Chapter 4
Reconstructing Scientific Theory Change by Means of Frames

Gerhard Schurz and Ioannis Votsis

Abstract This paper has two aims. The first is to show the usefulness and intuitiveness of frame theory in reconstructing scientific classification systems. The second is to employ such reconstructions in order to make headway in the scientific realism debate and, more specifically, in the question concerning scientific theory change. Two case studies are utilised with the second aim in mind. The first concerns the transition from the phlogiston theory to the oxygen theory of combustion, while the second concerns the transition from the caloric theory to the kinetic theory of heat. Frame-theoretic reconstructions of these theories reveal substantial structural continuities across theory change. This outcome supports a structural realist view of science, according to which successful scientific theories reveal only structural features of the unobservable world.

Keywords Frames • Scientific classification system • Structural realism • Theory change

4.1 Introduction

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heat. Frame-theoretic reconstructions of these theories reveal substantial structural continuities across theory change. This outcome supports a structural realist view of science, according to which successful scientific theories reveal only structural features of the unobservable world.

4.2 Frames and Scientific Classification

A frame represents a super-ordinate category (henceforth: ‘super-category’) and therefore its corresponding concept by a recursive system of functional attributes. Systems are recursive because attributes and even the values of attributes are themselves concepts and may therefore be analysed into further frames. We call collections of such nested frames ‘nets’. It should be obvious that frames and nets of frames define systems of classification for the objects of the underlying categories. This makes frames an excellent tool for the investigation of the conceptual systems of scientific theories and their respective ontologies (cf. Chen and Barker 2000; Chen 2003).

Figures 4.1 and 4.2 illustrate how frame-theory can be used to represent biological classifications. The frames exhibit many of the trademark features of frame-theoretic representations, features that are particularly apt at capturing the subtleties of scientific classification (see Petersen 2007). In what follows, we consider nine noteworthy features.

The first feature worth mentioning has already been mentioned. It is the recursive character of frames, illustrated in both Figs. 4.1 and 4.2 by the fact that certain

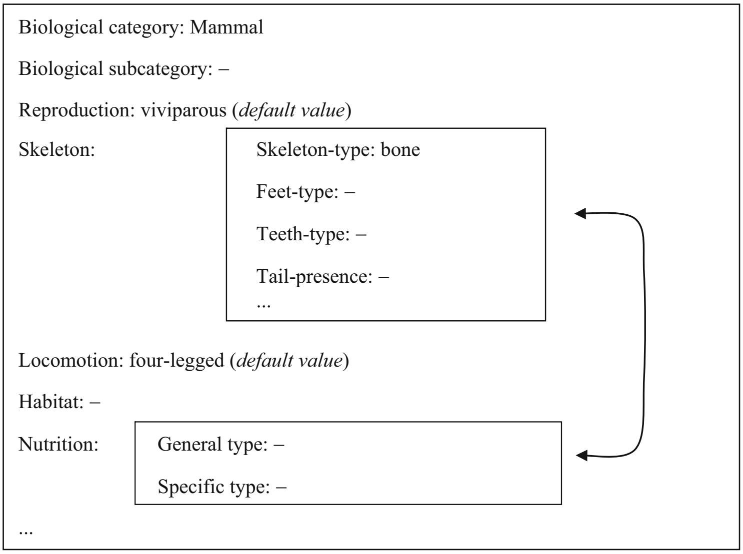

Fig. 4.1 Partial frame for the biological super-category “mammal”

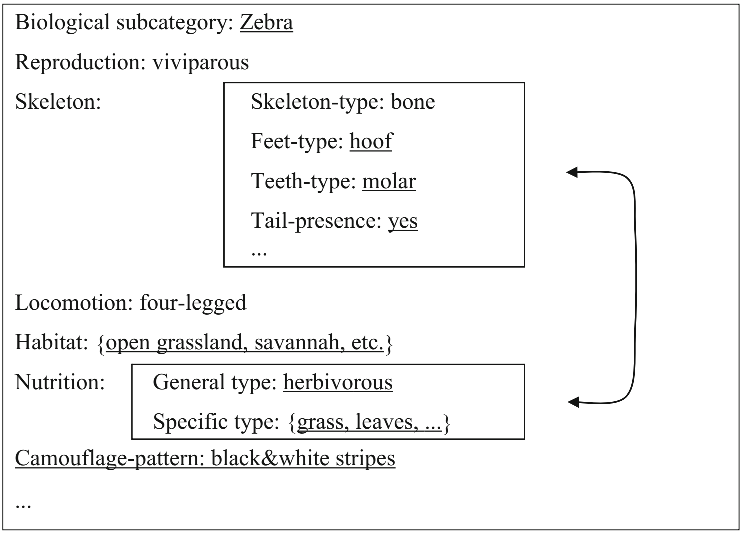

Fig. 4.2 Partial frame for the subcategory "zebra". New values instantiated by the zebra-frame are underlined

attributes correspond to (nested) frames. For example, the attribute "skeleton type" is also a frame, possessing its own attributes.

The second feature worth noting is that when representing super-categories the values of most attributes in the frame are not specified. This is illustrated by Fig. 4.1 which is a frame for the super-category mammal. Values are specified in the frames of the sub-categories. Thus, the frame for the sub-category zebra (i.e. Fig. 4.2) contains values for all the remaining mammal-attributes. Sometimes sub-categories leave some attributes uninstantiated. These attributes get instantiated in sub-categories further down the hierarchy.

This brings us to the third noteworthy feature. Frames may contain incomplete information regarding their target category. For example, not all attributes belonging to a category may be known. Such frames are called 'partial'. In science we often do not have the complete story regarding a classification system. So the ability to represent incomplete information in terms of partial frames is one of frame theory's strengths.

The fourth feature of note is that some values are there by default. This is the case with the value "viviparous" of the attribute "reproduction" in Fig. 4.1. It is a default value because most species of mammals are viviparous – they give birth to live young. Platypuses are mammals but are oviparous – they lay eggs. Default values become fixed lower down the hierarchy of frames, e.g. the value "viviparous" is fixed in the zebra-frame.

The fifth noteworthy feature is the type of constraints available. In both figures there is a constraint between the values of attributes "general type of nutrition" and "teeth-type", indicated by the double-edged arrow. In this case the constraint is a non-strict empirical correlation (or uncertain biological law): herbivorous nutrition correlates well with (but does not necessitate) molar teeth; carnivorous nutrition correlates well with (but does not necessitate) fang teeth, etc. Some constraints are strict, others are non-strict. Moreover, some constraints are synthetic (i.e. empirical), while others are analytic (i.e. they hold purely by virtue of the meaning of the concepts they relate).

The sixth feature worth noting also concerns types of constraints. In the paragraph above the constraints hold between the values of different attributes. These are called ‘value-value’ constraints. There are also ‘value-attribute’ constraints. Thus the value “zebra” for the biological sub-category brings with it the attribute “camouflage-pattern”. Moreover, there are ‘attribute-attribute’ constraints. Thus the attribute “specific type of nutrition” goes hand in hand with the attribute “general type of nutrition”.

Number seven in our list of notable features is that sub-category frames sometimes contain attributes not found in the frames of their respective super-categories. Thus in the zebra-frame the attribute “camouflage-pattern” is new.

The eighth noteworthy feature concerns how attributes ought to be understood. An attribute is not a property but a space of possible properties that belong to the same dimension. The simplest dimension is binary. For example, the attribute “tail-presence” takes either ‘yes’ or ‘no’ as values. Other more complex dimensions, e.g. real-valued ones, abound in science and can be accommodated within frame-theoretic reconstructions.

The ninth and final feature we make note of is that sometimes an attribute can take more than one value at the same time. For example, the attribute “habitat” in Fig. 4.2 has more than one value assigned to it for the simple reason that zebras can be found in different habitats.

The problem with the biological classifications in Figs. 4.1 and 4.2 is that they have low to moderate *systematic power*. This notion captures the degree to which all the values of a given frame are determined by the values of a few core attributes. Closely connected to systematic power is the notion of *diagnostic efficiency*. This captures the idea of how easy it is to diagnose whether an object belongs to a given category. Take the zebra-frame again. The values of the sub-frame “skeleton” do not determine many of the values of the other attributes. For example, hoofed animals need not live in open grassland or the savannah, as they can also be found living in mountainous terrain. This deficiency in systematic power also impairs the frame’s diagnostic efficiency. An example of a frame with an extremely high systematic power and diagnostic efficiency is that of the periodic table of elements in chemistry – see Fig. 4.3. The atomic number – and if we are also interested in nuclear stability and decay properties also the mass number – determines all further attributes and their values. This determination takes the form of a strictly general value-attribute and value-value constraint.

In sum, we hope to have made clear how frame theory’s central features facilitate the representation of scientific classifications in intuitive ways. It is now time to apply frame-theory to a central problem in the philosophy of science, namely that of the scientific realism debate and, in particular, the question of theory change.

Chemical category: Element

Chemical subcategory: – [Name of element]

Atomic number (= number of protons): –

Mass number (= number of protons and neutrons): –

Various further attributes, all strictly determined by atomic (and mass) number, e.g.:

Melting point: –

Boiling point: –

Electronegativity: –

Character: (metallic or semi-metallic or non-metallic): –

If metallic character: solubility in different kinds of acids;

If non-metallic character: solubility in different kinds of bases; etc.

Fig. 4.3 Partial frame for the periodic table – the values of all additional attributes are determined by atomic (and mass) number

4.3 Scientific Realism and the Question of Theory Change

There are different kinds of realists and anti-realists. What most realists agree on is that theories with enough predictive and explanatorily success entail true, or at least partially true, claims about the observable and the unobservable world.[1,2] Anti-realists deny this claim. They typically argue that it is not the case or at least that we cannot know whether scientific theories contain true or partially true statements. One of the arguments employed by anti-realists is that from the pessimistic meta-induction (PMI). According to this argument, the history of science supplies ample evidence against realism in the form of past successful theories that are now considered false and whose central theoretical terms refer to nothing. In other words, the argument questions the reliability of inductive inferences from explanatory and predictive success to truth or partial truth and to referential success. The PMI thus directly challenges the realists' no miracles argument (NMA). According to this latter argument, the predictive and explanatory success of theories is not a consequence of an exceedingly lucky series of coincidences but rather a consequence of such theories truthfully uncovering aspects of the observable and the unobservable worlds. The PMI also challenges a widespread expectation amongst realists, namely that successive and successful scientific theories converge towards the truth.

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[1] Following van Fraassen (1980), unobservables are understood as those objects, phenomena or events that we can only detect with instruments, i.e. never with our unaided senses.

[2] Realists often disagree on where to place the cut-off point concerning how much success a theory needs in order to entail true or partially true claims about the unobservable world. One popular criterion is the ability to make novel predictions, though even here there is considerable controversy – see Worrall (2002).

Most realists take the challenges issued by the PMI seriously and attempt to make sense of the historical record of science without sacrificing their adherence to the central tenets of realism. One important observation the realists made early on is that not all parts of a successful theory play an indispensable role in its success. For this reason not all parts are equally well-confirmed. Indeed some parts lack confirmation altogether. There is thus no reason for the realist to worry about the abandonment of such parts in the wake of scientific revolutions. What the realist should worry about is whether the well-confirmed parts survive. So long as they do, at least in some limit form, the realist has nothing to fear from the PMI. Even the convergence claim can be saved albeit in a more refined guise: If successful theories that supersede each other are to converge towards (or at least get closer to) a true description of the (observable and unobservable) world, then some of their claims about the unobservable world are expected to play an indispensable role in the production of at least part of that success and, unless non-rational considerations take precedence, these claims are expected to survive theory change at least in some limit form.[3]

As mentioned above, there are different kinds of realism. We are keen on structural realism, particularly the epistemic variety.[4] According to this view, successful scientific theories cannot reveal more than structural features of the unobservable world. This view separates structural realists from standard scientific realists as the latter put no such restriction on what we can know about unobservables. As a consequence of their view, structural realists expect the historical record to exhibit only structural continuity at the unobservable level. In more detail and largely following Worrall (1989), structural realists hold that scientific revolutions result in the abandonment of specific unobservable posits – in accordance with the PMI – but not of the structure of such posits when it plays an indispensable role for at least part of the success enjoyed by the abandoned theory – in accordance with the NMA. In the sections that follow we test this claim against two cases of theory change: (1) the transition from the phlogiston theory to the oxygen theory of combustion and (2) the transition from the caloric theory to the kinetic theory of heat.

Before we turn our attention to these case studies it is worth saying a few words on what it is that we hope to achieve with frame theory in this debate. Our investigation employs frame theory because it enables us to make explicit the inner structure of scientific concepts in an intuitive manner. Concepts belonging to distinct scientific theories can be compared with relative ease to find out whether, and, if so to what extent, any continuity between them exists. This ability is particularly valuable for the debate at hand since, as we just saw, a lot hangs on whether successive scientific theories exhibit continuities, what form these continuities take, whether the continuities are highly correlated with the successes of those theories and what is the best explanation for these correlations.

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[3] For the notion of survival or correspondence in a limit form see Redhead (2001).

[4] For a comprehensive critical survey of the literature on structural realism see Frigg and Votsis (2011).

4.4 The Phlogiston-Oxygen Case

The theory of phlogiston goes back to Johann Becher and Georg Stahl – the latter coined the term ‘phlogiston’ – and was developed, among others by Henry Cavendish and Joseph Priestley (cf. McCann 1978, Chap. 2). According to this theory, combustible substances contain phlogiston, which is the bearer of combustibility. When combustion, calcination or roasting of a substance *X* takes place, *X* delivers its phlogiston as a hot flame or an evaporating inflammable gas, leaving behind a dephlogisticated substance-specific residual (a so-called ‘calx’). This process is called *dephlogistication*, and the inverted process *phlogistication*. It is widely known today that the theory of phlogiston had difficulty explaining a number of phenomena – in Kuhnian terms it faced a number of anomalies (see Kuhn 1962). What is not so widely known is that it enjoyed some non-negligible measure of success in that it was able to predict and to some extent explain what would happen to metals during certain conditions we now associate with oxidation and salification as well as what would happen during the inverse of such processes – what we now associate with the retransformation of metal calxes into pure metals (cf. Carrier 2004; Schurz 2004, 2009).

Rivalling the theory of phlogiston was the oxygen theory of combustion and calcination developed in the 1780s by Antoine Lavoisier. The generalised form of this theory is now part of modern chemistry. According to Lavoisier’s oxygen theory, combustion or calcination of a substance *X* consists in the oxidation of *X*, i.e. in modern terms its forming a polarized bond with oxygen. In the generalized oxidation theory, the oxidizing substance need not be oxygen but it must be strongly electronegative, e.g. a halogen. Thus, according to the modern oxygen theory, the *oxidation* of a substance *X* consists in the formation of a polarized bond between *X* and an electronegative substance *Y*, in which the *X*-atoms become electropositive and donate electrons to their electronegative neighbour-atoms of type *Y*. The inversion of this chemical process is called *reduction*.

The assumption of a special bearer of combustibility was recognized by advocates of the oxygen theory to be explanatorily superfluous. Phlogiston simply does not exist. But how can we then explain the empirical success the phlogiston theory enjoyed at the time? In Schurz (2009) it is argued that the theoretical term “phlogiston” was empirically underdetermined. The theoretical expressions which performed the empirically relevant work for the theory of phlogiston and thus were not empirically underdetermined were phlogistication and dephlogistication. These concepts of the theory of phlogiston stand in the following correspondence relations with some of the central concepts of modern chemistry: (C_1) Dephlogistication of a substance *X* corresponds (and hence implicitly refers) to the donation of electrons of *X*-atoms to the bonding partner in the formation of a polarized or ionic chemical bond. (C_2) Phlogistication of *X* corresponds (and hence implicitly refers) to the acceptance of electrons from the bonding partner by positively charged *Y*-ions in the breaking of a polarized or ionic chemical bond. The two correspondence relations explain the empirical success of the theory of phlogiston. Moreover, they

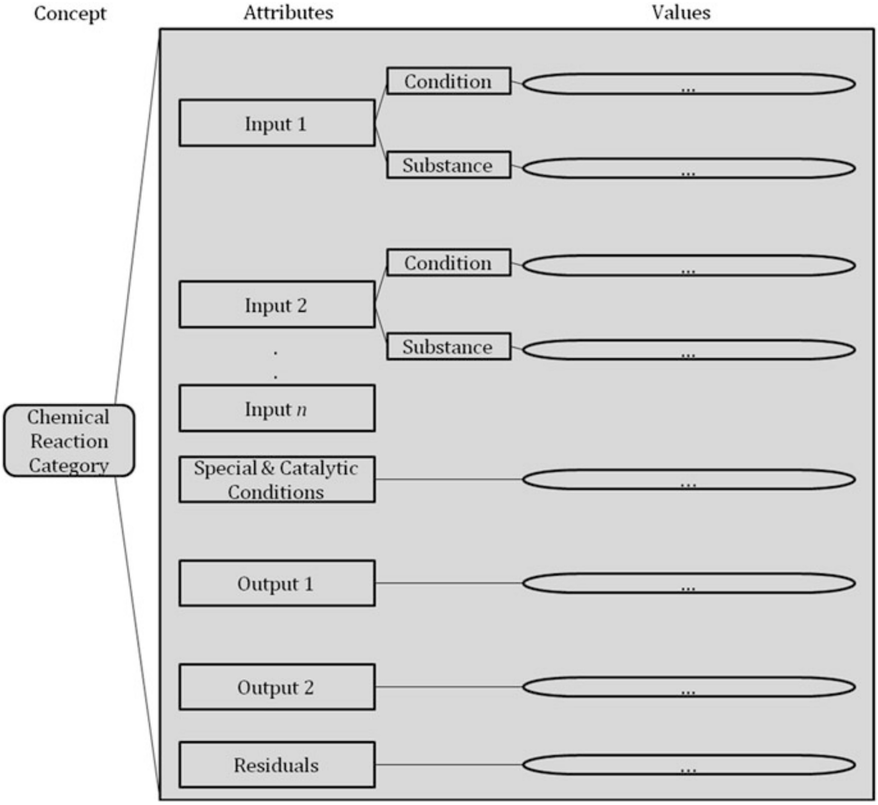

Fig. 4.4 Partial frame for chemical reactions. The *dotted* elliptic fields indicate that a number of values can be given to these attributes

support a structural realist view of science. This is because the structural form of the theoretical expressions that produce the empirical success enjoyed by the theory of phlogiston survived into the generalised oxygen theory.[5]

In order to reconstruct the structural correspondence between the theory of phlogiston and the generalised oxygen theory in a frame-theoretic manner, we have to first develop a general frame for chemical reactions – see Fig. 4.4. Roughly speaking, a chemical reaction consists of one or two input substances under certain conditions, which have to do with the substances as well as the circumstances of the reactions, together with one or two output substances and possibly some residuals. Two constraints govern chemical reaction frames. First, the chemical *law of equal proportions* requires that for all atoms (elements) of kind *i* involved in the reaction,

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[5] See also Ladyman (2011) for another structural realist account of the phlogiston-oxygen theory transition.

the number of moles of atom *i* among the input substances equals the number of moles of atom *i* among the output substances. Second, the *reaction-inversion principle*, according to which for every reaction, there exists one and only one inverse reaction.

At this point it is worth pointing out that the reaction-inversion principle is important for the development of frame theory itself. This is so because to properly represent the principle requires an inter-frame constraint as opposed to the intra-frame constraints discussed in Sect. 4.2. The principle thus demonstrates the need for extending the theory of frames to a theory of nets of frames where all sorts of relations between frames are expressible. We expect to discover many more such relations in our application of the theory of frames to case studies such as the current one.

Interestingly, the rough understanding of chemical reactions according to the proposed frame, together with its intra- and inter-theoretic constraints, was accepted by both phlogiston and oxygen theorists and experimentalists. This shows how frame-theory can be useful in revealing the hidden common principles shared by otherwise ontologically rival theories. What was different in the two theories was not the general understanding of chemical reactions, but the theoretical decomposition of the empirically given substances, i.e. the stuff both parties in the debate agreed was being tested regardless of their descriptions of them. In particular, what was understood as pure in one theory was understood as compound in the other theory, and vice versa. The different theoretical decomposition of substances concerned the following major chemical reactions: the calcination (or roasting) of metals, the salification (i.e. salt-formation) of metals through their dissolution in acids and the inversion of these two processes.

The schemata below represent four chemical reaction types as analysed by each of the two theories. Underlining indicates inter-theoretic correspondences. Substances which are underlined in the same way indicate the different theoretical decomposition each theory attributed to the same empirically given substance. For example, the pure chemical substance metal was understood as a non-compound by the oxygen theory, but as a compound, namely metal calx and phlogiston, by the phlogiston theory. Henceforth, “Phlog” stands for “pure phlogiston”. “X–Y” stands for a combination of X and Y” – for example, “Phlog-Air” stands for “phlogisticated air” while “Ash-Phlog” for “combination of ash and phlogiston”. The symbol “↑” indicates that the substance is an evaporating gas. The symbols “$^{+}$” (“$^{-}$”) designate electropositivity and electronegativity respectively. Items in brackets denote residuals. Finally, “H” stands for “hydrogen”.

Calcination of metals:

Oxygen theory: $\underline{\text{Metal}} + \text{Oxygen} \rightarrow \underline{\underline{\text{Metal}^{+} - \text{Oxide}^{-}}}\ [+ \text{HotAir} \uparrow]$
Phlogiston theory: $\text{Metal } (= \underline{\text{MetCalx}-\text{Phlog}}) + \text{Pure Heat} \rightarrow \underline{\underline{\text{MetCalx}}}$
$+\underset{\cdots\cdots\cdots\cdots}{\text{Phlog} - \text{Air}} \uparrow$

Salt-formation of metals in acids:

Oxygen theory: $\underline{\underline{\text{Metal}}} + \underset{- - - - - -}{\text{H}^+ - \text{X}^-}$ (=Acid) → $\underline{\text{Metal}^+ - \text{X}^-}$ (=Salt) + $\underset{\cdots\cdots}{\text{Hydrogen}}$ (H_2)↑

Phlogiston theory: $\underline{\underline{\text{MetCalx–Phlog}}} + \underset{- - -}{\text{Acid}} \rightarrow \underline{\text{MetCalx}-\text{Acid}}$ (=Salt) + $\underset{\cdots}{\text{Phlog}}$ (inflammable air)↑

Inversion of calcinations – reduction with coal:

Oxygen theory: $\underline{\underline{\text{Metal}^+ - \text{Oxide}^-}} + \underset{- - -}{\text{Coal}} \rightarrow \text{Metal} + \underline{\text{Coal}^+ - \text{Oxide}^-}\uparrow$ [+Ash]

Phlogiston theory: $\underline{\underline{\text{MetCalx}}}$ + Coal (=$\underset{- - - - - - - - -}{\text{Ash} - \text{Phlog}}$) → Metal + Ash [+ $\underline{\text{Phlog}-\text{Air}}$]↑

Inversion of salt-formation:

Oxygen theory: $\underline{\underline{\text{Metal}^+ - \text{Oxide}^-}} + \underset{\cdots\cdots}{\text{Hydrogen}} \rightarrow$ Metal + Water (= $\underline{\text{Hydrogen}^+ - \text{Oxide}^-}$)

Phlogiston theory: $\underline{\underline{\text{MetCalx}}} + \underset{\cdots}{\text{Phlog}}$ [+ Water-in-Air]) → Metal [+ $\underline{\text{Water-in-Air}}$]↑

Note that the identification of phlogiston with ‘inflammable air’ (i.e. hydrogen) does not hold in all domains. Moreover, we do not claim here that the theory of phlogiston worked well across the board. For example, it failed to explain why after combustion the weight of some substances increased instead of decreasing. Attempted explanations were based on wildly ad-hoc assumptions, e.g. postulating that phlogiston had negative weight. Nevertheless, the theory of phlogiston was empirically successful with respect to the domains of oxidation and salification of metals as well as the retransformation of metal calxes into pure metals. Lavoisier’s oxygen theory surpassed the success of its rival. Even so, it also had problems of its own. For example, Lavoisier assumed that salt-formation of metals in acids is always due to the presence of oxygen, whereas in actual fact oxygen is contained only in some acids.

We can now express the correspondence relations between the two theories by means of special chemical reaction frames. Consider first the calcination and salification frame of Fig. 4.5. Here the oxygen theory’s condition of being electropositive but in neutral-bond translates into the phlogiston theory’s condition of being rich in phlogiston. Acid is primitive in phlogiston theory but consists of hydrogen ions plus a negative oxydans in oxygen theory. Metal is primitive in oxygen theory but analysed as metal calx-plus-phlogiston in phlogiston theory (as explained above). In the case of calcination, the theory of phlogiston does not require a second input substance, but merely pure heat because the phlogiston is already contained in the first input substance. In the case of salt-formation, acid is the second input substance in both theories. In spite of the differences, we hope that the correspondence relations are clear for all to see. If, from the point of view of one theory, one or more input conditions and one or more input substances lead to a given output, then the same relation holds between the corresponding input conditions, input substances and output of the other theory.

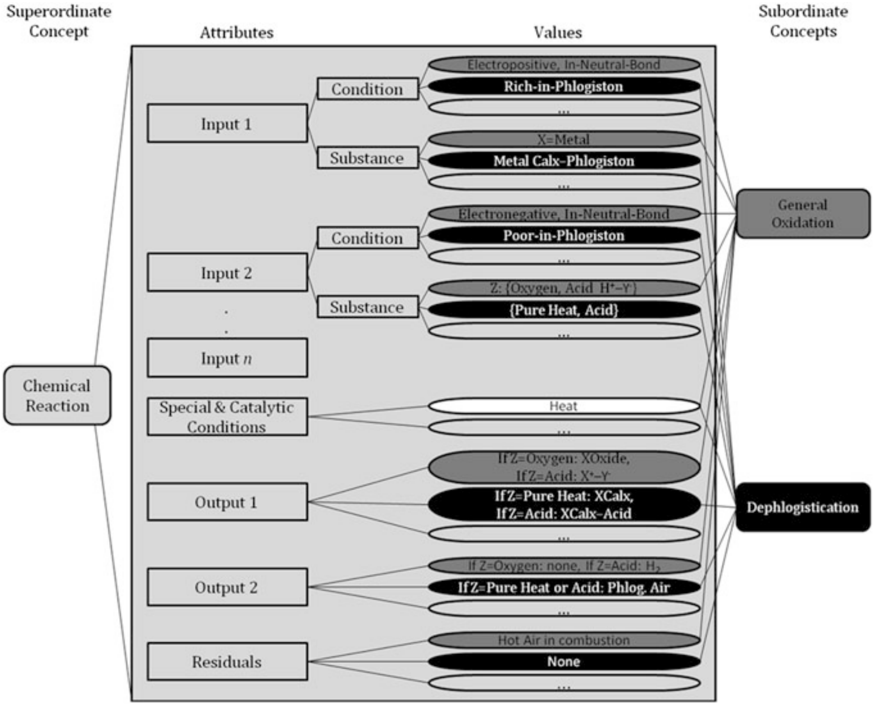

Fig. 4.5 Partial chemical reaction frame for the processes of calcination and salification. For expediency both the concept of dephlogistication and the corresponding concept of general oxidation are represented in one frame. The elliptic fields in *black* indicate the values of the subordinate concept of dephlogistication in phlogiston theory; the elliptic fields in *dark grey* indicate the values of the corresponding subordinate concept of general oxidation in general oxidation theory; the one *white* elliptic field indicates a default value associated with both subordinate concepts; the *dotted* elliptic fields indicate the possibility of more values

The inverted processes of calcination and salification are displayed in the frame of Fig. 4.6. Here, the different analysis of the residuals of the reactions is of special interest: ash, which is a residual for oxygen theory, is a proper output substance for phlogiston theory, while water, which is a residual for phlogiston theory, is a proper output substance for oxygen theory. As before, there are clear correspondence relations. If one or more input conditions and one or more input substances lead to a given output according to one theory, then the same relation holds between the corresponding input conditions, input substances and output of the other theory.

The frames in Figs. 4.5 and 4.6 show us in an intuitive way where the two competing theories converge and where they diverge. The message we hope is clear. Despite the divergence found in the different values each theory assigns to the inputs, outputs and residuals of the aforementioned chemical reactions, there is undeniably substantial convergence at the structural level. The case of the transition from the phlogiston to the oxygen theory of combustion thus seems to tell in favour of structural realism. Let us now turn to the other case.

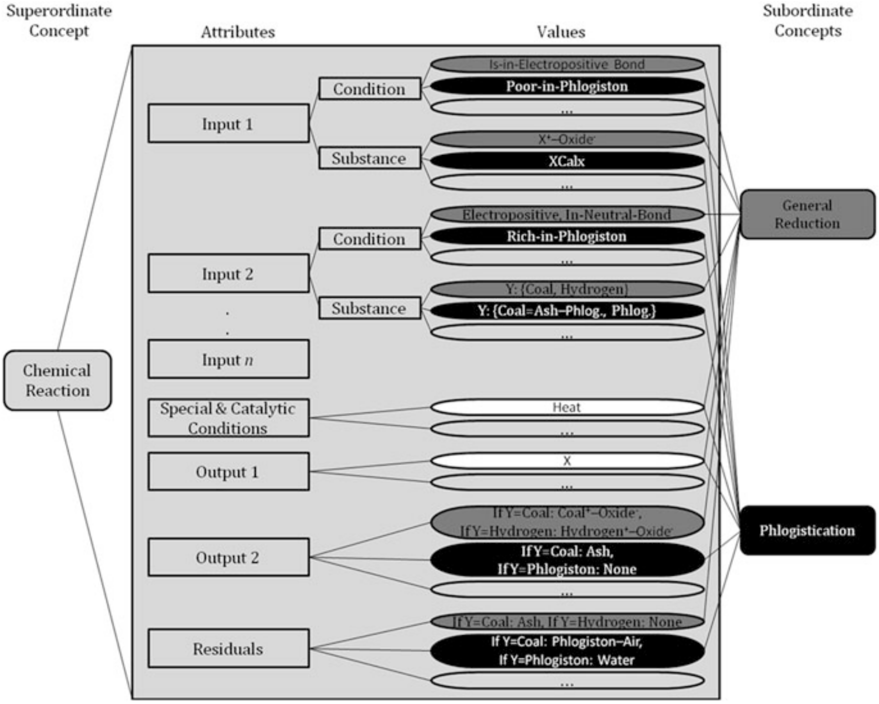

Fig. 4.6 Partial chemical reaction frame for the inverse processes. Once again for expediency both the concept of phlogistication and the corresponding concept of general reduction are represented in one frame. The elliptic fields in *black* indicate the values of the subordinate concept of phlogistication in phlogiston theory; the elliptic fields in *dark grey* indicate the values of the corresponding subordinate concept of general reduction in general oxidation theory; the two *white* elliptic fields indicate default values associated with both subordinate concepts; the *dotted* elliptic fields indicate the possibility of more values

4.5 The Caloric-Kinetic Case

The first sophisticated theory of heat was the caloric theory, developed chiefly by Antoine Lavoisier late in the eighteenth century.[6] Heat, according to this theory, is a kind of material substance that is imperceptible, or, nearly so, depending on the version of the theory advocated. Dubbed ‘caloric’, this substance was thought to be an elastic fluid that flows from warmer to colder bodies. Its particles were subject to two forces, one repulsive and holding between caloric particles, the other attractive and holding between caloric particles and particles of ordinary matter. Arguably, the caloric theory enjoyed some success in explaining and/or predicting phenomena. It

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[6] The material in this section (including all the figures) is a reformulated version of material found in Votsis and Schurz (2012). For more details please consult that publication.

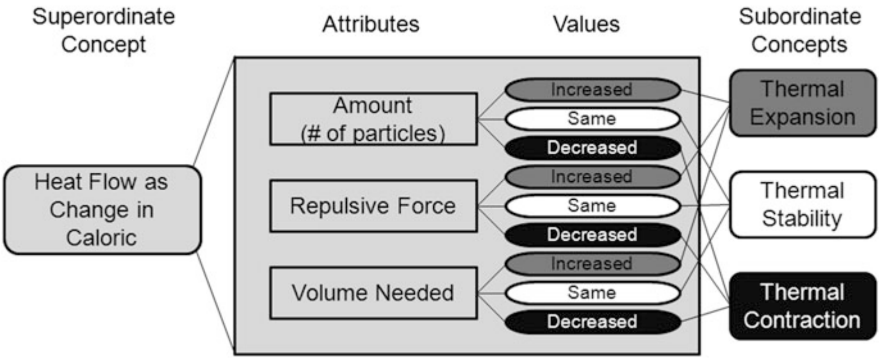

Fig. 4.7 Partial frame for heat flow as change in caloric. This frame illustrates the caloric explanation of thermal expansion, contraction and stability in terms of changes in the amount of caloric. Different shades indicate that the instantiated values correspond to different sub-ordinate concepts

was eventually displaced by the kinetic theory. The latter conceived of heat not as a material substance but in terms of the motion of particles of ordinary matter. Today we continue to understand heat in terms of motion but this idea has been further refined so that we now speak of heat as a kind, or instance, of kinetic energy.

In this section we consider two successes attributed to the caloric theory, namely (i) the explanation that matter expands by heating and contracts by cooling and (ii) the postulation of a special kind of heat, i.e. latent heat, to account for phase transitions. As explained earlier, for structural realism to gain support in this case, it must be shown that (i) and (ii) survived into the kinetic conception of heat. Moreover, it must be shown that the production of these successes was dependent on theoretical posits, the structure of which also survived. In what follows we consider each of these in turn.

The caloricists explained the thermal expansion, contraction and stability of bodies in largely intuitive terms. Expansion, they argued, ensues when caloric particles are added to a body. Since caloric particles repulse each other, the more such particles a body contains the more they push against the body’s boundaries leading to an increase in its volume. Contraction ensues when caloric particles are removed. Less caloric particles mean less pushing against the body’s boundaries and hence a decrease in volume. As you would have thought, a body is thermally stable when no caloric particles are added or taken away since the repulsive force between caloric particles already present in the body remains the same (see Fig. 4.7).

Explaining thermal expansion, contraction and stability is an ability that the kinetic theory of heat also possesses. Its theorists argue that an increase in a body’s kinetic energy increases its internal pressure. In the case of solids, this is because of an increase in the amplitude of vibration of the atoms, thereby resulting in an increase in the average distance required between neighbouring atoms. In the case of gases, this is because of an increase in the velocity of the freely moving atoms or

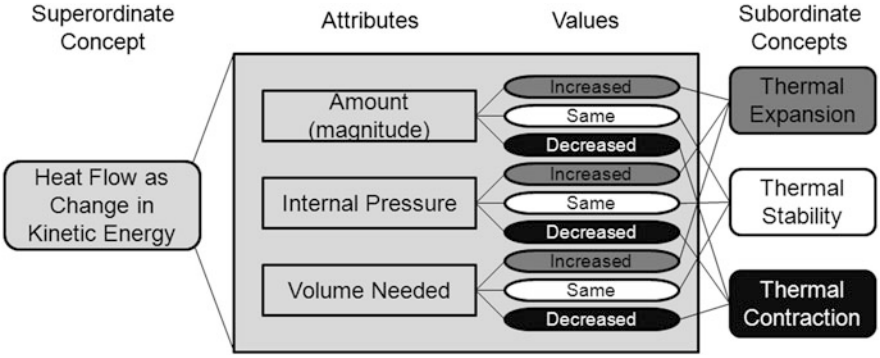

Fig. 4.8 Partial frame for heat flow as change in kinetic energy. This frame illustrates the kinetic explanation of thermal expansion, contraction and stability in terms of changes in the amount of kinetic energy. Different shades indicate that the instantiated values correspond to different subordinate concepts

molecules, thereby resulting in more frequent and more violent collisions with the body's boundaries than before. The result in both cases is an increase in the body's volume, i.e. an expansion. Contraction can be effected by decreasing the amount of kinetic energy present in a body, thereby leading to a decrease of internal pressure and hence to a decrease of the volume needed by those molecules. It will come as no surprise that stability emerges simply by maintaining the amount of kinetic energy contained in a body (see Fig. 4.8).[7]

The two explanations employ radically different conceptions of heat. Even so, they share the same structure. As the amount of caloric particles/kinetic energy in a body increases/decreases/remains the same, the repulsive force/internal pressure of that body increases/decreases/remains the same and that leads to (an) increase/decrease/no change in that body's volume. In other words, the concepts of "heat flow as change in caloric" and "heat flow as change in kinetic energy" are structurally identical in virtue of the correspondence relations that hold between their attributes and values. Thus, to the extent that the caloric explanation of such phenomena amounts to a genuine success, it is a success that survives into the kinetic theory, and, moreover, it can be accounted for in terms congenial to the structural realist viewpoint. The structure of the two explanations is identical save for the fact that the ontological posits of the predecessor theory, i.e. the caloric particles and the caloric's repulsive force, get replaced by those of the successor theory, i.e. kinetic energy and internal pressure. This is exactly what structural realism asserts ought to happen in the history of science. We may thus reasonably conclude that (i) lends credence to structural realism.

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[7] Frames higher up the hierarchy for both the caloric and the kinetic theory can be found in Votsis and Schurz (2012). These include the general frames for "heat as caloric" and "heat as kinetic energy".

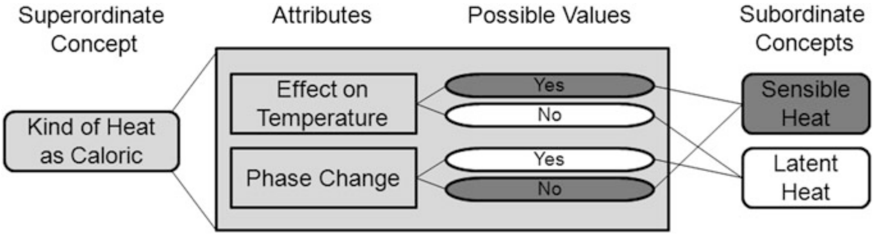

Fig. 4.9 Partial frame for kind of heat as caloric. This frame illustrates the caloric account of phase transition phenomena. Different shades indicate how the instantiated values correspond to the two subordinate concepts

Take next the postulation that a special kind of heat plays a pivotal role in phase transitions. Phenomena concerning phase transitions, e.g. melting, freezing and evaporation, were known for centuries. It was not until the eighteenth century, however, that a peculiar sort of phenomenon was recorded. Joseph Black, an experimentalist and renowned caloricist, observed that when ice melts through the application of heat the temperature of both ice and melted water remains the same. This contradicted the commonly accepted wisdom at the time that adding heat always raises the temperature of a body. In need of an explanation, Black posited that heat can exist not only in a sensible but also in a latent form, i.e. a form unable to influence instruments like thermometers (see Fig. 4.9). He reasoned that during melting the caloric being added to ice is converted from its sensible to its latent form. The latent caloric present in the melted water could then be converted back into its sensible form under the inverse process of freezing. The upshot of this explanation was that it saved the idea that the caloric is a conserved quantity, for any losses in the amount of sensible caloric a given physical system possessed could be accounted for by corresponding gains in the amount of latent caloric. That is, the quantity being conserved was total (sensible and latent) caloric.

Black's distinction between latent and sensible forms of heat has survived into the modern kinetic conception of heat. According to this conception, during phase transitions the temperature of the given physical system remains invariant but latent heat, now understood as a form of energy, is added to or taken away from the system. In the experiment just mentioned, when sensible heat, i.e. kinetic energy, is introduced into ice it does not increase the average kinetic energy of its molecules, i.e. their temperature, but rather acts so as to break up the bonds between those molecules, the result of which is melted water. As with caloric, this heat is not lost but converted into a latent form, namely potential energy, which is stored in the water and is capable of being released when water undergoes freezing (see Fig. 4.10).

Both explanations share structure at the observable level, namely the regularity that a system undergoing a phase transition maintains a constant temperature despite the addition or subtraction of heat. Beyond this observable level, there is also some structure sharing regarding the unobservable mechanism underpinning such

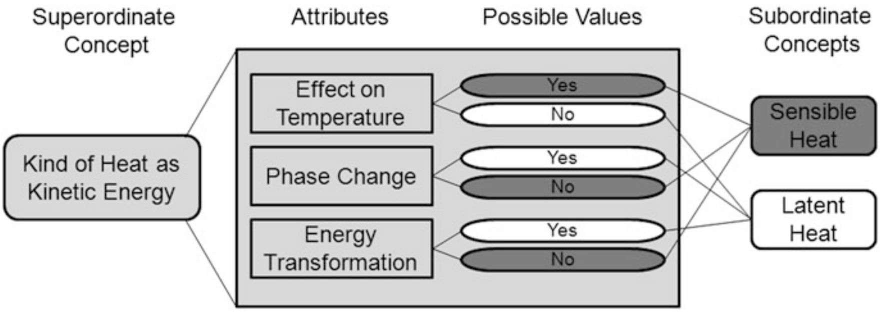

Fig. 4.10 Partial frame for kind of heat as kinetic energy. This frame illustrates the kinetic account of phase transition phenomena. Different shades indicate how the instantiated values correspond to the two subordinate concepts

phenomena. Although no details of this mechanism were given by Black or his fellow caloricists, they at least identified the need for a new unobservable posit, i.e. latent heat, to help them come to grips with the said phenomena. The kinetic theory adopts this unobservable posit and places it in the context of a mechanism that is well understood and independently confirmed, e.g. in terms of how the aggregate state of a body depends on molecular bonds and of what is required for these to break down.[8] The resulting structure convergence is modest, but it is convergence nonetheless. The upshot, once more, is that to the extent that the caloric theory enjoyed some success in explaining phase transitions that success is encoded in structural claims that survived into the kinetic theory of heat.

4.6 Conclusion

The two case studies provide some support for structural realism. Aside from this, they stand testimony to the usefulness of frame theory in finding plausible answers to problems in the philosophy of science. At the same time, our examples show how frame-theory itself can be sharpened and further developed by its application to this field.

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[8] Of course if structural realism is correct then we should only believe in the structural form of the mechanism posited by the kinetic theory.

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