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On Discerning Critical Elements, Relationships and Shifts in Attaining Scientific Terms: The Challenge of Polysemy/Homonymy and Reference

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Abstract Words with well-known meaning in colloquial language often make up an educational challenge when introduced as terms with formal scientific meaning. New connections must be established between the word, already constrained by existing meaning and reference, and the intended formal scientific meaning and reference. A two-dimensional semantic/semiotic analysing schema (acronym 2-D SAS) has been developed to clarify a given word/term in a structured mode both according to non-formal senses and referents and formal scientific meaning and referents. The schema is constructed on ideas from semantics, semiotics and history and philosophy of science. The approach is supposed to be a contribution to make a fine-gained analysis of the structure and dynamics of conceptual change. The role of referents and referent change in conceptual change is highlighted by analysing the character of the recurrent mix-up of the terms heat and temperature among students at different educational levels.

1 Introduction

1.1 Scientific Terminology and Learning

Reif (1995, 18) stresses that interpretation is essential is science learning and practice: "The difficulty is that one must be able to interpret a scientific concept unambiguously in any particular instance, a requirement *not* imposed on everyday concepts" and further "The ability to interpret a scientific concept is clearly an essential prerequisite for using the concept to make complex inferences or to do any scientific work with it". Halloun (2004, 80) raises the exclusive use of vocabulary in science compared to colloquial vocabulary and argues that part of students' learning problems originate when the exclusivity of terms is not enforced during instruction. This presupposes that scientific terms have unequivocal meanings available for the teacher and the learner. However, the existence of a precise scientific terminology have been discussed e.g. by Slisko and Dykstra (1997), who describe

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a confusing use of terms like heat, work, specific heat, heat capacity and thermal conductivity in text-books. Their recommendation, in polemics with Pushkin (1996, 1997), is conceptual multiplicity and diversity since there is no common scientific consensus among scientists, textbook authors and educators. What is forgotten in this discussion, or at least not mentioned, is the international decisions and recommendations on terminology done by the scientific community within the Système International d'unités (SI), the International system of quantities (ISQ) and in the dictionary, Vocabulaire international des termes fondamentaux et généraux de Métrologie (VIM).[1] Hence, the international agreements are unique entrances and guides to standardized and recommended formal scientific terminology. It makes up a baseline for both scientific research and science teaching and learning. The present investigation adopts this view of standardisation.

Weinberg (1939) and Johnson (1947) are early proponents of the importance of semantic awareness and clarity in physics teaching. Weinberg (1939) especially focussed on the correlation between symbols and referents in a learning process. He claims that the essence of good physical intuition of an individual is,

> […] if he can choose from the flock of physics symbols which he commands those symbols whose structure is most like the structure in the physical reality, and if he can recognize structure in the physical reality to which he can correspond known symbols of similar structure. (Weinberg 1939, pp. 107)

This thread of semantic awareness is followed up by other researchers.[2] Williams (1999) specifically addressed learning introductory physics, building on ideas about the importance of word meaning presented in Arons (1990). Williams analysed five introductory physics textbooks, finding unclear and questionable formulations of word meaning connected to Newton's laws of motion. He also assembled a short glossary of terms which carry the potential for student confusion if the possible interpretations are not distinctly separated.

It is not common in science educational research on concepts and conceptions to make scientific clarifications by explicitly expressing and discussing the scientific term as such. It is almost taken for granted and left to the reader. However, some researchers have saliently declared the need for such analyses. For instance Duit and Häussler (1994, 185) state in relation to students' conceptions of energy: "Consideration of content specific pedagogical knowledge in the domain of energy must begin with an analysis of the science energy concept". This need of scientific clarification is taken further in Duit et al. (2005). Another example is Viard and Khantine-Langlois (2001) who in their study of students' conceptions of electrical resistance made a clarification of the scientific concept of resistance both historically and contemporarily to get a sound base for their analysis of students' conceptions. This kind of approach, articulating the scientific view both synchronically and diachronically, is most valuable and contributes to increase the quality of the study.

Wiser and Amin (2001) have shown that metaconceptual teaching about heat, making the students aware of the fact that words have multiple meanings in the everyday and

[1] VIM (3rd edition, ISO/IEC Guide 99-12:2007) is bilingual presenting terms and definitions in English and French. It is elaborated in cooperation between seven international standardizing organisations, viz. BIPM, Bureau international des poids et mesures; IEC, International Electrotechnical Commission; IFCC, International Federation of Clinical Chemistry; ISO, International Organization for Standardization; IUPAC, International Union of Pure and Applied Chemistry; IUPAP, International Union of Pure and Applied Physics; and OIML, Organisation internationale de métrologie légale. Another source for information of standardization is the "The Green Book", 'Quantities, units and symbols in Physical Chemistry' published by IUPAC (Cohen et al. 2007).

[2] See e.g., Touger (1991), Williams (1999), Rodrigues and Thompson (2001), and Itza-Ortis et al. (2003).

science views, can improve their acquisition of the science view. Additionally, and contrary to most other investigations their approach is also an attempt to integrate everyday views with the scientific view by letting the latter be an explanation of the former. Another attempt to bring together everyday and scientific language is Brown and Ryoo (2008) and Brown and Spang (2008) who have shown positive learning results in empirical studies where students have been instructed in science vernacularly before introducing the formal language of science. Brookes (2006) and Brookes and Etkina (2007) argues for an explicit account of scientific terms and language, e.g. according to ontology in the learning situation to minimize the "overextensions" made by learner novices of the analogies and metaphors used in science. Brookes (2006) argues that:

> […] when physicists speak or write they refer to […] analogical models by using systems of conceptual metaphors. They tend to say "X is Y," rather than "X is like Y in certain respects." Thus when physicists generate knowledge, they use analogies. But when the knowledge is already established, physicists use metaphorical language without worrying about the limits of the picture. (Brookes 2006, p. 46)

In sum, there is an unanimous attitude among science education researchers that students' awareness of the use of language can facilitate science learning.[3]

1.2 Students' Conceptions and Theories of Conceptual Change

Research on students' ideas of scientific knowledge predominantly takes students' *conceptions* of scientific concepts as analysing units. The immense number of investigations on students' and teachers' conceptions of scientific concepts is a salient expression of this fact (cf. Duit 2009). Foundational scientific terms like force, temperature, electric current, heat and energy are repeatedly found to be difficult to grasp and attain[4] among learners at both elementary and advanced levels. Words used both as terms in science and non-formally in colloquial language like e.g. work, energy and force but with different meaning need to be addressed. If this fact is not explicitly on the agenda in educational settings, there is a possibility that the exclusive meaning of the word in science will be hidden for the student. Even among high-school teachers deficiencies and lack of coherence about the definitions of physical concepts have been identified (e.g., Galili and Lehavi 2006).

Theories of conceptual change have been developed to identify and come to grips with experienced conceptual difficulties when shifting from an everyday conception to the scientific concept.[5] Piagetian theory (e.g., Piaget 1952) of concept acquisition and Kuhn's (1962/1979) paradigm theory of the historical development of scientific knowledge in the context of philosophy of science have been strongly influential in science educational research on conceptual change. In his exposition of educational conceptual change Duit (2003, 673) concludes: "In a general sense, conceptual change denotes learning pathways from students' pre-instructional conceptions to the science concepts to be learned." This

[3] See e.g., Sutton (1992), Lemke (1993, 1998), Hodson (1998), Fischler and Lichtfeld (1992), Mercer (2000), Clerk and Rutherford (2000), MacKinnon (2002), and Fensham (2004). Three main research traditions could be distinguished in the study of language in science education: conceptual change, developed within the cognitive tradition (e.g., Chi et al. 1994, diSessa and Sherin 1998, Vosniadou 2008). The sociocultural tradition, developed from the ideas of Vygotsky focussing on social and cultural processes, stressing the communicative role of language (e.g., Lemke 1993, Mercer 2000, Wertsch 1991). The third one is that language should be studied from its use (e.g., Halliday 1993).

[4] The words attain and attainment are used here with the meaning *accomplish, acquire, achieve.*

[5] See e.g., Posner et al. (1982), Strike and Posner (1985, 1992), diSessa (1993), Chi et al. (1994), Vosniadou (1994); for an overview of research on conceptual change see Vosniadou (2008).

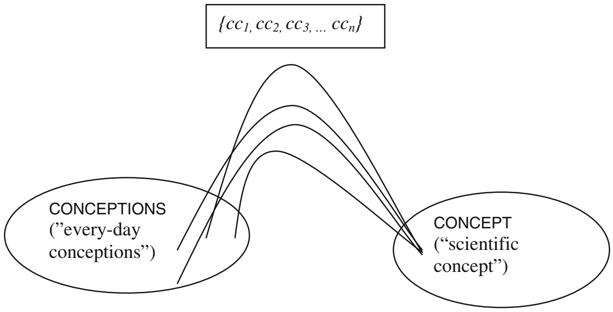


Fig. 1 The standard conceptual change approach

statement can be labelled as the *standard conceptual change approach* to the learning of science concepts (See Fig. 1).

Even if this standard approach on a general level is invariant, there are different conceptual change (cc) theories {$cc_{1,}$ $cc_{2,}$ $cc_{3,\ldots}$ cc_n} modelling the conceptual transition from non-formal everyday (mis-, pre-, naïve, alternative) conceptions to the formal scientific concept. The dynamics of the conceptual change process has been characterised as revolutionary (radical) or evolutionary, sudden, slow, "chunk wise", "piecemeal", compounded (mixed), etc. The structural change has been comprehended differently, from more or less a question of reorganisation of current perception based knowledge to a complete new construction of the target, the scientific concept.[6]

The five most common theories of conceptual change, here denoted $cc_{1,}$ $cc_{2,}$ $cc_{3,}$ $cc_{4,}$ $cc_{5,}$ can be differently categorized, but are here broadly separated in two categories: those who have their main emphasis in explicitly stating something about the nature of conceptions and concepts ($cc_{1,}$ $cc_{2,}$ cc_3) and those who state something about the general conditions for the process of change ($cc_{4,}$ cc_5).

(cc_1) diSessa (1993) introduced the idea of the existence of phenomenological primitives (p-prims) as separate piecemeal knowledge entities or cognitive functional schemas among learners, based on and repeatedly confirmed by everyday experience. The acquisition of scientific knowledge is generally looked upon as a refinement and reconstruction of p-prims. From the research on conceptual change it is advocated the everyday conceptions can act both as 'facilitators' and 'inertia factors' (obstacles) in the process of conceptual change, the latter sometimes by being robust. In favour of the facilitator view Greiffenhagen and Sherman (2008) look upon science learning as a specialization of what the students already know. Leaning science is an activity to use available resources, which is in line with diSessa (2008) ideas about reorganization of existing p-prims (also cf., Sherin 2006).

(cc_2) Vosniadou and Brewer (1992, 1994) are pointing to the presence of synthetic concepts among learners mixing different mental models influenced by implicit framework theories. The remediation is to exempt the learner's mental model construction from inadequate constraints of ontological and epistemological assumptions.

[6] Chinn and Brewer (1998) summarized research results and theories of conceptual change by highlighting knowledge acquisition, initiation, the role of previous knowledge, intermediates, and meta-awareness.

The different perspectives of diSessa and Vosniadou about students' conceptions as knowledge in pieces, p-prims, vs. more or less coherent theory-like knowledge are discussed in depth by diSessa et al. (2004). They compare their own view of the acquisition of the concept of force with an empirical study on the same concept carried out by Ioannides and Vosniadou (2002). The differences between their perspectives can be summarized as a question of grain size analysis. diSessa (2008) applies to fine grain size analyses and descriptions of students conceptions, while Vosniadou et al. apply a more holistic approach. Contextuality, individual diversity, specification and relational structures are brought up by diSessa to be decisive components to pay attention to in the 'pieces vs. coherence' controversy. According to Brown and Hammer (2008) the different approaches can be looked upon as complementary.

(cc_3) Chi and Slotta (1993), Chi et al. (1994) and Chi (2005) approach conceptual change by sorting out the issue of "robust misconceptions" as a question of ontology confusion. Chi and collaborators have found that students tend to apprehend scientific concepts like force, light, heat and electricity as materialistic, substance-like entities, instead of emergent phenomena. Critique has recently been levered by Gupta et al. (2010) against Chi's approach by being characterized as "static ontology"—thinking, since both students and experts benefit from ontology blending in science reasoning and learning by using analogies and metaphors. However, metaphorical and analogical talk about a phenomenon in the learning process is one thing and the intrinsic ontology of a phenomenon as decided upon in science is another. As far as I understand, Chi is talking about the intrinsic ontology of a phenomenon as decided upon in science and the conditions for its attainment. To reach a level of understanding there can be different paths, e.g. including metaphor and analogy reasoning.

(cc_4) In contrast to the mentioned three theories the influential theory of Posner et al. (1982) and Strike and Posner (1985, 1992) focuses on how to convince the learner about the advantageous qualities of a scientific concept in comparison to everyday conceptions. The idea is to make the scientific concept intelligible, plausible, and fruitful by inducing dissatisfaction of every-day conceptions by creating cognitive conflicts. However, recent neurobiological studies, by using fMRI (functional magnetic resonance imaging), on learners struggling with the scientific meaning of 'force' indicates that just presenting anomaly information to create cognitive conflict to challenge their alternative theories activates parts in the brain that rather inhibit than facilitate reconstruction of knowledge (Petitto and Dunbar 2004). Pintrich et al. (1993) added to the Posner and Strike-theory affective, motivational and social factors as possible important determinants of success or failure in conceptual change processes.

(cc_5) Caravita and Halldén (1994) stress the importance of contextualisation. To learn new concepts is a question of focusing on the adequate context. Concept learning is not primarily a matter of change, but an enlargement of the conceptual repertoire. In challenging the conceptual change approach in physics, Linder (1993) has also given support to focusing on context. From a social-cultural point of view Saljö (1999) advocates that the main problem of adopting the scientific concepts among learners is insufficient access to authentic discursive practices in which they are functional. Arons (1997) and Mercer (2000) also emphasises the importance of developing contexts for a proper use of the scientific language.

The often general and implicit, or less systematic treatment of what happens in conceptual change processes in physics learning is addressed by diSessa and Sherin (1998) who posed a straight question to the science education research community by putting the title "What changes in conceptual change?" to a paper about the current position of conceptual change research. The authors made a substantial critical analysis of what is meant by a concept. Their conclusion was that fine-grained analyses of students' conceptions are needed and that scientific concepts could be dealt with in a more appropriate way by treating them within their own 'coordination class theory'. It is easy to agree on the need of a more fine-grained and detailed analysis of the structure and dynamics of conceptual change and conceptual understanding. To take a step further in that direction there is a need to extend the present set of analysing tools. Hence, complementary to the previous research approaches on semantic awareness in science teaching and learning and the five common theories of conceptual change presented above, an analysing schema is developed taking its point of departure in the detailed properties of *words*[7] used both colloquially and scientifically. The schema is constructed in the context of semiotics, semantics and history and philosophy of science to be sensitive and transparent about a word's both conceptual and referential aspects, synchronically and diachronically. Even if the schema analyses single words it is done in dialogue with the contexts where they belong. The analysis is supposed to be a contribution to sort out on word level the semantic and semiotic entities and relationships for a fine-grain description of what changes in conceptual change processes.

The present paper is predominantly communicating an introduction to the analysing schema. No specific learning or teaching theory is applied in the construction of the schema. However, the analysis schema provides information on critical elements, relationships and possible conceptual and referential shifts with potential instructional implications.

2 Aims

This study aims at,

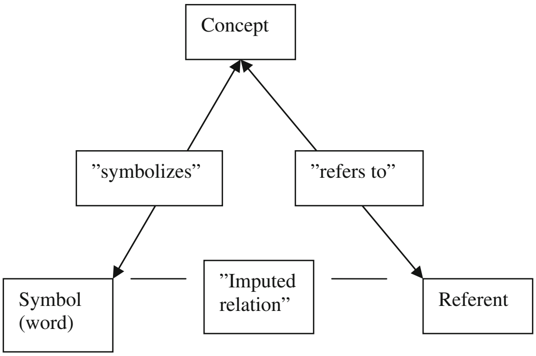
- presenting a *two-dimensional semantic/semiotic analysing schema (acronym: 2-D SAS)* for terms (words) used in formal science language and non-formally in colloquial language.
- highlighting the coherent category of physical quantities, their SI units and quantity calculus as essential entities in the 2-D SAS analysis.
- making a contribution to inform the structure and dynamics of conceptual change by especially identifying the role of reference (*referent and referent change*) in concept formation and conceptual change.

3 The Two-dimensional Semiotic/Semantic Analysing Schema (2-D SAS)

The proposed analysing schema is expanded in two dimensions, one semiotic and one semantic. The construction of the schema will be presented by first introducing the two dimensions individually, eventually combining them into the 2-D SAS approach.

[7] The present version of the analysing schema is constructed for analyses of words, but could be expanded to analyses of other symbols and modalities used in scientific representations, e.g. formula, pictures, animations, diagrams, etc.

Fig. 2 The semiotic triangle (cf. Ogden and Richards (1989 [1923], p. 11))



3.1 The Semiotic Dimension

The elements of the *semiotic triangle*[8] make up one dimension of analysis of words (terms) in the 2-D SAS schema. The semiotic triangle, portrayed in Fig. 2, comprises three elements: *symbol* (word, signifier), *concept* (alt., signified, sense, meaning, mental representation, thought, or semantic category) and *referent.* The *symbol,* which is treated here as a word[9] has no inherent connection to the topical referent in symbolic languages (cf. the 'imputed relation' in Fig. 2). Hence, different scientific terms in different languages like e.g. *heat* (English), *värme* (Swedish) and *chaleur* (French) denote the same scientific concept modelled on the same referent. This is the arbitrariness or conventionality of symbolic language (cf. Hockett 1960, 1966), in contrast to iconic languages where the symbols are more or less depicting referents (cf. Mandarin). *The referent* is the entities that are represented by the word and concept; the non-linguistic counterpart embedded in theories about the phenomenal world, the delimited aspect of a directly or indirectly perceived phenomenon/object/property related to observations, experiments or measure procedures in specific domains (e.g. the thermal domain, the domain of physical motion, and the electricity domain).[10]

Margolis and Laurence (1999) and Murphy (2002) have collected extensive overviews of the different ideas about concepts, both encompassing the classical theory of definition and the contemporary theories revolving around typicality (prototype and exemplar models). At present there is no consensus about an unambiguous meaning of a concept according to ontology, structure and nativeness. Different theories of concepts exist in parallel. In this study the concept *scientific concept* is tentatively in alignment with Arabatzis (2007):

> I take a concept to be the set of features that are ascribed to its putative referent, by the theory in which the concept is embedded. In case that no such systematic theory has been developed, a concept would consist of the characteristics attributed to its counterpart in nature, by the group of scientists who are using it. (Arabatzis 2007, pp. 57–58)

[8] Cf. Ogden and Richards (1989 [1923]), cf. also Frege (1892a, b), de Saussure (2002), Peirce (1931–1958, 2.228).

[9] A graphical and phonological form, e.g. 'heat' [hi:t].

[10] The question of connecting world and language, reference, is also an issue in artificial intelligence and robotics, among others discussed by Roy (2005) and Roy and Reiter (2005).

In science education research there seems to have been an attitude on presuming the referents to be invariant or just taken for granted, and not explicitly pointed out in modelling the conceptual change processes. Vosniadou et al. (2008) write:

> […] If concepts change than it is not clear how they can continue to refer to the same entities and processes. Adopting a realist stance requires an account of concepts that keep reference constant as the meaning of the concepts changes […]. (Vosniadou et al. 2008 footnote 3, p. 28)

Vosniadou et al. (2008) also note that Carey (1991) attempted to divorce conceptual change from issues of reference. In Carey (2009) we find an exposition of her approach leaning on Kitcher's idea of "local incommensurability" as a key concept in conceptual change where reference is preserved.[11] She writes:

> […] I use "conceptual change" to refer to the relation between successive incommensurable theories of overlapping domains of phenomena (for there is change in the conceptual primitives in terms of which the phenomena are represented and explained), as well as to the relation between particular ancestor–descendant pairs of concepts involved in these theory changes. (Carey 2009, p. 365)

The use of the expressions 'overlapping domains of phenomena' and 'the phenomena' in this text indicates invariant reference. In Carey's explication of the historical differentiation of the single concept 'degree of heat', used by the seventeenth century Academy of Florence, into the separate concepts temperature and heat, no explicit statement is made about referents of neither the single concept nor the differentiated concepts.[12] The over all impression is that referents are not made an explicit issue in the mainstream conceptual change research. It seems to align to the Putnam–Kripke causal theory of reference (Putnam 1973; Kripke 1972, 1977) implying that the original baptising and rigid designation of a concept always maintain original reference. But this theory, which functions very well for proper names and observable natural kinds, is questioned for natural kinds that are not directly detectable by the unaided senses (un- or non-observables) and theoretical concepts. These non-observables are connected to the issue of existence. In history of science we have witness that theoretical and unobservable concepts as phlogiston, ether and caloric are concepts that lack existence and reference and thereby have been abandoned in science (cf. Laudan 1981). Discussing the category of 'fish' as a natural kind observable Arabatzis (2007) argues that,

> Even if the reference of that concept changed, the existence of the individual organisms that were classified as fish would not be questioned. And that is because the existence of these organisms is

[11] Kitcher (1978, 1988) in the dispute about the 'incommensurability issue' (Kuhn 1962; Feyerabend 1981) and its philosophical threat against realism focused on the importance of referent-fixing as a precondition for successful communication between different scientific paradigms. Explicit descriptions of referents make communication possible. Kitcher's prototypical example is taken from the history of science. The definition of 'phlogiston' as 'the principle given off during combustion' lacks a referent from our contemporary point of view. In the contexts where 'phlogiston' is used as in the term 'dephlogisticated air' by the description of an experimental outcome we can identify it as sharing referent of the gases oxygen or oxygen-enriched air in our present terminology in chemistry. Kuhn accepted Kitcher's argumentation that agreement of the referents of terms is necessary but there must also be agreement of what is said about the referents for successful communication. It is worth noting that Thagard (1992) contrary to Kitcher, explicitly excludes referents in his conceptual change investigations:

> My approach to the problem of conceptual change is based on the organization of mental representations. In contrast, Kitcher's (1988) approach is concerned with the reference of terms. On his view, failures of communication in scientific disputes arise from different ways of fixing the referents of key theoretical terms. Our two approaches are probably compatible, but my concern in this book is with the organization of concepts, not with how or whether they refer to things in the world. (Thagard 1992, p. 39)

[12] Cf. Carey (2009, 371–376) referring to Wiser and Carey (1983) and McKie and Heathcote (1935).

> established on grounds independent of our system of classification. That is not the case, however, when the natural kind concept refers to unobservable entities. Besides the fact that such concepts have been abandoned, even when they have been retained, the lack of independent, physical access to the entities denoted by those concepts makes problematic the claim that, in case of conceptual change, their referents remain stable. (Arabatzis (2007, p. 53)

Shapere (1989) claims, supported by historical evidence, that the communication between earlier and later uses of a term in consecutive theories is maintained, not being incommensurable, by a continuous *chain-of-reasoning* against a background of accumulated knowledge. A use of a term is however not fixed once and for all, but can be changing over time due to scientific development. The provisional endeavour of science admits a seamless chain of reasoning, making incommensurability an obsolete feature. This is in line with the cognitive-historical approach developed by Nersessian (e.g. 2008, x) who argues that the incommensurability problem is grounded in just comparing the endpoints of a long process "…, and did not take into account the fine structure in between." Additionally, the change of referent of a term is no violation of realism if reality is looked upon as the perceived phenomenal reality (Andersen 2001).

Out of my interpretation of Shapere (1989), Andersen (2001), Arabatzis (2006, 2007) and Nersessian (2008) there is no objection against a change of referent of a scientific term in a conceptual change process. It is what history of science can tell us of the consecutive referents and senses of a term that matters for a proper comprehension of the conceptual and referential changes. When it comes to theoretical terms, such as 'force', 'mass' and 'acceleration' Andersen and Nersessian (2000) claim that these cannot be pointed out in isolation, but rather as interacting participants in complex structures, understood in relation to each other by a theory or a law, in this case Newton's second law. Physical quantities in general are such terms and get their reference within the theory where they appear, corroborated by existence of corresponding phenomena in the perceived phenomenal world, e.g. realized by instances of observation, experiments and measurement.

Since educational conceptual change theories mainly have been modelled on the paradigm theory of revolutionary conceptual change in science (Kuhn 1962/1979) the idea of referent invariance in scientific conceptual change has also been inherited. The fact that contemporary philosophy of science support a view of possible referent change in scientific conceptual change, it also opens up for referent change in conceptual change theories in science education. Even this being so, reference and referent change is an issue to be empirically investigated (Strömdahl 1998, 2009a). The referents connected the topical term (word) used formally and non-formally need to be established. If the non-formally and formal scientific referents are different, than a change needs to be done to the scientific referent, if the intention is to attain the scientific concept. Or more correctly, the referent of the scientific topical term has to be explicitly pointed out. Hence, reference is an essential entity of the semiotic dimension.

3.2 The Semantic Dimension

The second dimension in the construction of the 2-D SAS analysing schema is semantics. What is directly transferred in speech and text is the conveyance of phonological and textual (pictorial) form. It is up to the individual to construe the words 'mental content' (meaning) and what they are referring to according to context. A word could be looked upon as a *mnemonic key* for retrieving meaning from memory (cf. Halloun 2004, 79). Word meaning is determined by the past and current experiences of the individual. Since individuals interpret words with a background of unique experiences (different individual cognitive and emotional biographies), individuals interpret the same word in different ways. There is no guarantee that the construed meaning of a word run together with the intended meaning of the same word in an educational context. Overwhelming and convincing evidence of this fact is found in the research literature on students' and teachers' conceptions of scientific concepts.

Polysemy is the semantic term indicating that one word is used with two or more interrelated meanings, making up a set of meaning variants (e.g. Löbner 2002; Saeed 1997/2001). Löbner (ibid., 44) states "Each of these meaning variants has to be learnt separately in order to be understood". In their overview of the phenomenon of polysemy, Ravin and Leacock (2002) declare that polysemy is rarely a problem for ordinary communication among people:

> We are so adept at using contextual cues that we select the appropriate senses of words effortlessly and unconsciously. The sheer number of senses listed by some sources as being available to us usually come as a surprise: Out of approximately 60 000 entries in Webster's Seventh Dictionary 21 488, or almost 40 per cent, have two or more senses, according to Byrd et al. (1987). (Ravin and Leacock 2002, p. 1)

A common example of polysemy is the word *paper* with meanings like the material made from pulp, a sheet of paper, a newspaper, an article in a journal etc., meanings that could be seen as related, however not by simple semantic overlap (see e.g., Klein and Murphy 2001, 2002). Brugman (1981) has studied in depth nearly one hundred sense variants of the preposition *over*. Lakoff (1987) building on Brugman's results has by schemas presented precise relations among the spatial senses of *over* and described metaphorical extensions. As noted in the quotation from Ravin and Leacock (ibid.), contextual cues solve polysemy of colloquial words. But, an explicit semiotic/semantic analysis is essential when it comes to the complexity of a word used as a term in scientific contexts. For instance, when talking about the concept heat, the definite article in the singular indicates that the word 'heat' in the expression '*the heat concept'* is monosemic—has just one meaning—is one single concept. But from the lexicon, science and empirical investigations in science education research we know that the word 'heat' has many different legitimate meanings for different individuals—the word 'heat' is *polysemic*, that is, the one and same word has related but different meaning variants and referents. The word heat is also a *homonym*—has non-related meaning variants and referents—e.g. referring on the one hand to thermal phenomena and on the other to a race or competition. Another example is the word *bat* meaning both "a wooden instrument with a cylindrical handle and broad blade used to strike a ball at cricket or similar games" and "a small nocturnal mouse-like mammal…" (Cassell 1994, p. 108). The use of the word *bank* as an institute of finance and as a raised shelf or ridge of ground at a river or see is another common example of homonymy.

Thus, a polysemous word has a single lexical entry with sense variants and homonyms have different lexical entries which, in their turn, can be polysemous. In science educational settings learners meet a lot of familiar words used in colloquial language like e.g. work, force, heat, energy, and power with encoded senses that are not congruent with the intended scientific meaning—polysemy is at hand. This fact is profoundly confirmed by the research summarized under the common label 'student's conceptions' (cf. Duit 2009). The awareness of occurrence of polysemy and homonymy is essential for a proper understanding of words used both in science and colloquially.

3.3 The Analysing Schema

By combining the semiotic and semantic dimensions accounted for above, a two-dimensional schema is constructed as depicted in Fig. 3. The vertical axis is the semantic

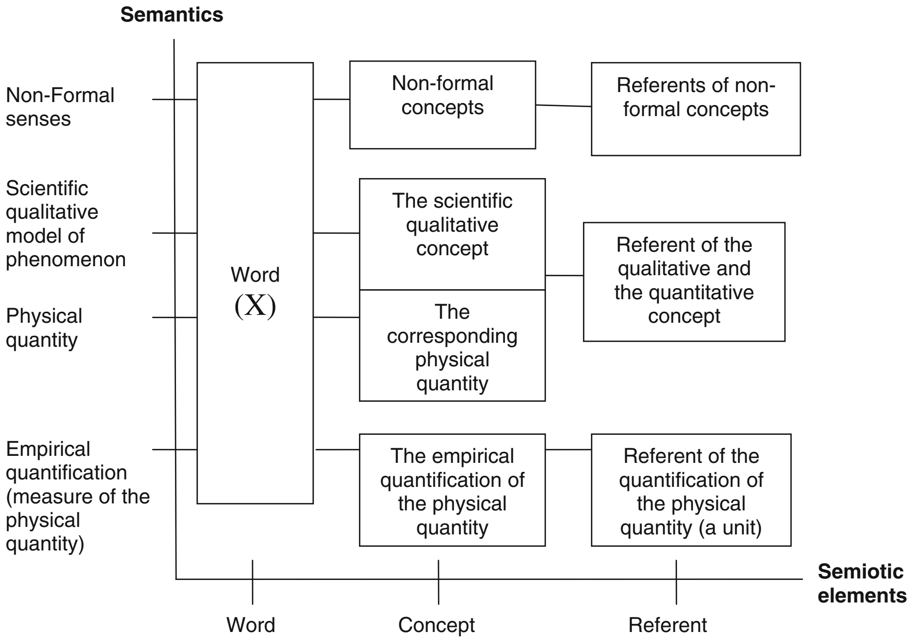


Fig. 3 The two-dimensional semiotic semantic analysing schema, 2-D SAS

dimension referring to various meanings (polysemy/homonymy) of a word and the horizontal axis is the semiotic dimension referring to the semiotic elements word, concept and referent. According to Cruse (1986, 71–74) polysemy can be looked upon as a continuous *sense-spectrum*, a meaning potential. In practice by participating in different lexical fields, there is a discontinuous set of *local senses* according to convention and context. In the present approach the semantic axis is divided in four separate meaning entrances; a set of non-formal senses, a scientific qualitative meaning, a meaning of a physical quantity, and a meaning of operational empirical measurement, the quantification of the physical quantity, all modelled on corresponding referents. To settle if the semantics is polysemous or homonymous is a question of empirical investigation in the specific case.

The analysing schema structures a given word X in the four meaning entrances and the semiotic elements. The qualitative scientific concept is modelled on a scientifically delimited referent. The physical quantity is the mathematical model of that referent. Both the qualitative modelling and the quantitative modelling (mathematical modelling) of referents are more and less subjected to simplifications, abstractions and idealisation (cf. e.g. Song et al. 2001; Portides 2007). The physical quantity is carried into effect as a quantifier established by an operational definition of a standard unit on the referent for measurement, a phenomenon or object.[13] The difference between *the physical quantity* and the numerical *quantifier* is evident by looking upon energy as one and the same invariant physical quantity, even if the empirical quantification of that physical quantity could be measured in different defined units like 1 calorie, 1 BTU (British Thermal Unit), 1 Joule

[13] Cf. the SI-unit, the second which is based on a phenomeon by being the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom. The SI-unit for mass, the kilogram is based on an object with the mass equal to the mass of the international prototype of the kilogram.

and 1 eV (electron Volt) referring to different natural phenomena and different measuring instruments. By this last discernment[14] a separation is done between the mathematical modelling of a physical quantity and the quantification of that quantity (cf. de Berg 2006, 495–496).

Distinguishing between the physical quantity and its referent is in alignment with Landolt (de Boer 1995), who was involved in the axiomatization of quantity calculus and stated that quantities are concepts (Ger. Begriffe) which are attributed to the world of events and phenomena. Physical quantities are not the physical phenomena as such (Ger. 'an sich') but the imaginary (Ger. 'gedankliche') physico-mathematical model, which we make of these phenomena.

The approach by Tarantola (2006) is supporting the differentiation between the scientific qualitative concept (physical quality) and the corresponding physical quantity when stating that some types of physical qualities are measurable by physical quantities. He is exemplifying by saying that "… an object may have the property of being cold or hot. We will talk about the cold–hot quality. The advent of thermodynamics has allowed us to quantify this quality, introducing the quantity 'temperature' T" (ibid, 105–106). He also presents a reverse formulation of this fact: "It is clear that behind a set of quantities like temperature—inverse temperature—logarithmic temperature, there is a qualitative notion: the 'cold-hot' quality." (ibid., vii).

In the case the term X in Fig. 3 is *just* denoting a phenomenon or entity and not a physical quantity, like e.g. combustion, light, osmosis, photosynthesis, protein, molecule and atom, the analysis encompasses non-formal senses and the scientific qualitative sense, modelled on the corresponding referents.

From a historical point of view and the extent of contemporary sophistication of scientific qualitative concepts and referents, not at least for non-observable entities and processes, there is also a variation on the semantic entrances, making up a set of formal scientific senses (some revised and some abandoned in the historical progression of science), which however have been omitted in this broad outline of the 2-D SAS approach.

3.4 The Analysing Schema Presented in a Formal Fashion

In Fig. 4 the analysing schema, introduced in Fig. 3, is given a formal shape, also featuring relationships between the concepts and referents. The concepts are denoted by the symbols $C_{\{NF\}}$, C_{SP}, C_{PQ}, C_{MQ} and corresponding referents $R_{\{NF\}}$, R_{SP}, R_{PQ}, R_{MQ}, where the indices denote the different senses: NF = non-formal, SP = qualitative scientific phenomena, PQ = physical quantity and MQ = measure of physical quantity. The symbols rC1 and rC2 denote relationships (r) between the concepts (C), rR1 and rR2 the relationships between the referents (R), and rCR is the relationships between concepts and referents.

Apart from accounting for the traditional educational conceptual change approach, mainly the relationship rC1 in Fig. 4, however without a distinct discernment of the qualitative and quantitative meaning of the topical term, the analysis schema brings to the fore three new aspects to take into account:

- the explicit introduction of the referents of concepts which permits the possibility to account for 'referent change' (the relationship rR) in the concept formation/attainment process.

[14] The words discern and discernment are here used with the meaning *distinguish, discriminate, demarcate.*

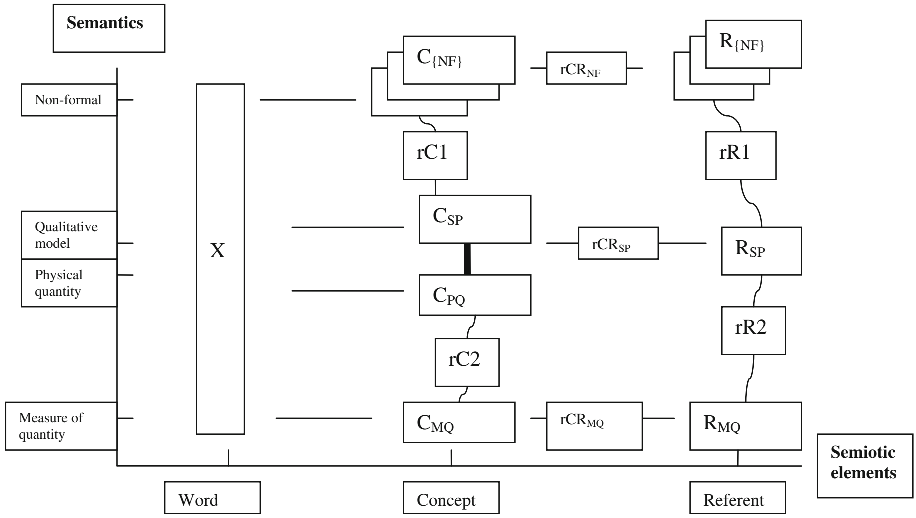


Fig. 4 The formal two-dimensional semiotic semantic analysing schema, 2D-SAS

- the separation of the formal scientific concept into a scientific qualitative concept, C_{SP}, a physical quantity C_{PQ}, and the quantification concept C_{MQ} with attendant referents. The relationship between the qualitative scientific concept and the mathematical modelling of that concept is indicated by the fat vertical line in the middle of Fig. 4.
- the assumed relationships rC, rR and rCR between the different concepts and referents to be explicated in topical cases.

By performing empirical investigations of a word's different senses, referents and their relationships there seems to be reason to have a specific focus on referents and 'referent change'. For instance, in the history of science when the caloric theory was overruled by the energetic view it was a change of referent of the concept *heat* from being a supposed substance 'caloric' to the transfer of molecular motion (energy). It is also worth noting that Carnot (1986 [1824]) made his important mathematical modelling of generalised heat-engines based on the caloric idea, the valid qualitative 'heat'- referent at that time. Carnot also used the analogy of the behaviour of water in a waterfall to describe the role of caloric in processes happening in a heat-engine. However, Carnot's mathematical modelling is still valid in classical thermodynamics even if the contemporary scientific qualitative sense of heat and its referent have changed.

Another example of referent change in history of science is the still valid mathematical modelling of electric current, made long before the introduction of the contemporary valid qualitative sense of electric current as based on the referent electrons/ions (charges) in motion. From empirical science education research results we know that common everyday conceptions of 'heat' are modelled on different referents relating to the generic 'sensational perception of relative hotness' as a property of single bodies. A fact that points to the role of referents if the intention is to attain the scientific concept heat referring to the specific aspect of transition of molecular motion (energy) from one physical system to another according to temperature differences. Thus the word 'heat' is a symbol for different concepts modelled on different referents, one everyday and one scientific, however both belonging to the thermal domain. Proper interpretation of the word 'heat' is due to its contextual use.

In the following sections the different concepts and referents discerned by the 2-D SAS approach will be explicated. First, a comment on the relationships rC, rR and rCR.

3.5 The Relationships rC, rR and rCR

The relationships rC1 and rR1 points to the shift between non-formal and the scientific uses of a word. The relation rCR_{NF} is accounting for the modelling of the non-formal concept on the aligning referent. Mainly the relation rC1 has been focussed in conceptual change research. The other relationships have attracted less attention. Here the 2-D SAS approach exhibits a field for generating new research questions. The relationships rCR_{SP}, rCR_{MQ}, rR2 and rC2 are nodes for clarifying the character of the modelling of the scientific uses of the word.

The four entrances in Fig. 4 make up possible categories of polysemous words. But what is the character of these categories? Polysemous senses do not seem to form neither taxonomic nor thematic or goal-derived categories (Klein and Murphy 2002, 566). Several linguists[15] argue for the idea that polysemous words are created by a radial or chained process. In *radial* or *chained categories* the term denotes one original sense but after multiple changing events (sense extensions) the term includes objects/phenomena that are not similar to one another. The theory 'principled polysemy' developed by Evans (2005) and collaborators is building on this idea. It implies that there is a diachronic evolution of the senses. Löbner (2002, 45) states, "Polysemy plays a major role in the historical development of word meanings because lexemes continually shift their meanings and develop new meaning variants." This coincides with Shapere's (1982) claim that a use of a scientific term is not fixed once and for all, but can be changing over time due to scientific development. Following that line of reasoning the relationships rC, rR and rCR is on one hand what history of science can inform us about the evolution of the consecutive senses and referents of words like heat, temperature, force, etc. On the other hand the relationships also accounts for contemporary non-formal and formal scientific views.

An extensive number of studies have been carried out to map the development of scientific terms, especially in history of science but also in science education. For instance Roche (2003, 2005, 2006) has investigated the physical quantities *potential energy* (also including *energy* as such), *mass* and *momentum*. In science education research Strömdahl (1996) carried through an in-depth analysis of the development of the physical quantity *amount of substance* and its SI-unit 1 mol. Recently Kanderakis (2010) has focussed on the emergence and development of the concept of *work*. From a linguistic perspective, applying the theory of "principled polysemy", Evans (2005) has made an extensive study of the meaning and use of the word *time*. Haglund et al. (2010) have combined the 2-D SAS approach with the principled polysemy approach investigating the polysemy of the word *entropy*.

The educational implication of this kind of studies, clarifying the relationships rC, rR and rCR historically, pointing to the origin, evolution and formation of scientific terms is essential for eliciting the mechanism of attaining this kind of terms contemporarily (cf., Matthews 1994, 2000; Matthews et al. 2005; Brookes 2006).

3.6 Non-Formal Concepts and Non-Formal Referents

Common words are full of "multiple meanings of the life world" as stated by Schutz and Luckmann (1973). The elements in the set $C_{\{NF\}}$ denote individually and socially shared

[15] E.g., Cruse (1986), Murphy (1997), Sweetser (1990), Evans (2005).

concepts in colloquial language related to perceived referents $R_{\{NF\}}$. These concepts can only be identified empirically. Solomon (1985) was talking about making empirical investigations that are "… ethnographic, to present as full a picture as may be of the range of ideas that can commonly be found." Here the set $C_{\{NF\}}$ makes up the collected pool of ethnographical data. In science education research the elements of the set $C_{\{NF\}}$ are generally denoted 'alternative conceptions' (Driver and Easley 1978). I will argue that these 'alternative conceptions' and some considerable number of other denotations of conceptions like misconceptions, preconceptions, children's conceptions and the like are mistakenly identified as alternative, since they are not alternative to something, but are concepts on their own right, connected to the immediate interface between man, culture and world (life-world) and presumed, or taken for granted referents $R_{\{NF\}}$. They need to be seriously considered as such. This kind of knowledge entities, disregarded their specific differences, have also been named schemata (e.g. Kant 1965 (1787), 182; Bartlett 1932; Piaget 1952; Kelly 1955) scripts (Schank and Abelson 1975) phenomenological primitives (diSessa 1993), and the like.

Research in science education has generally focussed on identifying non-formal senses just as a base-line to challenge them in connection to the formal scientific senses. Few studies have allocated explicit interest to explore the referents of these non-formal senses (e.g. about 'heat' in Amin (2001). In the 2-D SAS analysis the role of the non-formal referents ($R_{\{NF\}}$) are supposed to play an essential role for comprehending the process of conceptual change via explicit identification of the topical referents. The senses of the set $C_{\{NF\}}$ are generally unconsciously used correctly in natural non-formal language even if polysemy, homonymy and vagueness are present. Common every-day contexts will disambiguate the meaning and reference in natural language communication supported by emotional engagement and empathy. In other words, in natural language meaning can be negotiated in the specific situation, so at least partial and sufficient agreement can be reached resulting in successful communication. However, as is clear from the collected research on students' conceptions, it is an educational challenge to communicate and attain the very precise scientific senses C_{SP} and C_{PQ} and their referent designated by the same word as a set of non-formal senses $C_{\{NF\}}$ and their referents.

3.7 Scientific Formal Qualitative Concepts and Their Referents

The qualitative concept C_{SP}, is the model of some discerned feature or aspect of a delimited natural phenomenon, the referent R_{SP}, conventionally agreed upon in science. The C_{SP} is stipulated defined and context invariant. Unequivocalness, coherence and well-defined relations to other C_{SP}'s are characteristics. The modelling process is often accompanied by *abstraction* and *idealisation* to reach a level of generality in the representation and to be available for a subsequent mathematical modelling (cf. Nersessian 1995). Here, history of science informs us a lot what has been focussed on during the evolution of a C_{SP}. Often it has been a process of *differentiation and delimitation of referents*[16] within the theories of a specific discipline but also *coalescence,* e.g. the unification of heat, work and vis viva in the concept of energy. Thagard (1992), however not focussing on referents, points to the importance of changes in kind- and part-hierarchies, conceptual combinations, abduction and explanatory coherence as driving forces in the conceptual development.

[16] Cf. the separation of temperature and heat within the theory of thermodynamics.

The naming of a C_{SP} could be a mere question of arbitrariness, however usually consciously done by conventional considerations, thereby most possibly to be traced to a word originally used non-formally or being a predecessor in the evolution of science.[17] A clear comprehension of a formal scientific term encompasses in existing cases both the qualitative aspect and the aspect of a physical quantity. This is illustrated by the scientific term heat, C_{SPheat}, which as a qualitative concept is the transfer of energy on the molecular level between two bodies with different temperatures being in thermal contact. As a physical quantity it has the dimension of energy, $C_{PQenergy.}$

The concepts C_{SP} and C_{PQ} are (con-)temporarily fixed and invariant by definition, but are, as noticed above, subjected to ongoing interpretative considerations on different levels of sophistication, scientific progress and to changes of agreements within the scientific community. However, in practise there could always be some dispute about the proper definition. It is in that kind of situations the international conventions expressed in SI, ISQ and VIM play a standardizing role.

3.8 Scientific Formal Concepts as Physical Quantities and Numerical Quantifications

A *physical quantity* is a mathematical model of a property of a physical system to which a magnitude can be assigned. The quantification of a physical quantity is defined by prescribing the experimental procedure that will measure a standard unit, resting upon a measuring theory and a measuring device, or manners of calculation. Thus, in the proposed analysing schema there is a discernment made between the theoretical mathematical model, the physical quantity C_{PQ} and the numerical quantification, C_{MQ}. In a system of physical quantities a *base physical quantity* is chosen by convention. In the most important customary current system, The International System of Quantities ISQ, there are seven (7) base physical quantities (the dimensional symbols are L = length, M = mass, T = time, I = electric current, Θ = thermodynamic temperature, N = amount of substance and J = luminous intensity). In Système International d'unités (SI), the metric system, every base physical quantity has its own unit. A *derived physical quantity* is defined as a function of the base physical quantities and hence gets derived SI units.[18] Any physical quantity Q can be written in the form of a dimensional product,

$$\dim Q = L^{\alpha} M^{\beta} T^{\gamma} I^{\delta} \Theta^{\varepsilon} N^{\zeta} J^{\eta}$$

where the dimensional exponents $\alpha, \beta, \gamma, \delta, \varepsilon, \zeta$, and η, generally are small integers, positive, negative or zero. Some physical quantities are independent of the base physical quantities (all dimensional exponents are equal to zero) having the dimension 1 (one), sometimes called dimensionless quantities. An example of a derived physical quantity is energy (dim E) and is derived from the base physical quantity dimensions mass (M) length (L) and time (T), $\dim E = M\,L^2\,T^{-2}$. The Newtonian concept force (F) is derived from the same base dimensions, $\dim F = M\,L\,T^{-2}$.

Even if the introduction of the 3rd edition of Quantities Units and Symbols in Physical Chemistry, "The Green Book", published by IUPAC (Cohen et al. 2007, xii), stresses that

[17] E.g. Wiser and Carey (1983) found support in the history of science of an undifferentiated concept 'degree of heat' comprising both temperature and heat in the thermal theory of the seventeenth century Academy of Florence. For instance the term heat has remained in contemporary thermopdynamics, however with a different meaning.

[18] Information about the base physical quantities and units is available at the homepage of Bureu International de Poid et Measure, BIPM (http://www.bipm.org/en/si/base_units/).

the book is not "…a list of recommendations in the form of commandments.", the definitions of physical quantities have an imperative character as long as the scientific society agrees upon them, not at least to foster "good practice of scientific language". The over all intention is "… to improve the international exchange of scientific information…" (ibid., ix). Also Mills (1997) has stressed the importance of paying attention to the ultimate use of scientific terms and language, not at least regarding the physical quantities.

The concept *physical quantity* was eventually fully introduced in Maxwell's (1873) "Treatise on Electricity and Magnetism" even if it was mentioned already in Maxwell and Jenkin (1863). Maxwell wrote:

> Every expression of a quantity consists of two factors or components. One of these is the name of a certain known quantity of the same kind as the quantity to be expressed, which is taken as a standard of reference. The other component is the number of times the standard is to be taken in order to make up the required quantity. The standard quantity is technically called the Unit and the number is called the Numerical Value of the quantity. (Maxwell 1873)

It took some time to get agreement upon the use of physical quantities, but Wallot (1953) was the great pioneer of full scale calculus with physical quantities (quantity calculus). He stressed that the symbols in mathematical formalism should represent physical quantities and not numerical values—thereby avoiding dependence on choice of a unit. Wallot advocated that physical quantities are not the product of a numerical value and a unit, but physical quantities are themselves the primary concepts. This is in accordance with Maxwell—since a unit indicates a specific reference quantity, it is in itself a 'physical quantity' proper. The numerical value of a particular quantity is the ratio of the current quantity to the corresponding unit, and is then a pure number. The physical quantities are of primary importance—they are fundamental in the mathematization of Nature. Units are of importance in the interface between theory and experiment, nota bene in measurement.

To explicitly discern the single physical quantity, C_{PQ}, and its category membership in the super-ordinate category of physical quantities comprising the sub-categories *base physical quantities* and *derived physical quantities* is essential, thereby putting attention to a sharp coherent system of ideas of fundamental importance to understand the mathematical modelling of nature. By the 2-D SAS analysis the physical quantity is saliently exposed.

A study of the importance of measurement in the development of physical quantities, specifically a reconstruction of how the physical quantity *temperature* was established, has recently been done by Mäntylä and Koponen (2007), based on Chang's (2004) elaborated account of the historical development of the scientific concept temperature. Apart from investigations of the general importance of physical quantities and units in science education by e.g. German researchers (e.g. Burger et al. 1983; Weninger 1998; Lobemeier 2005), no investigation in science education research has approached the question of learners' difficulties of science learning and teachers' teaching of science by explicitly focussing the coherent system of physical quantities and units in SI. On the other hand Sherin (2001) presented an extensive study of how students understand equations which, however implicitly, implies the importance of understanding physical quantities and quantity calculus. The coherent structure of physical quantities and quantity calculus is therefore a salient issue to deal with in educational settings to counteract the often experienced fragmentation and 'formulae exercise' among students in their science studies (cf. Strömdahl, 2009b). It is not enough to clarify the meaning of isolated terms, but the terms have to be seen as nodes in a coherent structure (cf. Andersen and Nersessian 2000). Those terms denoting physical quantities belong to such a structure.

4 Implications

There is a potential spectrum of applications of the 2-D-SAS approach. Specifically it could be used to scan previous research in science education, especially conceptual change studies, to identify gaps according to the fine-grained word analysis made possible by the 2-D SAS approach. Research questions could be generated and reanalyzes could be performed. Generally the 2-D SAS approach is supposed to,

- systematically elicit the space of the 'sense/referent-spectrum' of terms non-formally and scientifically and their relationships
- distinguish the meaning of the qualitative, mathematical and quantitative modeling of the current scientific referent
- appreciate the physical quantities as making up a coherent category and structure
- analyze the use of terms in textbooks, curricula and by individuals in educational settings
- inform the process of attaining a scientific term, by alternative design of teaching sequences
- elicit the demand put on the learner and the teacher to discern the categories of distinct meaning and referents of the one and the same polysemeous word (term).

The explicitly expressed role of referent change in conceptual change is an addition, a partial answer, to the demanded fine-grained analysis of what change in conceptual change. To illustrate this claim the well known educational problem of separating the concepts of heat and temperature is analysed by the 2-D SAS approach.

4.1 An Illustration of the Role of Referents

The following analysis includes scientific clarifications and reanalyses of results from empirical studies of students' conceptions of temperature and heat, available in the research literature. The reasoning will be addressed mainly from a microscopic point of view, an approach to thermal physics that have been considered advantageous in educational settings, thoroughly discussed by e.g. Reif (1995) and Chabay and Sherwood (1999). The analyses schemas of heat and temperature respectively are arranged so the referents are facing each other. The following reasoning should be read with Fig. 5 in mind.

First, let us look at a clarification of the formal scientific terms temperature and heat from the perspective of the kinetic gas theory where the gaseous state is considered as ideal and mono-atomic. From this view the referents R_{SPheat} and R_{SPtemp} are different but related aspects of gas-particles and their motion. On the one hand the referent R_{SPtemp} accounts for the aspect of motion of the particles in a delimited system, precisely modelled by C_{SPtemp} as the average kinetic translation energies of the particles. The physical quantity temperature is mathematically modelled as an intensity variable $C_{PQ\ temp}$, a base physical quantity in SI and made operational via C_{MQtemp} by the definition of the unit 1 K (Kelvin) available for measurement by thermometers. On the other hand the referent R_{SPheat} accounts for the transfer of microscopic motion between two delimited systems of particles A and B of different average motion until the unified system reaches a joint average motion. This is modelled by C_{SPheat} as the process of equalizing the difference between the average kinetic translational energies of A and B, viz. the different temperatures of A and B, which is a spontaneous process when A and B are in thermal contact. Warren (1972, p. 296) describes heat as work "… done on the molecular scale, but not macroscopically". The difference between the average kinetic translational energies in A and B is accounted for by the

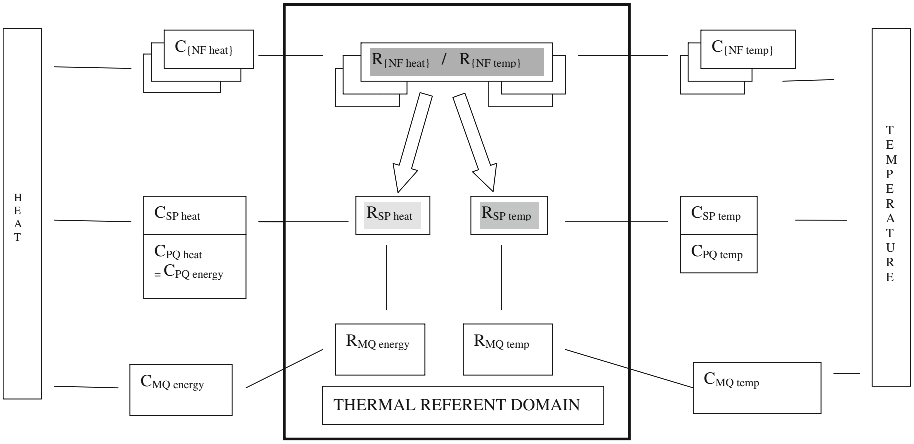


Fig. 5 Senses and referents of the terms heat and temperature distinguished by the 2-D SAS analyses. (For detailed description see the text)

extensive variable of energy. Thus, C_{PQheat} as a physical quantity is conflating with the derived physical quantity $C_{PQenergy}$ and is made operational by $C_{MQenergy,}$ with the derived SI-unit 1 J (Joule).

The physical quantity C_{PQtemp} can be accounted for at different levels of mathematical modelling. As said above, due to the kinetic gas theory (ideal gas) it is connected to the average kinetic translational energy of the particles of a system. In classical thermodynamics temperature is introduced by a partial derivative $(dS/dU)_{V,N} = 1/T$ (where U is internal energy, S = entropy, V = volume, N = number of particles and T = thermodynamic temperature). As modelled in statistical thermodynamics it is identified as the Lagrange multiplier β when deciding on the Boltzmann distribution of the canonical ensemble, and is a typical statistical entity. By analogy with classical thermodynamics β is identified as temperature via $\beta = 1/kT$, where k is Boltzmann's constant ($k = 1.38 \times 10^{-23}$ J/K). Other aspects of modelling are added when it comes to liquids and solids. For instance, in the solid state theories, temperature is connected to the theory of phonons.

The empirical quantification, C_{MQtemp}, rests on the definition of a standard unit in SI, 1 Kelvin, by reference to the physical phenomenon of the triple point of water. In praxis temperature is generally measured in Celsius degrees, unit 1°C, or Fahrenheit degrees, unit 1°F, with measuring instruments (thermometers) based on a property proportional to temperature variation, e.g. volume variation of gases, mercury or sprits.[19]

Distinctions leading to our contemporary scientific conceptualizations of temperature and heat demanded painstaking efforts as is described in the history of science. The confusing relation between temperature and heat was just initially resolved about 200 years ago by Joseph Black who distinguished *the equilibrium of heat* between bodies of different substances by stating:

[19] For detailed temperature scales see e.g. Kitell and Kroemer (1980, 445–452) and for an extensive historical account of temperature measurements see Chang (2004).

> The nature of this equilibrium was not well understood until I pointed out a method of investigating it. Dr. Boerhaave imagined that when it obtains, there is an equal quantity of heat in every volume of space, however filled up with different bodies […].
> But this is taking a very hasty view of the subject. It is confounding the quantity of heat in different bodies with its intensity [temperature], though it is plain that these are two different things, and should always be distinguished, when we are thinking of the distribution of heat. (Black 1803/1977, pp. 132–133)

Count Rumford accomplished investigations leading to the apprehension of heat as an emergent phenomenon and not as an imponderable material substance:

> Being engaged lately, in superintending the boring of canon, […] I was struck with the very considerable degree of heat which a brass gun acquires, in a shot time, in being bored; and with the still more intense heat (much greater than that of boiling water, as I found by experiment,) of the metallic chips separated from it by the borer. […]
> And in reasoning on this subject, we must not forget to consider that most remarkable circumstance, that the source of the heat generated by friction, in these experiments, appeared evidently to be *inexhaustible*. It is hardly necessary to add, that any thing which any *insulated body*, or system of bodies, can continue to furnish *without limitation*, can not be a *material substance*: and it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of any thing, capable of being excited and communicated, in the manner the heat was excited and communicated in these experiments, except it be MOTION. (Count Rumford (1798/1977, p. 183, p. 186)

In common parlance the word heat is denoting that which excites the sensation of warmth, especially at high degree, e.g. redness of the skin; vehemence, passion and sexual excitement. Science education research has revealed a lot of ethnographic information on how the words heat and temperature are used among learners.[20] Extensive research has also been done on teaching and learning heat.[21] A recent approach to inform the teaching of heat and temperature in first year university chemistry by using history of science has been elaborated by deBerg (2008). He has also summarized some ideas of temperature and heat found in the research literature that are at variance with those contemporarily accepted in science Among such ideas it is found that learners often think of heat and cold as substances and with opposite properties. Engel Clough and Driver (1985) found that learners have unexplained stereotypes like "heat rises", "hot things expand" and "heat travels through metals".

Specific learners' frameworks have also been identified (Watts and Gilbert 1985). Learners' approach to explain thermal phenomena associated with mixing portions of water of different temperatures and heat conduction in different materials is not invariant but highly dependent on context and level of education. Learners try to find a reasonable explanation in the specific situation and context by generating a range of ideas based on what is instantly available in their minds. Different ideas out of their own idiosyncratic conceptual repertoire come to the fore.

The 'matter-like fluidness' (liquidness) of heat and cold is identified as a very selective continuously updated confirmatory experience among learners with similarity to the weightless fluid 'caloric' accounted for in the historical theories of heat. From that perspective it is not surprising that novices and or mis-educated students show these senses. If heat is grammatically comprehended as a noun, it is easy to be interpreted and apprehended as of materialistic character (cf. Chi et al. 1994). Besides the common conception of an identity "heat is temperature", the use of the words heat and temperature are accounted for

[20] E.g. Roller (1950), Tisza (1966), Shayer and Wylam (1981), Stavy and Berkovitz (1980), Tiberghien (1983, 1985), Wiser (1987), Kesidou and Duit (1993), Kesidou et al. (1995).

[21] E.g. Zemansky (1970), Warren (1972), Heath (1974), Tripp (1976), Erickson (1979, 1980), Summers (1983), Se-Yuen Mak and Young (1987), van Roon et al. (1994).

in different manners, e.g. "heat is hot but temperature can be cold or hot "and "temperature as a means for measuring heat" however not as a physical parameter associated to the condition of a material (Tiberghien 1983). Hence, no clear distinction is made either between the terms heat and temperature as two distinct separate scientific concepts, or how they are individually used (cf. e.g. Amin 2001). To sum up, all these empirical studies characteristically show that students to a large extent use the two words temperature and heat undifferentiated and interchangeably connected to bodily sensory experiences of hot and cold objects and viewing heat as a materialistic fluid flowing in and out of bodies.

Ambiguities are also unfortunately manifested in e.g. the scientific jargon like 'heat energy' (cf. e.g. Pushkin 1997; Brookes 2006) and 'heat transfer', even in university texts and in titles of books like "Introduction to heat transfer" (cf., e.g. Incropera and DeWitt 2002). Since heat as a contemporary scientific term denotes *transfer of energy* between bodies of different temperatures, the expressions 'heat energy' and 'heat transfer' will be tautological/confusing, something like '*transfer of energy* energy' and '*transfer of energy* transfer', respectively. Leff (1995) has characterised the expression "heat transfer" as an oxymoron.

From the assembled empirical data in the science educational research literature it is evident that the non-formal sensational experience labelled by the adjectives warm and cold is basically steering the meaning of the words temperature and heat. They are therefore categorized as terms denoting perceptual entities, viz. the non-formal referents are the concrete perceptions of warmth and cold. Temperature is preferably used as a measure of this perception and heat is connected to warm or cold substances occupying bodies. Out of this interpretation it is most relevant to reason that heat and temperature in a non-formal sense have the same or a partly coinciding referent. This is marked in Fig. 5 by the conflating referents $R_{\{NF\}temp}$ and $R_{\{NF\}heat}$ resulting in conflating concepts $C_{\{NF\}temp}$ and $C_{\{NF\}heat,}$ however labelled by different words. In some sense the words temperature and heat are here used synonymously. The basic learning problem of $C_{SP\ temp}$ and $C_{SP\ heat}$ is subsequently a question of referent change from the non-formal conflated referent to the separate referents $R_{SP\ temp}$ and $R_{SP\ heat}$, being the ground on which the scientific concepts are modelled. Without identifying the correct scientific referents there is no possibility to attain the corresponding scientific concepts, weather being qualitative or quantitative. To investigate this claim a qualitative explanatory study is done by Jeppsson and Strömdahl (2010). The results show that the identification of the referent of temperature is decisive for correct reasoning on a thermodynamic task in a group of science teacher training students and doctoral students.

4.2 A Reminder of the Embedded Word

Research on students' and teachers' conceptions in science has mainly focused on individual scientific concepts (cf. Duit 2009). Also the 2-D SAS analysis is focussed on single entities, words, however with the intention to clarify the complex structure of word meaning and reference. Investigations dealing with concepts in coherent conceptual structures are less frequent. Some researchers in physics education have pointed to the issue of hierarchical knowledge organization as beneficial for the understanding of physics (e.g. Van Heuvelen 1991; Reif 1995). Fortunate learning in science seems to be depending on appreciated coherence including formalism and clear conceptual distinctions. Regarding physics learning, Hammer and Elby (2003) state:

> Students who have difficulties often view physics knowledge as a collection of facts, formulas, and problem solving methods, mostly disconnected from everyday thinking, and they view learning as primarily a matter of memorization. By contrast, successful learners tend to see physics as a coherent system of ideas, the formalism as a means for expressing and working with those ideas, and learning as a matter of reconstructing and refining one's current understanding. (Hammer and Elby 2003, p. 54)

Tentatively, these findings also seem to be relevant in other scientific fields than physics. The general appreciation, interpretation and attainment of scientific terms and their structural relations are foundational in science learning. In that vein the preciseness (accuracy) of scientific language (terminology), systematicity, coherence and consistency seems to make up essential ingredients in science understanding. These distinctions are more or less imperative to make if one wants to find out what is takes to learn a scientific term against a background of an often internalised meaning of the term/word used in colloquial language. This is also a prerequisite in designing qualified teaching/learning sequences where a topic term is at fore. Marton and Tsui (2004, 230) stress that a necessary condition for bringing about learning is that learners are able to focus on the object of learning and to discern its critical features. The elements and relationships discerned by the 2-D SAS analysis are such critical features.

The interpretation of a word is depending on its functional use in sentences. Language as a syntactic system is digital and linear. Sentences deliver "chunks" of meaning in a more analogue and continuous way when apprehended by the interpreter. Hence, apart from identifying the formal scientific definition of concepts there is additional knowledge that is decisive for the proper interpretation of them. Critical attributes (Bagno et al. 2000, 17) or features characterizing the proper use of the terms need to be stated as explicitly as possible in the learning situation including different semiotic representations (language, pictures, symbols, diagrams, equations, etc.).

The meaning of a term is identified by constructing an organized web of statements to form a coherent structure. This is a negotiating process which needs a *method of interpretation* in learning situations (cf .Reif 1995). These processes could be executed by the learner individually by "negotiating" with texts, but collaborative learning in meaningful contexts can here be given support (cf. the conceptual change theory cc_5 about contextualisation in Sect. 1.2 above) The role of the teacher as an expert on scientific patterns and knowledge organization of subject content could not be overestimated in the negotiation process with the learners as proposed by e.g. the theory of "zone of proximal development" (cf. Vygotsky 1986). In other words the *scientific term* is embedded in a set of interconnected statements. Strömdahl (1996, 185) describes this as a *conceptual locality* of a term, where the definitional statements make up a proximal region, and the other statements a distal region of equal importance for proper comprehension.

4.3 A Hypothesis

The 2-D SAS analysis highlights the role of the referent for correct interpretation of a scientific term. This fact opens up for an alternative teaching design. Let us assume a learner who has some fixed internalised non-formal comprehension of a term comprising non-formal conceptions and referents. Then there are at least two possible trajectories to attain the scientific meaning of the term. The first one is to start with the term arousing its possible meanings and then confronts the non-formal referents with the scientific referent by variation, contrasting, discrimination, discernment and explicitly pointing out the differences and similarities between the referents. The overall aim is to temporarily bracket the non-formal referents and be open for instruction of the intended scientific concept by identification of the correct referent. This is similar to the "cognitive conflict" model in the traditional constructivist conceptual change approach.

The second trajectory is to start in the referent of the intended scientific concept without mentioning the topical term. An account of the radial or chained processes of historical development indicated by the relationships in the 2-D SAS approach can be a part of the instruction to facilitate comprehension by paying attention to science research as an ongoing endeavour to create provisional sustainable statements about Nature. In that way the learner is exposed to the struggles that physicists had to come to grips with the question at issue hypothesizing that these difficulties are crucial for students to develop real understanding. In the phase of introducing the topical term the student can be puzzled since for him/her the name (word) put on this new concept and corresponding referent also denotes non-formal concepts connected to non-formal referents. This situation could be met by pointing out the differences between the non-formal and formal referents and their corresponding concepts and to state that the word (term) is polysemeous and must be disambiguated according to context.

Following the first trajectory implies that the learner has to struggle with the present non-formal concepts and referents of the term at the same time as to be convinced to change sense and referent of the term (conceptual change) as it is used in science. Following the second trajectory a concept is constructed from a referent without competing with an already internalised non-formal concept and referent. Objections from the learner about how the term is to be construed are now emerging as a second phase and could be treated on its' own concern. The two instructional trajectories are equivalent to the semiotic *onomasiological* analysis (analysis from referent to word) and *semasiological* analysis (analysis from word to referent) respectively. It is a hypothesis that the cognitive load is less following the onomasiological approach, more rapidly resulting in a successful attainment of the scientific term. Additionally, learning the meaning and reference of a term that is only used in science ought to be easier to attain than a term (word) that is used both colloquially and in science. However, here we can have problem anchoring the meaning to something that is familiar to the learner. These ideas need further research.

5 Discussion and Conclusion

The recurrently recognized difficulties among learners to attain the scientific meaning of words like energy, heat, temperature and force, common words also used in colloquial language, have been extensively investigated in previous research by focussing students' and teachers' *conceptions* of these terms as analysing units. Differently, the present study approaches the issue by taking the *word* (term) and its semantic/semiotic properties as the analysing unit. A two-dimensional semantic/semiotic analysing schema (acronym 2-D SAS) is proposed to account for polysemy/homonomy and the semiotic elements symbol, concept and referent of words. The schema discriminates between four categories of meaning variants: a set of non-formal senses and referents, the sense and referent of a scientifically discerned phenomenon and the sense and referent of a physical quantity, the last discriminated as a mathematical model and as a numerical quantification. According to the theory of polysemy there are relationships between the sense variants to be empirically revealed, e.g. by investigation of the historical development of the topical word.

The 2-D SAS approach permits a systematic and coherent semantic/semiotic analysis of words used both in colloquial and scientific language. Especially the referent stands out as a crucial entrance to understand the formation of a concept since it is the ultimate base for modelling the concept. What is generally comprehended as a scientific concept in singular, is by the 2-D SAS analysis under some conditions discerned as three concepts, a qualitative concept modelled on a referent, a physical quantity, modelled on the same referent and eventually a third concept of a numerical quantification of the physical quantity with its own referent.

The category physical quantities discerned by the analysing schema together with quantity calculus make up a coherent structure which is of importance to notice from an educational point of view. Learners with difficulties in learning science often see quantitative terms and equations as piecemeal and something to be memorized as isolated entities, without realizing their coherent structure (cf. Hammer and Elby 2003). The aspect that quantitative science according to the International system of physical quantities (ISQ) and International system of units (SI) builds on seven base quantities and corresponding units, and that all other quantities are derived from these by mathematical modelling has been neglected, taken for granted or less stressed in previous science education research (cf. Strömdahl 2009b).

The traditional science educational research taking students' conceptions/concepts as a primary unit of analysis has gained a lot of valuable knowledge to inform instruction. But the question "What changes in conceptual change?" remain. The widely appreciated theory of conceptual change proposed by Posner et al. (1982) and Strike and Posner (1985, 1992) is an import of ideas about science knowledge formation in revolutionary phases in the history of science (Kuhn 1962/1970). Four preconditions for conceptual change were proposed by Posner et al. (1982). On the one hand dissatisfaction with a current conception and on the other hand appreciated fruitfulness, intelligible and plausible properties of the target scientific concept. However, contrary to revolutionary knowledge formation in disciplinary science attaining 'normal science' in educational settings is a quite different activity. Here, Kuhn (1962/1972) is talking about the importance of text-books and an 'exegetic' activity, interpretation, which is at fore when a learner tries to become acquainted and familiar with foundational normal science. The learner needs to be equipped and sustained with interpreting tools to make the meaning transparent and thereby master the scientific terminology. The investment from the learners' perspective is to interpret the meaning, the ideas labelled by scientific terms within the contemporary language of science. So, in learning normal science the situation is quite different from that proposed by Posner et al. (1982) and Strike and Posner (1985). It is not a question of a revolutionary activity in the disciplinary meaning but an interpreting activity. Besides, the Kuhnian approach applied to individuals has been questioned by Greiffenhagen and Sherman (2008).

Interpretation as an essential activity in science learning has been noticed by Sutton (1992, 72) by advocating that "… the principal object of study should be not nature itself but *sets of ideas*, as represented in the written or spoken words of people. Telling about these ideas, and puzzling over them, should be the core of lessons". However this does not mean that learning science should be disconnected from nature, but nature has to be discussed using the current ideas and terms in contemporary science. The proposed 2-D SAS analysis is a contribution to facilitate the interpretative activity.

Chi et al. (1994) and Chi (2005) state that the set of concepts comprising heat, electricity, light and force are ontologically similar concepts by being *emergent processes*. Students' problems are related to "robust conceptions" of these concepts as *materialistic substances*. Chi's et al. conclusion is that remediation efforts must be focussed on the change of ontology. In the 2-D SAS analysis the relevant change is referent change which naturally includes ontology. But ontology in Chi's et al. meaning is not enough, a specification of an aspect/feature is needed, otherwise concepts' with similar ontology (in Chi's sense) conflate, e.g. entropy and energy as extensive state variables. Thus, to attain the scientific concept is not only a question of general ontology, but to discern the scientifically delimited referent by its specific aspects of the current phenomenon. From the perspective of the 2-D SAS analysis Chi et al. are treating heat, electricity, light and force as qualitative concepts. Hence, Chi's theory is not accounting for the fact that heat and force are terms also denoting mathematical models making up the physical quantities, heat and force ($C_{PQ\ heat}$ and $C_{PQ\ force}$). In contrast to these two, light and electricity are concepts just accounting for qualitative models of referents of natural phenomena.

The p-prims, primitive knowledge entities introduced by diSessa (1993) can be interpreted in the 2-D SAS approach as non-formal concepts modelled on experienced phenomena, a set of non-formal referents $R_{\{NF\}}$. According to diSessa's theory of p-prims and 'coordination class theory', the p-prims are looked upon as a resource in the process of reorganisation and reconstruction into scientific knowledge structures, even if being fragmentary and separate. Similar to Chi, diSessa makes no explicit discernment between qualitative and quantitative scientific concepts, viz. discerning the qualitative concepts and the physical quantities as making up distinct, but related categories. In connection to this discernment: What role does p-prims play to infer physical quantities?

Vosniadou and Brewer (1992, 1994) are pointing to the presence of synthetic concepts among learners, mixing different mental models influenced by implicit framework theories. In the 2-D SAS perspective this problem can be diagnosed as mixing up referents when modelling a concept. Such a mixing could explain the lively discussed issue of children's conception of the Earth both as a flat surface and as a sphere, building on the direct experience of the flatness of the near environment and socially induced ideas about the Earth as a sphere. Also the difference found about children's conceptions of the shape of the Earth when a globe is present or absent in the research setting can in the 2-D SAS analysis be considered as a question about referents. Without a globe or any other artefact present in the research setting the child introduces her/his own referent. In the presence of the globe the referent is saliently given. However, in the latter case there is no guarantee that the child identifies the globe as a model of the Earth, but just as the concrete object it is. This analysis can be an explanation why inconsistent results of children's conceptions of the shape of the earth are gained in different research settings. The idea that the referents are decisive is touched upon by Ehrlén (2007) in her study about children's conception of the Earth when she conclude that, "Failings may arise when explanations are contextualized in the context of the representation rather than in the context of the referent." However, she has not elaborated this idea further and is not using the term *referent* elsewhere in her study.

Conclusively, the 2-D SAS approach has the analytical potential to include essential parts of the three mainstream theories of conceptual change but adds fine-grained analytical power by the discernment of referents, the scientifically delimited phenomenon or object, and the scientific qualitative and quantitative modelling of concepts based on referents. Especially the explicit discernment of the referent stands out as decisive in the acquisition of a concept. Intended conceptual change is not possible if the correct referent is not in place as an entrance in the meaning making of a scientific concept. Slotta and Chi (2006) touch upon a similar idea when they state that one should not try to "bridge the gap" between students' misconceptions including a wrong ontology and the target concept if the ontological status of the latter is not clear for the student, since there is no tenable pathway between distinct ontologies. It is clear from the 2-D SAS analysis that properties of the referent, where ontology makes up one general aspect, but also the specific aspect of the current phenomenon is decisive in modelling and attaining the correct scientific concept. By the analysing schema a fine-grained discernment of critical elements, relationships and shifts of a term (word) is made explicit. However, especially the relationships between the critical elements have to be further elaborated.

The proposed two-dimension semantic/semiotic analysis has mainly been presented in a theoretical fashion. To judge its merits as an instrument for productive research it needs to be tested in empirical investigations. Haglund et al. (2010) and Jeppsson and Strömdahl (2010) are two pioneering studies.

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