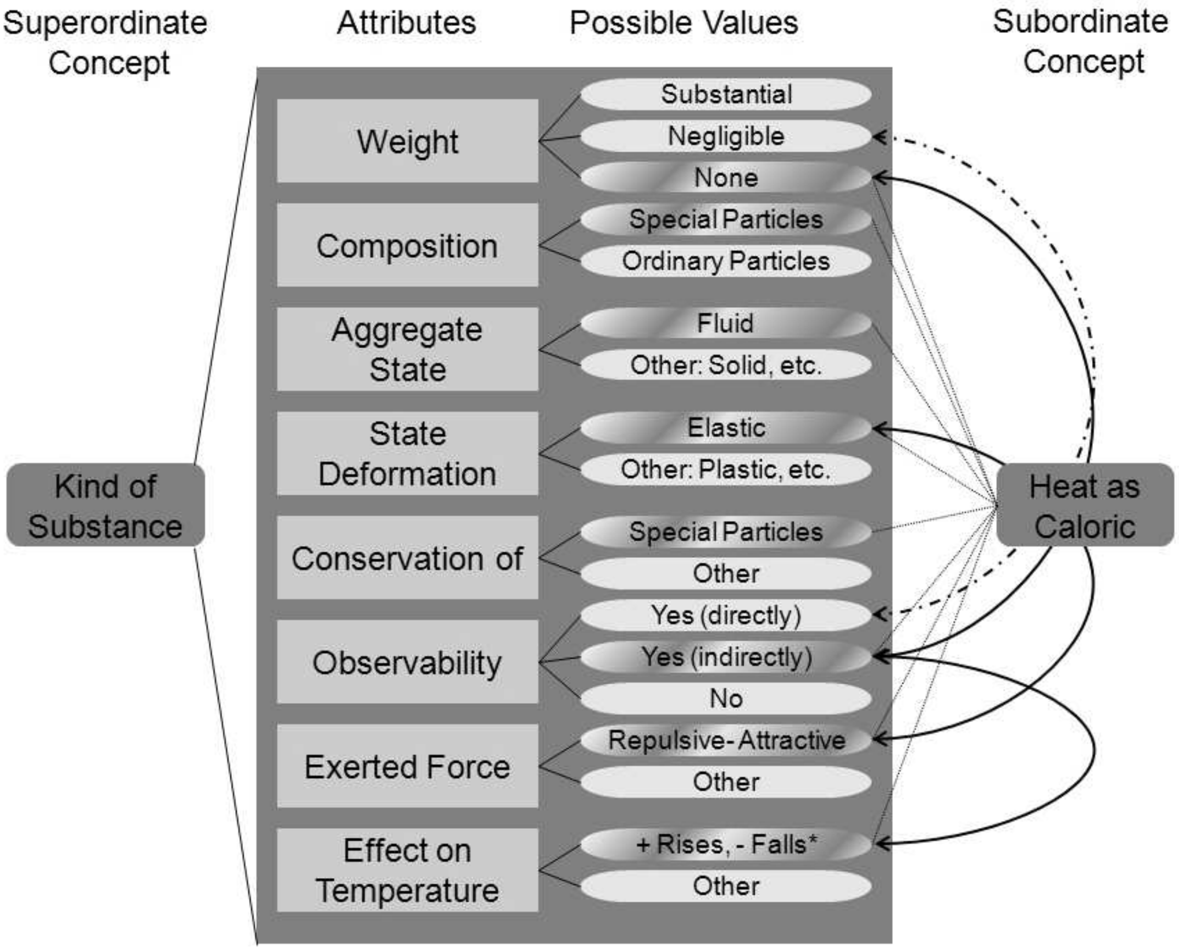

Figure 4. The partial frame for Lavoisier's notion of heat as caloric which is shown here as an instantiation of the more general frame 'kind of substance'. Fields of instantiated values are shaded. The star in the instantiated value of the attribute EFFECT ON TEMPERATURE indicates that this relationship holds typically but not always.

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 Figure 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 heat. According to this theory, whose roots also go back to Antiquity, heat is a consequence of the *motion* of particles. Whether it 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

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[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.

nineteenth 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 two ice sheets, the kinetic theory could not successfully compete with it (see, for example, Fox 1971). In what follows, we will consider the frame for the modern version of the kinetic 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. In Figure 5, we have constructed the partial frame for kinetic energy. It is an instantiation of the more general frame for the superordinate concept ENERGY. The attribute KIND is left uninstantiated in the frame for kinetic energy.

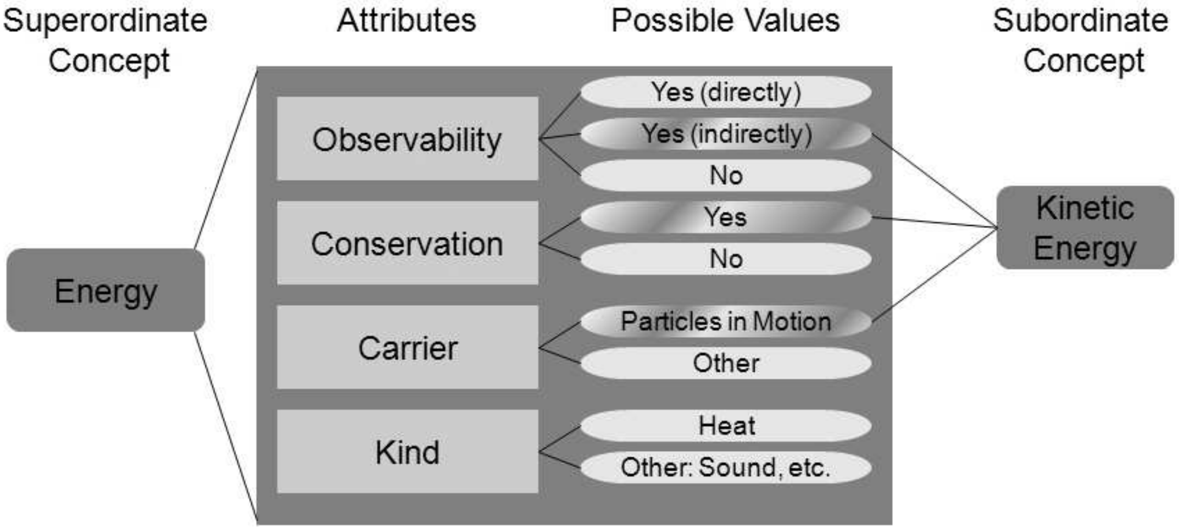

Figure 5. The partial frame for kinetic energy as an instantiation of the frame for energy. Instantiated values are shaded. The attribute ‘kind’ is left uninstantiated.

There are various forms of kinetic energy, among them electrical, sound and heat. We are, of course, interested in the last mentioned. Heat, according to the kinetic theory, is a process that takes place when energy is transferred from one object to another. In simple words, heat is the kinetic energy possessed by the relevant physical system. Figure 6 displays the frame for the concept HEAT AS AN INSTANCE OF KINETIC ENERGY. It arises by instantiating the attribute KIND of the frame for kinetic energy to the value HEAT. 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.

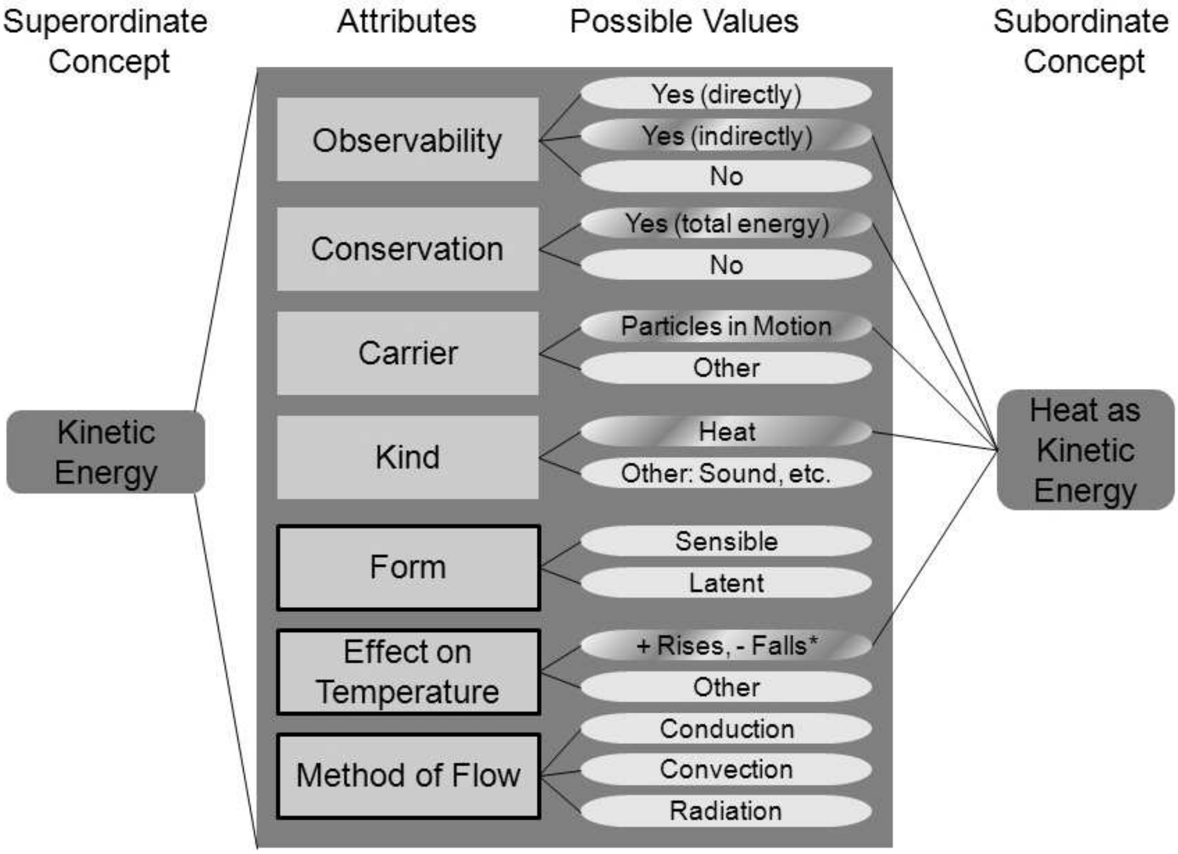

Figure 6. The partial frame for heat as kinetic energy. Three attributes (shown here with a black outline) are added to this frame by way of value-attribute-constraints as in Figure 3 above.

How can the contents of the caloric theory and the kinetic theory of heat – whose concepts are prima facie incommensurable in Kuhn’s sense – be compared by means of frame theory? We observe that the frame for HEAT AS AN INSTANCE OF KINETIC ENERGY in Figure 6 is similar in some respects to the frame for HEAT AS CALORIC in Figure 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 theories are not entirely incommensurable but share three attributes. However, this 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 trivially satisfiable. In the section that follows, we will argue that there are more robust cases of correspondence between the two frames.

6. Testing Structural Realism

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 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 these parts are in fact solely responsible for the success the caloric theory enjoyed. Of all the realist views, we take structural realism to be the most defensible one.[9] 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 our limited space here we will test the above views against only two of the caloric theory's successes that we listed earlier. These are: (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.

The caloricists explained thermal expansion and contraction by arguing that the first involves the addition of caloric to a body while the second involves its removal (see Figure 7). 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. The kinetic theory explanation of the same phenomena involves the increase and decrease of kinetic energy (see Figure 8). When a body's kinetic energy is increased, its 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 of 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.

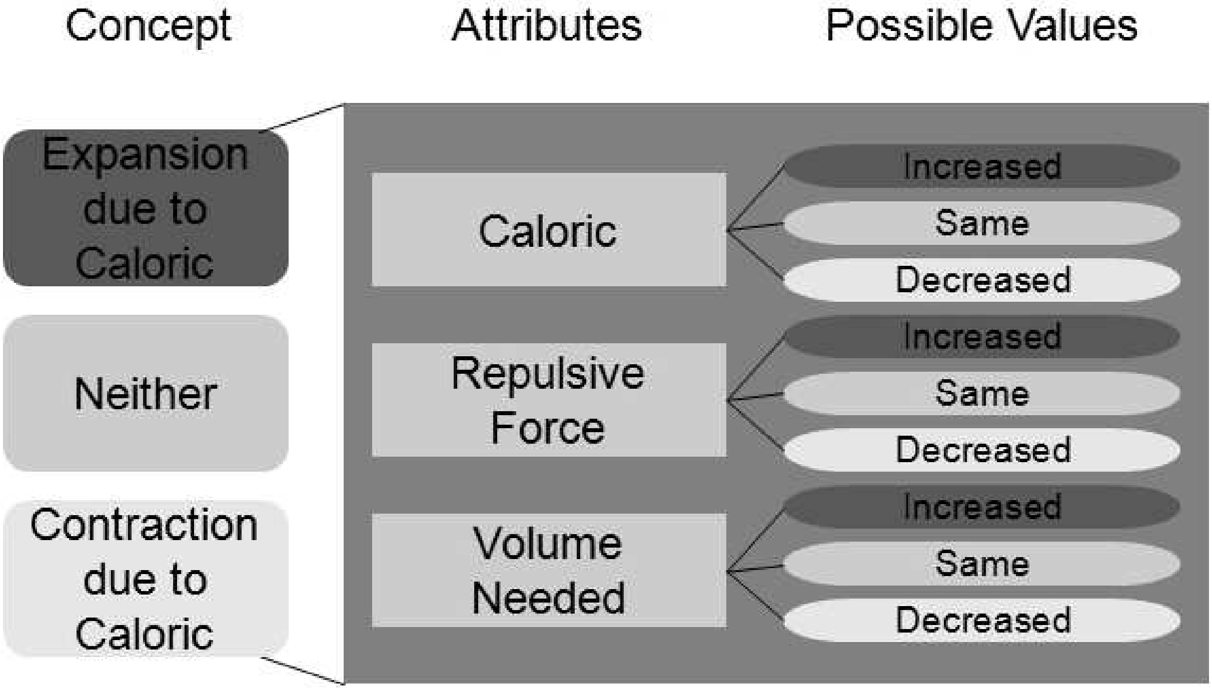

Figure 7. The partial frame for the caloric explanation of the thermal expansion and contraction of a substance. Different shades indicate that the instantiated values correspond to the sub-concepts of thermal expansion and contraction.

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[9] Although we have both independently argued for structural realism elsewhere (see, for example, Votsis 2005 and Schurz 2009), neither of us is blindly committed to the view.

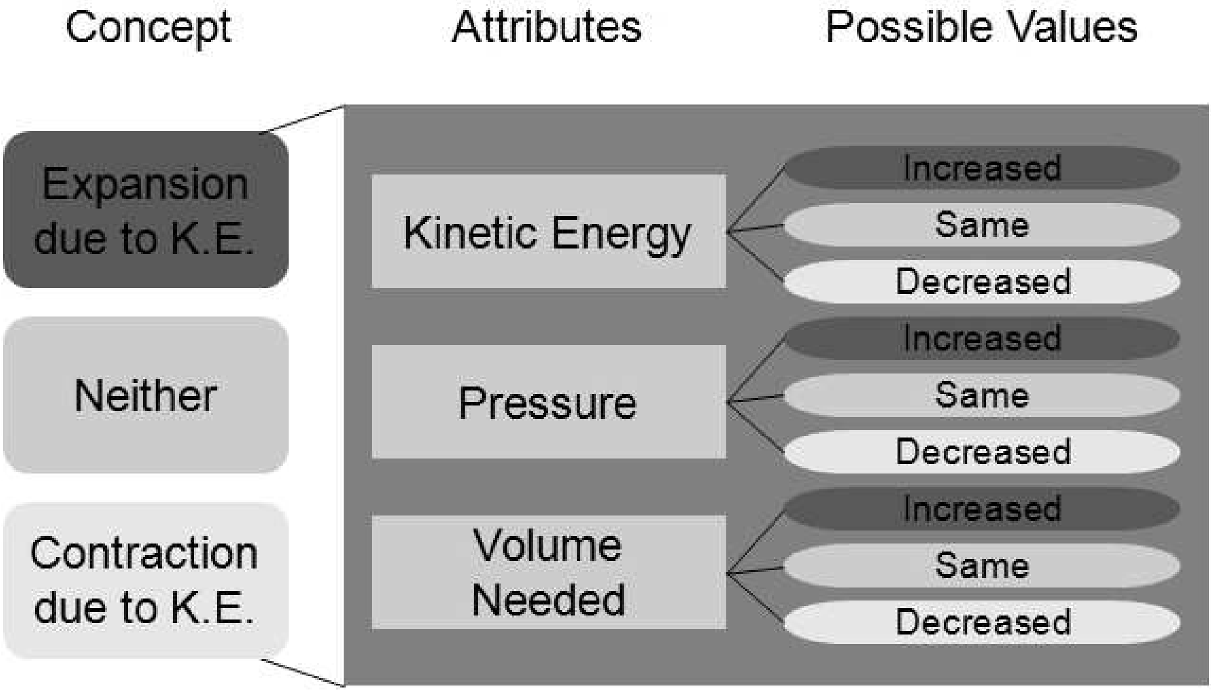

Figure 8. The partial frame for the kinetic explanation of the thermal expansion and contraction of a substance. Different shades indicate that the instantiated values correspond to the sub-concepts of thermal expansion and contraction.

It should be painfully obvious that although the two explanations employ different conceptions of heat they still share the same structure. As the quantity of heat (caloric in the one case, kinetic energy in the other) is increased/decreased the force (repulsive in the one case, pressure in the other) is increased/decreased and that in turn leads to an increase/decrease in volume needed. If we take the kinetic explanation of these phenomena to be true or at least approximately true 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 ontology were wrong, i.e. the existence of caloric and its repulsive force. This is precisely the kind of result that lends credence to structural realism (as opposed to traditional realism or anti-realism). That is, to the extent that the caloric explanation of expansion and contraction enjoyed genuine success, the structural parts responsible for that success have been incorporated into the kinetic theory of heat.

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.[10] To

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

explain this phenomenon, Black distinguished between *latent* and *sensible* forms of caloric (see Figure 9). According to Black, when ice melts 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.[11] Non-latent or ordinary heat was called 'sensible' for obvious reasons.

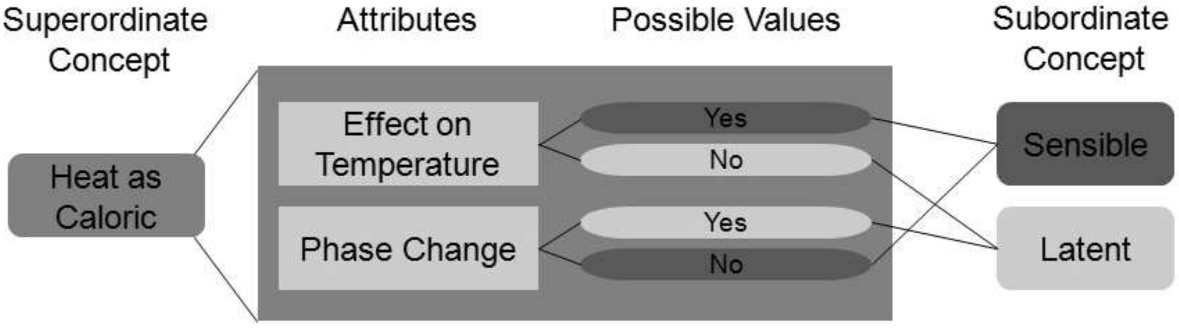

Figure 9. The partial frame for the caloric 'explanation' of phase change. Different shades indicate how the instantiated values correspond to the two sub-concepts.

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 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 Figure 10).[12]

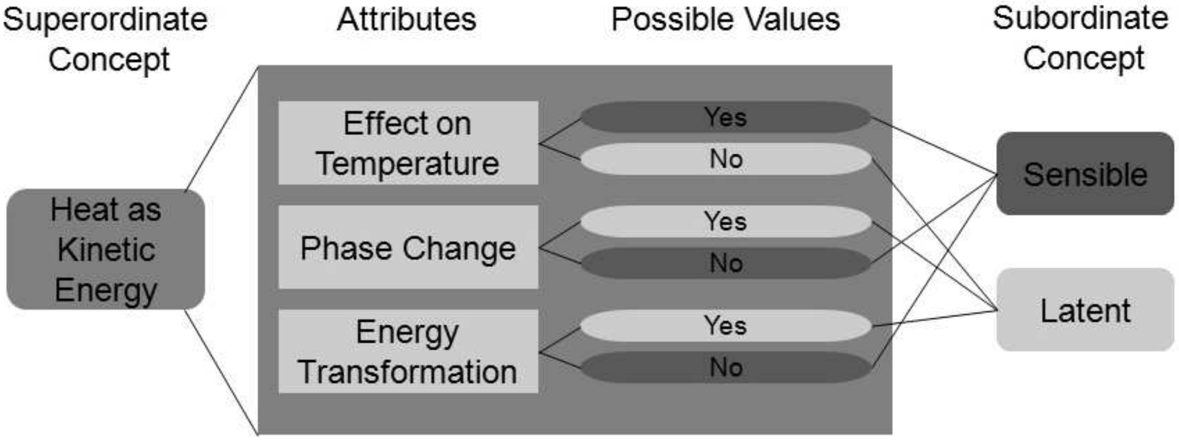

Figure 10. The partial frame for the modern explanation of phase change. Different shades indicate how the instantiated values correspond to the two sub-concepts.

Unlike the expansion-contraction case, the correspondence between the two 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

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[11] 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.

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

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 during this process (viz. turned into potential energy) 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. Someone like van Fraassen (2006) would happily point out that the preservation of empirical substructures 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'. Thus the caloric and the kinetic explanation share at least some theoretical structure, namely that there exists an additional cause that plays a role in phase transitions. Once more, we can assert that to the extent that the caloric explanation for phase transitions enjoyed genuine success, the structural parts responsible for that success 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, Barker and Chen'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, this principle is violated when the introduction of a new concept in a successor frame subdivides into concepts that were not classified together in the predecessor frame (p. 89). In other words, the principle is violated when the new classification is inconsistent with the old one. The caloric and kinetic frames discussed above thus seem to qualify as incommensurable. 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 CALORIC and gain the attribute KINETIC ENERGY. Moreover, the corresponding concept for kinetic energy subdivides into concepts that were taken to be separate under the caloric theory, e.g. HEAT and ELECTRICITY (see Figure 6).

We find Andersen, Barker and Chen's analysis of the notion of incommensurability inadequate for two reasons. First, on the most widely accepted understanding of incommensurability, according to which two frames are incommensurable if they cannot be compared on methodological, observational or semantic grounds, the caloric and kinetic frames considered above come out perfectly commensurable.[13] Throughout the eighteenth and nineteenth centuries scientists supporting one theory of heat understood the other theory and fruitfully compared the two. 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. 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.[14]

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 potential similarities. This is all the more astounding because Andersen, Barker and Chen employ frame theory to presumably supply a more sensitive analysis. Perhaps what they mean by incommensurability is not incomparability but inconsistency. After all, the violation of the no-overlap principle implies the existence of an inconsistency between two frames. But, if that's the case, 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, Barker and Chen seem oblivious of this result and happily describe cases of inconsistent frames as involving communication and translation failures.[15]

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 unperturbed by such inconsistencies. 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 in the successor theory. Paradoxical as it may sound inconsistencies often explain why a predecessor theory is not as successful as its successor. For example, a successor which allows more precise calculations of a given quantity necessarily conflicts with the calculations of its predecessor.[16]

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

[14] 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).

[15] 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).

[16] 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.

8. Conclusion

We hope to have provided compelling evidence that, at least in the two cases considered, the structural parts responsible for the caloric theory's successes are preserved in the kinetic theory of heat. Needless to say, more effort is required to ascertain whether the rest of the caloric theory's successes are similarly preserved but we are cautiously optimistic that this will be the case. The same optimism underwrites our attitude towards other scientific theories that have successful predecessors. The proof, as they say, is in the pudding.

Acknowledgements

We would like to thank the German Research Foundation (Deutsche Forschungsgemeinschaft) for funding our project B6 (part of the interdisciplinary research unit FOR 600 'Functional Concepts and Frames') under which this paper has been written.

References

Achinstein, P. (1964). On the Meaning of Scientific Terms. *Journal of Philosophy*, *61*(17), 497-509.
Andersen, H., Barker, P. & Chen, X. (2006). *The Cognitive Structure of Scientific Revolutions*. Cambridge: Cambridge University Press.
Barsalou, L. W. (1992). Frames, concepts, and conceptual fields. In A. Lehrer & E. F. Kittay (Eds.), *Frames, fields, and contrasts* (pp. 21–74). Hillsdale, NJ: Lawrence Erlbaum Associates.
Bird, A. (2000). *Thomas Kuhn*. Princeton, NJ: Princeton University Press.
Black, J. (1803). *Lectures on the Elements of Chemistry*. published from his manuscripts by John Robinson, Edinburgh: Mundell and Son.
Fox, R. (1971). *The Caloric Theory of Gases*: *From Lavoisier to Regnault*. Oxford: Clarendon Press.
Home, R. W. (2003). Mechanics and Experimental Physics. In R. Porter (Ed.), *The Cambridge History of Science*, vol. 4: Eighteenth-Century Science, Cambridge: Cambridge University Press.
Laudan, L. (1977). *Progress and its Problems*: *Toward a Theory of Scientific Growth*. Berkeley: University of California Press.
Psillos, S. (1999). *Scientific Realism*: *How Science Tracks Truth*. London: Routledge.
Schurz, G., & Votsis, I. (2010). A Preliminary Application of Frame-Theory to the Philosophy of Science: The Phlogiston-Oxygen Case. Paper presented at the Duesseldorf CTF07 conference, published in this volume.
Schurz, G. (2009). When Empirical Success Implies Theoretical Reference: A Structural Correspondence Theorem. *British Journal for the Philosophy of Science*, *60*(1), 101-133.
Sneed, J.D. (1971). *The Logical Structure of Mathematical Physics*. Dordrecht: Reidel.
Van Fraassen, B. (2006). Structure: Its Shadow and Substance. *British Journal for the Philosophy of Science*, *57*(2), 275-307.
Votsis, I. (2005). The Upward Path to Structural Realism. *Philosophy of Science*, *72*(5), 1361-1372.