

Semantic Networks: A Tool for Investigating Conceptual Change and Knowledge Transfer in the History of Science

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Over the past four decades, historians of science have devoted much attention to certain problematic aspects of terms such as *mass* and *force*. The usage and sense of such terms varies between theories, and the meaning of such terms resists explication in language belonging to a different theoretical context. In what follows, we shall consider these phenomena — not in the light of philosophy or psychology — but from a *linguistic* perspective. In this paper, we suggest that *semantic networks* serve as a useful model for understanding the terminology of scientific texts, and we introduce some computational methods that may be of value for the study of conceptual change in the history of science. We then consider: the nature of relations that exist between nodes in a network; the ability of lexicalizations to serve as proxies for concepts; and the application of semantic network analysis to the study of a diachronically extended corpus of texts intended for investigating long-term developments in the history of mechanics. It is our hope that the approaches outlined here may contribute to an understanding of the conceptual structure of mechanical knowledge and its transformations.

1. CONCEPTS, LEXICALIZATIONS, FIELDS, AND MEANING

A single concept may be represented in language in various ways. We call these ways *lexicalizations*. Conversely, a single lexicalization may represent multiple concepts, especially when it occurs in different contexts. As a simple example, we consider two short (English language) texts that deal with FORCE.¹ The first is a sociology paper that discusses police brutality in the United States. The second is a physics paper that deals with the W boson and

¹ We use small capitals to indicate concepts. Lexicalizations are italicized if they are in the Roman alphabet; otherwise they are unmarked.

the weak force. We expect that *force* will mean different things in the two papers. But how do we evaluate or verify this intuition? Using automatic computational techniques, we can find the most frequent lexical *associates* of *force* in the two papers. Figures 1 and 2 represent these associations graphically. In both figures *force* is connected to its five most frequent associates, and these associates are in turn connected to their most frequent associates. The association lines reflect information that is particular to the relevant content domain of each text. *Force*₁ that is *excessive* is *persistently* used against *black males* by the *police*.² The *weak* and *strong* nuclear *forces*₂ are two of the fundamental interactions in physics; the W and Z *bosons* are the quanta of the *vector fields* that mediate the *weak force*₂.

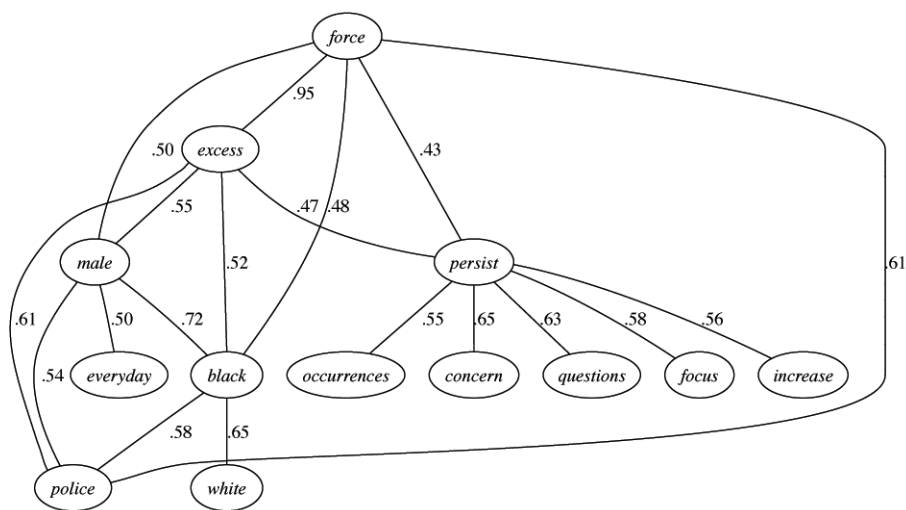


Fig. 1: Associates of *force*₁

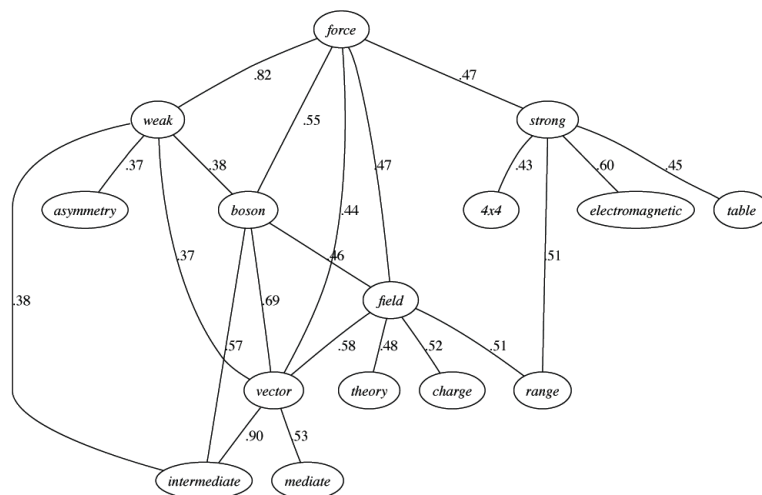


Fig. 2: Associates of *force*₂

2 In the analysis, morphologically related forms such as *persist*, *persistent*, and *persistently* have been conflated according to a modified version of Porter's (1980) algorithm.

The set of lexicalizations applied within a particular content domain is termed a *lexical field* (Lyons 1977, 250–269; cf. Barsalou 1992, 63).³ Lexicalizations within the field participate in relations of contrast and affinity with one another. These relations are both paradigmatic (e.g. synonymy, antonymy, hyponymy, meronymy) and syntagmatic (e.g. agent, patient, instrument, source). In figures 1 and 2 we see both types of relations: paradigmatic (the *strong* and *weak nuclear forces*₂ are exclusive; *black* and *white* are antonyms) and syntagmatic (*police* are the agents that inflict *force*₁ upon *black males*, the patients; W and Z *bosons* mediate the *weak force*₂). Such relations of contrast and affinity are part of our lexical and conceptual knowledge and are constitutive of the *meaning* of lexicalizations within a field. Lexicalizations can be viewed as the *nodes* of a *semantic network*; these nodes are connected by *associative links* that correspond to the paradigmatic and syntagmatic relations.⁴

On this account, the meaning of a lexicalization is a function of its associative links with other lexicalizations (cf. Kuhn 2000, 62–63; Chaffin 1992, 254). Meaning is a holistic property of the semantic network and ceases to be defined in the absence of the network. Obviously, however, there is a difference between meaning in the abstract (that is, divorced from a particular context) and meaning in a context. Here we distinguish, in the network model, between potential and actual meaning. The potential meaning of a word is given by its position within the network: by the words with which it is associated, and the words with which those words are in turn associated, and so on. The actual meaning of a word, however, is given by “the nodes that have actually been activated in the particular context of use” (Kintsch 1998, 413). The actual meaning, then, is related to the potential meaning, but it is determined by the meanings of the words in the syntagmatic context and by the architecture of human linguistic and conceptual processing.

Some links are more important than others. The importance of an inbound link to the meaning of the lexicalization is termed its *criteriality* (Collins & Loftus 1975, 408). The numbers that appear along the edges of our graphs are surrogates of such criterialities; they will be further explained below, section 3.

3 Here we follow Lyons in distinguishing between *lexical field* and *conceptual field* (1977, 253). The distinction is related to that between a lexical memory and a semantic memory for concepts (Collins & Loftus 1975, 411).

4 The notion that memory is associative in nature is a commonplace in psychological literature of the twentieth century (Quillian 1968, 218; Collins & Loftus 1975). We see the notion in inchoate form as early as Aristotle’s *De Memoria* (cf. Cole et al. 2006, 21).

2. FORCE IN (PS.-)ARISTOTLE

We turn now to some historical material, namely, the Aristotelian vocabulary related to the concept FORCE. We concentrate on passages from the *Problemata Mechanica*, a Peripatetic text of unknown authorship that exercised considerable influence on mechanical thinking during the sixteenth and seventeenth centuries (Drake & Drabkin 1969, 11, 14–15). In the relevant lexical field we find three lexicalizations, none of which appear in interchangeable contexts: *ἰσχύς*, *ῥοπή*, and *δύναμις*. The distinction between these lexicalizations resembles nothing that is familiar from Newtonian or contemporary mechanics.

The basic term — and the most frequent — is *ἰσχύς*. It is the closest analogue of the later Arabic *quwwat* and Latin *vis*, with all three terms sharing an ordinary language meaning ‘physical strength’. Alongside *ἰσχύς* (20 occurrences), we find also:

ῥοπή (11 occurrences), the o-grade noun corresponding to *ῥέπω* ‘incline’ (13 occurrences) and

δύναμις (9 occurrences), the standard Aristotelian term for POTENTIAL, which, however, acquires a specialized usage in the context of analyzing motion.

To give a sense of the difficulty posed by this terminology, we might consider that a modern translator (Hett, in the Loeb) renders *ῥοπή* variously as *weight*, *swing*, and *influence*; and *δύναμις* as *power*, *strength*, and *force*.

If we study the *Problemata*, it becomes evident that *ῥοπή* is intrinsically related to the balance-lever model; it refers to the inclination of the beam and the cause of this inclination.⁵ Thus *ῥοπή* involves *disequilibrium* of the balance. ‘*Ῥοπή* is closely associated with weight and results in vertical motion *κατὰ φύσιν* (*per naturam*); by contrast, horizontal motion for Aristotle must always be forced *παρὰ φύσιν* (*contra naturam*).⁶ In analyzing the wheel (for example, of a

5 On the balance-lever model, see Damerow et al. (2002).

6 See esp. 858a14–15 where it is hypothesized that the horizontal motion of a projectile is caused by the *ἰσχύς* of its mover, whereas its downward motion is caused by *ῥοπή* (*ἢ διὰ τὴν ῥοπήν, εἰάν κρείττων ἢ τῆς ἰσχύος τῆς ῥιψάσης*). The fundamental study of the terminology here is Krafft (1970, 47–78); see also Micheli (1995, 64–65) and Carteron (1923, 269–270). Krafft (1970, 147) sees a precedent for the Aristotelian conception of *ῥοπή* in Archytas of Tarentum, but he makes use of a spurious fragment, and his argument is to be regarded with skepticism (Huffman 2005, 78 n. 13).

cart; or a roller upon which a heavy object is moved), the author applies the model of the balance (851b15–852a13). At rest, the wheel touches the ground at a single point; the diameter drawn through that point is vertical and divides the weight of the wheel equally. When the wheel is turned, the weight becomes so distributed that there is more weight (or, to put it differently, greater *ρόπή*) in the direction the wheel is rolling — and thus it is easier to keep pushing it in that direction.

As for *δύναμις* anything so termed should be a CAPACITY — in other words, not yet actualized, in which case it would be an *ἐντελέχεια* or *ἐνέργεια*. While this may be a potential FORCE, it seems at other times to be closer to POWER, which is a concept (from a modern standpoint) related to ENERGY, and which can be exhausted. “[An object in motion] stops when that which is pushing no longer has power to act so as to push the thing in motion, and when the weight of the thing in motion causes (downward) inclination greater than the *power* of that which is pushing forward” (858a20–23). At *Physics* 249b27 ff. Aristotle defines *δύναμις* (POWER) in terms of weight, distance, and time, a relation we might schematize as $P = wd/t$ (cf. Graham 1999, 171). Still, *δύναμις* is not univocal, and even in a single passage both the POWER sense and the FORCE sense may be active.

The foregoing description is of a traditional philological character. Some of the conclusions we have reached, however, are already evident in an automatically produced visualization of the semantic network of the *Problemata*. In the case of *ρόπή* (figure 3) we see strong associations with *εὐκίνητος* ‘easy to move’ (5 occurrences) and *δυσκίνητος* ‘hard to move’ (2 occurrences), terms related to MECHANICAL ADVANTAGE, a highly salient feature of the lever model. There are also direct and indirect links with *ρέπω*, the cognate verb of *ρόπή*. (It is important to note that this association arises via automatic induction from contiguity data; there is no knowledge of derivational morphology built in to the software that produces the model.) The verb *ρέπω*, we can observe, is strongly associated with the adverbs *ἄνω* ‘upwards’ (7 occurrences) and *κάτω* ‘downwards’ (9 occurrences). This affinity reflects the fact that *ρόπή* involves *vertical* motion *κατὰ φύσιν*. The associates of *δύναμις* (figure 4) register its bivalence FORCE and POWER. The associates *ἄνθρωπος* ‘human’ (3 occurrences), *οἴαξ* ‘handle of the rudder’ (2 occurrences), and *πλοῖον* ‘ship’ (14 occurrences) stem from the problem in which the rudder of a ship is modeled as a lever (850b28–851a37). A single *person* (*ἄνθρωπος*) is afforded sufficient mechanical advantage that by moving the *handle of the rudder* (*οἴαξ*) he is able to to

turn the entire *ship* (πλοῖον). The associate παύω ‘stop’ (2 occurrences) relates to the POWER sense and to the Aristotelian idea that projectile motion ceases when the power associated with the force presumed to move the object is exhausted (858a17–23). Finally, the associate μέγεθος ‘quantity’ is connected with both FORCE and POWER senses; these attributes are conceived of as QUANTITIES rather than QUALITIES (cf. Bottechia Dehò 2000, 38; Krafft 1970, 75; Carteron 1923, 17).

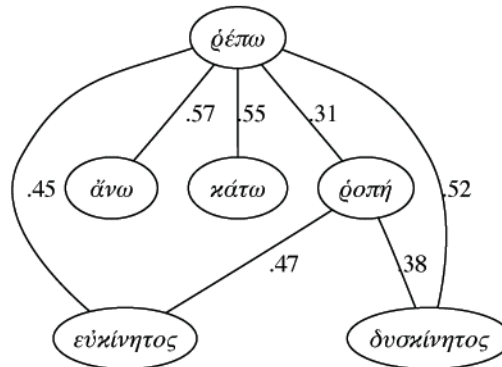


Fig. 3: Associates of *ρόπή*

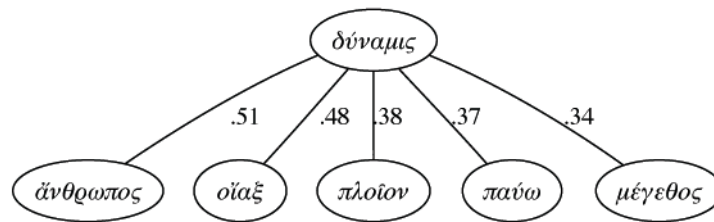


Fig. 4: Associates of *δύναμις*

3. COMPUTATIONAL TOOLS FOR SEMANTIC ANALYSIS

We step back now from this illustrative discussion of Aristotelian terminology and consider some automatic computational techniques related to the view of semantics expounded in section 1. The utility of this view may not be immediately apparent. We should hardly wish to abandon the notion of an essentialist *Grundbedeutung* only to fall back on vague effusions concerning “semantic holism”. Yet with computational techniques we are able quickly and easily to model the semantic network associated with a particular content domain. The resulting visualization of a semantic network is, of course, an artifact that itself demands interpretation. Yet the automatically generated model may serve a valuable function by providing external

confirmation for intuitions we have achieved via another point of departure — and it may also give us a “bird’s-eye view” of the complete set of lexicalizations encountered in a given text or corpus. We attend now to the computational details.

Our method relies on a technique called Latent Semantic Analysis (LSA), which arose in the Information Retrieval (IR) community in the 1990s (Landauer et al. 1998). The technique allows for the automatic, computational construction of a *semantic space* in which lexicalizations correspond to vectors, and the angle between vectors is a measure of the *semantic relatedness* of the corresponding lexicalizations. We begin with a matrix, the columns of which correspond to semantic units we call *containers* (these are typically sentences of one or more texts, but they are actually arbitrarily sized units, where the size is determined by our immediate needs), and the rows to individual lexicalizations. In each cell is the number of occurrences of the given lexicalization in the given container. We then transform this matrix by substituting for the raw frequencies *log-entropy weights*. This preprocessing step is intended (in psychological terms) to reflect the growth function of simple learning and the conditioning rules related to word stimuli (Landauer & Dumais 1997, 216). We now perform a dimensionality reduction on the data, which eliminates dependent dimensions and induces semantic structure that is *latent* in the data. Here we use a mathematical method known as Singular Value Decomposition (Jackson 2003, 189–196). From the resulting matrices of singular vectors and singular values, we can produce a least-squares best approximation of the original matrix for a given dimensionality (Berry et al. 1995). A vector space of several hundred dimensions has been demonstrated empirically to be well-suited for representing the relations between lexicalizations. In this space, it is easy to compute the cosine of the angle between any two lexicalization vectors, which we take as a measure of the strength of association between the pair (or, in other words, as an approximation of the criteriality of the link).

In order to visualize the semantic space, we set a threshold θ and an upper bound n , such that we may define the *immediate neighbors* of a lexicalization w as: 0 – n lexicalizations whose cosine similarity to w is $\geq \theta$. Each of these lexicalizations becomes a node in the semantic network graph, and each shares an edge with the node w . We call the subgraph consisting of w and the immediate neighbors of w the *immediate lexical neighborhood* of w . By generating a graph based on a threshold function from the high-dimensional continuous vector space, we sacrifice a considerable amount of the information contained in the LSA model. We gain, however, a

readily comprehensible visualization that represents semantic distance in part by the number of edges encountered in node traversal. The following discussion involves the neighborhood for ζυγόν ‘balance’ in the *Problemata Mechanica* (figure 5).

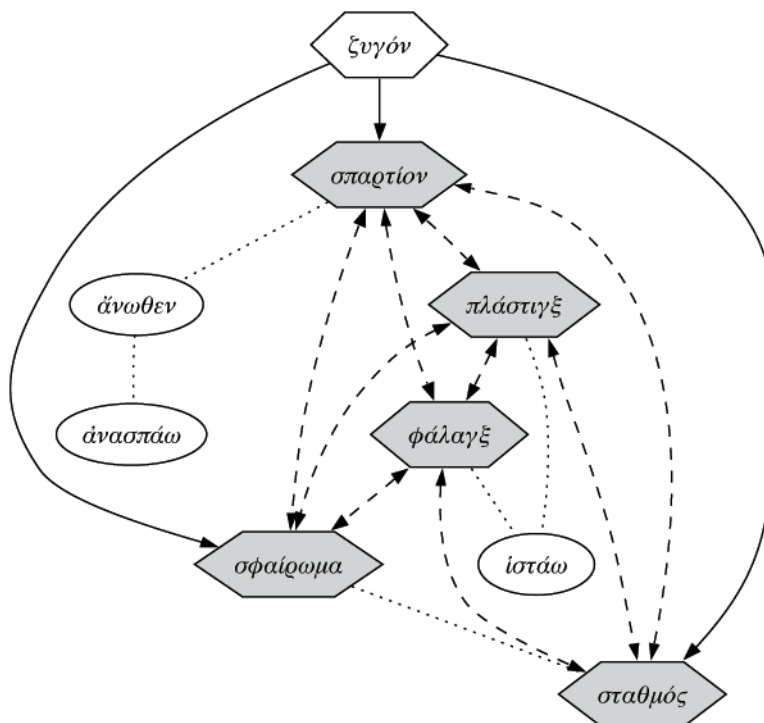


Fig. 5: Semantic neighborhood of ζυγόν

4. SEMANTIC RELATIONS

Traditionally, the edges (also called “arcs” or “associative links”) of semantic networks have been labeled with relations, such as IS-A-KIND-OF or IS-A-PART-OF (Chaffin 1992, 254). Fully labeled in such a way, the semantic network becomes equivalent to an *ontology*, a formal structure for representing domain knowledge (Uschold & Gruninger 1996; Morville 1995, 127–134). (Even so constructed, it still falls considerably short of an adequate system for representing human behavior: among the missing constituents are “schema-like structures with default-slots and procedural knowledge that links cognition and action” (Kintsch 1998, 412).⁷) Our automatically constructed networks are simpler structures and have unlabeled edges.⁸ Yet

⁷ For an elaborated account of frame-based semantics, see Barsalou (1992).

it is interesting to note that very many edges can be labeled easily with terms from a standard repertoire. In the lexical neighborhood of *ζυγόν*, five nodes denote parts. Since these nodes are not all connected directly to *ζυγόν*, we must distinguish two relations: (1) the IS-A-PART-OF relation (= meronymy), to label an edge that connects a part directly to *ζυγόν*; (2) the IS-A-CO-MERONYM-WITH relation, used to label an edge that connects a part to another part. In figure 5 the semantic relations are indicated visually (by hand coding): parts of the balance (*σπαρτίον* ‘cord from which the balance is suspended’, *πλάστιγξ* ‘scale pan’, *φάλαγξ* ‘arm’, *σφαίρωμα* ‘round weight’, *σταθμός* ‘weight’) are gray-filled hexagons, and edges of the IS-A-PART-OF type are solid, whereas edges of the IS-A-CO-MERONYM-WITH type are dashed.

That the relation between nodes connected by an edge so often belongs to a recognizable paradigmatic category suggests that the semantic analysis has induced similarity and contrast relations from contiguity relations. The raw data for the analysis consist solely of contiguity (syntagmatic) relations: word collocations. Yet what frequently emerge in the network diagram are standard paradigmatic relations such as ANTONYMY (*μέγας* ‘large’ : *μικρός* ‘small’; *έκτός* ‘outside’ : *έντός* ‘inside’), SYNONYMY (*ήρεμία* ‘rest’ : *στάσις* ‘rest’; *χωρέω* ‘change position’ : *μετακινούμαι* ‘change position’), and PART-WHOLE (*άψίς* ‘rim’ : *τροχός* ‘wheel’; *ύπομόχλιον* ‘fulcrum’ : *μοχλός* ‘lever’). One might compare the fact that children during their second year shift from relying on syntagmatic/contiguity relations and develop a lexicon that is organized around paradigmatic lexical-semantic relations, which have presumably developed out of the earlier syntagmatic relations (Jaeger 2005, 311–384; Markman 1989, 21–26; Quillian 1968, 234).

That some edges (e.g. *σπαρτίον* : *άνωθεν*; *φάλαγξ* : *ίστάω*) cannot be labeled with a relation type drawn from a small set of standard (lexicalized) types is not an aberration; rather, it reflects the fundamental psychology of semantic relations, which encompasses *relation ambiguity* (more than one relation may be identified between a pair) and *relation creativity* (novel relations may be identified) (Chaffin & Herrmann 1988). In fact, the relations are quite perspicuous. The *scale* is suspended *from above* (*άνωθεν*) by a *cord* (*σπαρτίον*). The *scale* is used to *weigh* (*ίστάω*) things, which lie in the *scale pan* (*πλάστιγξ*), suspended from the *arm* (*φάλαγξ*).

8 The edge types cannot easily be induced from the data. Moreover, as Chaffin (1992) has shown, semantic relations are themselves prototypical concepts with complex internal structure. Not all such relations are lexicalized (Chaffin 1992, 265–268).

5. LEXICALIZATIONS AS PROXIES FOR CONCEPTS

In the history of science, however, we are concerned not with *lexical* structure but with *conceptual* structure. These structures are related bidirectionally: language reflects the world of concepts, and the conceptual world is built at least in part through language. In studying historic scientific texts, words serve as *proxies* for concepts. This is not to say that concepts are necessarily acquired through language (they may, for instance, be acquired through a practitioner's direct experience), or that concepts are fundamentally linguistic — although concepts are indeed bound to language in a close way (Markman 1989, 37). But semantic analysis can provide a starting point for the process of reconstructing the conceptual systems reflected in a text. The semantic network approach shifts the focus from *words in isolation* to *words in relation*; thus it offers a method better suited to the study of cognition and conceptual change than the method exemplified by countless philological studies of individual terms.

6. INVESTIGATING LONG-TERM DEVELOPMENTS IN MECHANICS

The next phase of this research project is to apply the techniques described here to the extensive commentary literature on the *Problemata* that appeared roughly during the last quarter of the sixteenth century and the first of the seventeenth. The following texts are available in digitized form that facilitates analysis:

Alessandro PICCOLOMINI, *Parafrasi di Monsignor Alessandro Piccolomini arcivesco di patras, sopra le mecaniche d'Aristotile*, Rome, 1582.

Henri de MONANTHEUIL, *Aristotelis Mechanica, Græca, emendata, Latina facta, & Commentariis illustrata*, Paris, 1599.

Giuseppe BIANCANI, *Aristotelis Loca Mathematica ex universis ipsius Operibus collecta & explicata*, Bologna, 1615.

Bernardino BALDI, *In Mechanica Aristotelis Problemata Exercitationes*, Mainz, 1621.

Giovanni di GUEVARA, *In Aristotelis Mechanicas Commentarii*, Rome, 1627.

In addition, we have available seminal treatises on mechanics from this period — significantly influenced by the content of the *Problemata* —, including most notably Girolamo Cardano’s *Opus Novum de Proportionibus* (1570), Guidobaldo del Monte’s *Mechanicorum Liber* (1577) and Galileo’s manuscript *De Motu Antiquiora* (ca. 1590). This body of texts (roughly 1,800 pages in extent) offers an excellent opportunity for exploring, by means of semantic network analysis, the developing tensions that finally gave rise to the new “classical mechanics” inaugurated by Newton’s *Principia* in 1687.

The work described here is closely integrated with several larger research frameworks. First, it forms a part of sub-project A6 of the SFB 644 »Transformationen der Antike«, entitled “Weight, Energy and Force: Conceptual Structural Changes in Ancient Knowledge as a Result of its Transmission”. Second, it is closely integrated with the working group “Mental Models in the History of Mechanics” at the Max Planck Institute for the History of Science. Third, our work makes use of digital texts and tools developed by the Archimedes Project, an international German-American venture aimed at creating an open digital research library that would allow scholars new and more efficient means of studying long-term developments in the history of mechanics. In much the same way that computational tools have revolutionized many branches of science (e.g., computational molecular biology), we expect that information science techniques will have a salutary effect on research in the historical disciplines (Abbott 2001).

We believe that by studying the semantic networks derived from these texts we can gain insights into the conceptual change that results in a new mechanical world-view. Within the context of semantic network theory, semantic change is a concrete and readily investigable phenomenon, inasmuch as it is just observable change within the network structure. By examining the transformation of the semantic domain corresponding to mechanics, we will be able better to articulate the transformation of mechanical concepts. This type of analysis is not intended as an alternative to the high-level description of scientific history by means of mental models; rather, it serves as a preliminary for that description, and it constitutes a new and powerful way of locating the semantic nexuses that correspond to conceptual structures of interest and of identifying the critical points where concepts conflict, compete, evolve, and are replaced.⁹

9 I am immensely grateful to Peter Damerow, Phoebe Pettingell, Matthias Schemmel, Mark Schiefsky, and Ludmila Selemeneva for their comments on drafts of this paper.

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