

A General Model for Developing, Validating and Evaluating Nature of Science and Other Science Curricula and Instructional Materials

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ABSTRACT

Nature of science research continues to generate a high level of interest among educators and scholars. Despite the fact that the nature of science is a continually evolving and highly complex instructional endeavour, there are no comprehensive instructional models available for researchers that can systematically capture and organize this theoretical 'universe' of content and then translate this content into educationally sound and validated classroom materials, activities and representations. In addressing these issues, this article further elaborates a general model of instructional materials development initially formulated by Carifio (1974, 1976 & 1977) which has recently been used by others to develop curricula and instructional materials in non-science areas, and applies the model to nature of science studies in particular and science curricula in general. The implications of this model are discussed.

Keywords: *Science Curricula Development, Science Curricula Validation, Nature of Science, Nature of Scientific Change, Nonlinear Dynamics, Teaching Nature of Scientific Change.*

1. INTRODUCTION

In different forms and at varying levels of complexity and urgency, an understanding of the nature of science and scientific knowledge has continually been identified as a highly needed and critical component of the science curriculum, from the elementary to the post-doctoral level, by leading scientists, philosophers of science, educational philosophers and science educators over the past century (Conant 1945; Dewey 1910; Duschl 1990; Fleck 1935/1979; Gould 2002; Kuhn 1962/1996; Martin 1972; Matthews 1994; Schwab 1962, among others). Further, in almost all major science education reform documents and writings in the past decade, understanding the nature of science has been identified and strongly emphasized as a critical component of scientific literacy, particularly at the high school and undergraduate level (Lederman 1992; McComas 1998; Matthews 1994; National Academy of Sciences [NAS] 1998; National Research Council [NRC] 1996; National Science Teachers Association [NSTA] 1998, 2001). However, translating and communicating complex scientific, philosophic and epistemic concepts, such as those associated with the nature of science, into effective and sound instructional materials is a multifaceted, complex and difficult task (Olson & Clough 2003). Furthermore, the methods used to extract, translate, filter and teach these concepts in science education have tended to be implicit (see Khishfe & Abd-El-Khalick 2002) and not very systematic.

Despite the fact that the nature of science is a continually evolving and highly complex instructional

endeavour, there are no comprehensive instructional models available for researchers that can systematically capture and organize this theoretical 'universe of content' and then translate this content into educationally sound and validated classroom materials, activities and representations. In addressing these issues, the main purpose of this paper is to describe a general (macro) model and theory of instruction and instructional materials development initially formulated by Carifio (1974, 1976 & 1977), and to apply this model to nature of science studies, and particularly to various ideas of scientific change and progress. Specifically, we would like to show how this model was used to:

- a. Develop a theoretically based model of scientific change;
- b. Systematically generate developmentally appropriate (linguistically and conceptually) materials to teach undergraduate teachers and students about this model of scientific change and its related content; and,
- c. To validate and field test these materials for effectiveness.

The three goals stated above, it should be noted, follow a logical transition from theory to practice. Concretely illustrating all three goals, however, is not possible in this work (it has been done in other work) because we are somewhere between the second and third goal in our research program now. Nevertheless, what is possible at this time and perhaps helpful to many is a basic description of the guiding framework we are using to make the transition from a highly theoretical, complex and elegant

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model of scientific change (described below) to instructionally valid materials and activities based on that model. For this reason, much of this paper's language is didactic and anticipatory.

A review of the literature found no previous attempt to use a macro model and general theory to develop and validate instructional materials in the area of philosophy, let alone the intersection of philosophy and science, which has come to define contemporary NOS studies. Further, it should be noted that this macro model is not limited to nature of science studies or science education, but can be applied to any form of instruction (or content area) looking to use a systematic and theoretically grounded model to make the transition from theory to practice. It should also be noted that this model makes explicit what most educational researchers do (or should do) implicitly in developing high quality and valid instructional materials. This approach to instructional materials development is consistent with the current emphasis and thrust in the United States on making research in education more systematic, rigorous and scientific (see Shavelson & Towne 2002).

a. A Model of Instructional Materials Development

The general (macro) model and theory of instruction and instructional materials development presented here and formulated by Carifio (1974, 1976 & 1977) has been used successfully in variety of scientific and non-scientific contexts with a wide range of learners at different ability levels (e.g., Carifio et. al 1978; Carifio & Kermis 1992; Dagostino & Carifio 1994a; Flores 2005; Nasser & Carifio 1993; Pelliter 2004; Schewdel & Carifio 1985). These macro models and theories look to develop a comprehensive knowledge base in a particular domain and to translate key and critical features of this knowledge base into appropriate instructional materials validly and with fidelity that teachers and students can understand, operationalize and use in multiple and generative ways. For example, Dagostino & Carifio (1994a) developed a comprehensive theory and model of evaluative reading and assessed whether practicing teachers could translate the theory into instructional materials (practice) that independent ratters (other teachers trained in the theory) were able to judge as valid exemplifications of the theory or not. Although no formal field-testing with students was performed in this study, the results clearly demonstrated that the critical (theory-to-practice) phase of the model was successful.

Using a similar model and approach, Carifio & Kermis (1992), developed a conceptual/theoretical model of elementary mathematics, which they were successfully able to translate into field-tested instructional materials and

activities for special needs students. These materials significantly improved the performance of these students state wide as compared to the materials that were in use in that state at that time. This study replicated the results of a study done by Carifio, Biron & Sullivan (1978) that developed and tested alcohol education instructional materials for grades seven to twelve. More recently, Flores (2005) established a critical and high quality knowledge base for successfully teaching Hispanic-Caribbean students, which was translated into instructional materials and subsequently field-tested and validated by a panel of experts in the field of minority education. Pellitier (2004) showed that a formal model and theory could be developed and externally validated from the corpus of writings on interpretive reading over a twenty-year period. Nasser and Carifio (1993) as well as Carifio and McBride (1997) showed that this model could be used to develop appropriate theory-based tests and assessments that could be linked to instruction developed using this macro model. Carifio (1976) originally developed and piloted the prototype of this macro model for the United Sates Navy to use as a standard model in developing scientific-technical instructional materials in all of their instructional efforts where it was effective in a variety of different instructional contexts. This macro model has been successively developed, extended and elaborated since its initial development and field-testing in the United States Navy.

The current research formalizes the specifications of the general (macro) model of instruction and instructional materials development outlined in each of the instantiations described above. This more formalized macro model (see Figures 1, 2 & 3) will be used to guide the development and validation of instructional units (text and materials) to teach undergraduate teachers and students about a model of scientific change referred to as the Kuhn Cusp Catastrophe Model (KCCM, described below) and its related content.

The development of instructional text and materials, it should be noted, is in most instances a highly noisy and highly fuzzy process and endeavour, and this is one of the problems this research looks to address. The question is can this process be otherwise and reproducibly so and to what extent and with what consequences. This question is especially important for NOS studies, as one needs to have 'text to specification' to do any meaningful research on NOS related concepts and their understanding and learn ability by students. This research is field-testing this macro model for philosophical content and the various higher order cognitive

processes involved with philosophical understanding, reasoning and thinking.

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The macro model developed here should be capable of logically guiding the instantiation of various representations of subject specific content and knowledge bases. The specifications used for this instantiation are what define the different (micro) models, which focus on some of the relationships and variables in a system (Fisher 1992). The purpose and intent of the macro model and micro models employed in this research is to guide the logical development of a series of instructional units (described below) for teaching undergraduate science majors about theory change and progress in science using the KCCM (a nonlinear qualitative model of scientific change) and its associated content.

b. Macro and Micro Models

For sake of clarity, it should be emphasized that there are several models referenced in this paper. The KCCM and its associated content is a model of scientific theory change that will be operationalized via a general or macro model of instructional materials development, which includes various micro models of instructional materials development (see Figure 1 for details). The definition of a macro and micro model or theory used here is consistent with the general and standard usage in the sciences and particularly in the field of econometrics. The link between instructional design and econometrics is quite natural considering that the aims and scope of both fields is strikingly similar if one adopts a scientific and rigorous

approach to the development of instructional models and materials. For example, econometrics is concerned primarily

with (a) the formulation of models, (b) statistically testing these models and the estimation of their parameters and (c) the predictive value of these models (Bergstrom 1993). These concerns should also be major concerns of instructional and instructional development models (see Carifio 1976).

A macro theory or model is defined as a more general and inclusive model or theory compared to a micro model, which is nested in it. Micro models (sometimes referred to as sub models or sectors) have a truncating effect as they focus on only some of the relationships and variables in a system and in greater detail and specificity compared to macro models (Fisher 1992). Many of the macro variables are 'exogenous' (independent, predictor or upstream) variables in the micro model. That is, exogenous variables exist outside the micro models 'sector of interest', but are endogenous to the macro model, or the system as a whole (Fisher 1992).

As can be seen in Figure 1, macro models or theories always tend to be broader in scope and application (and therefore less detailed) than micro models (the big picture or 'frame') and macro variables tend to be 'indices', collections, or aggregates of variables at the micro level (Kerlinger & Lee 2000). It should also be pointed out that the way in which 'frames' and 'levels' are constructed and sectors and variables selected, is relative and somewhat arbitrary and capricious and basically an instance of the 'axiom of choice' in mathematics (i.e., a good or poor choice rather than a correct or valid or wrong and invalid choice).

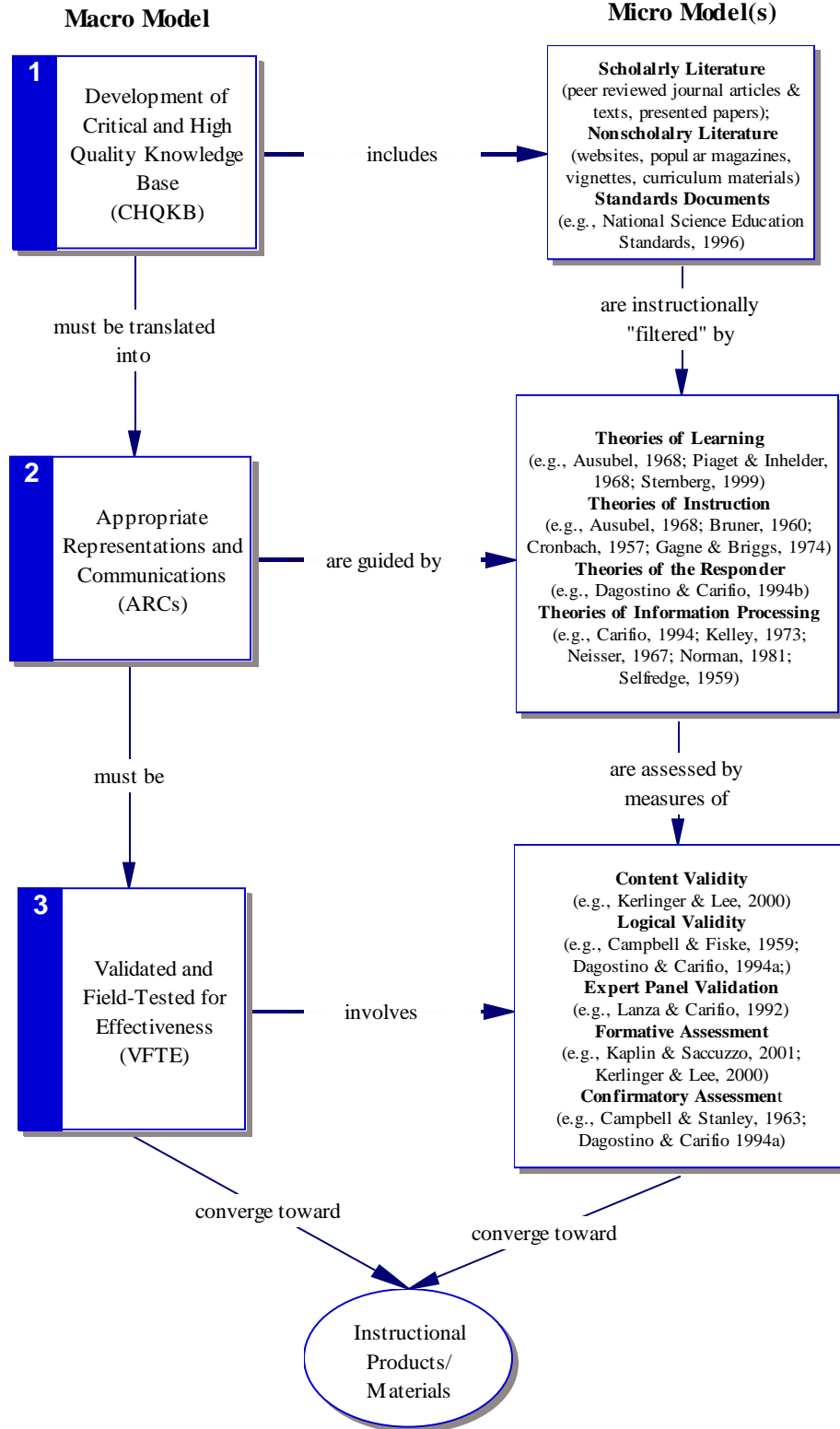


Fig 1: The specific formalizations of Carifio’s macro and micro models used in this study.

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Looking at Figure 1, it also becomes apparent that there are three qualitatively different levels or types of theoretical referents in this kind of systematic approach to instructional materials development. The CHQKB process is linked to content-based theoretical referents (and decisions or judgments); the ARCs process is linked to learning theory-based theoretical referents (and decisions and judgments); and the VFTE process is linked to psychometric and assessment-based theoretical referents (and decisions and judgments). Although understanding how these qualitatively different (yet related) referents interact in the process of materials development is a key issue, this concern goes beyond the scope of the present paper, which only looks to provide a basic blueprint for developing instructionally valid materials related to a specific content area.

Figure 2 provides a simplified version of Carifio's formalized macro model in Figure 1. This simplified version of the macro model provides a general overview and a quick visual reference of how each of the elements in the macro model interacts and contributes to the target instructional materials. The simplified model also demonstrates a more fluid, dynamic and interactive model than is represented in Figure 1. It should be stressed that despite the fact that Figure 1 is depicted in step-wise fashion for presentation purposes, the relations between the elements in the macro model and their associated sub-models is dynamic and consistent with a cognitive view of leaning and instruction (Ashcraft 2002) and reading comprehension (Dagostino & Carifio 1994b).

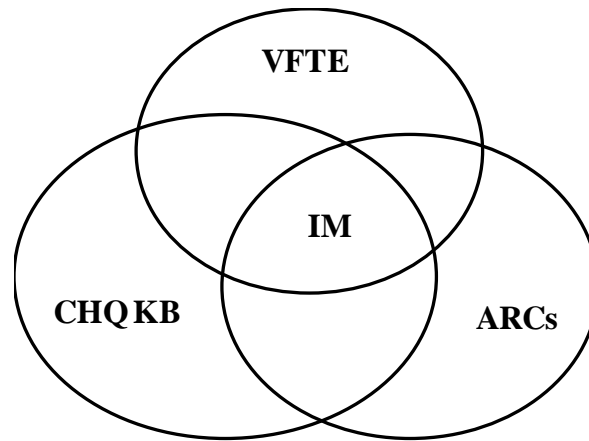


Fig 2: Simplified version of Carifio's macro model. The point where all areas intersect represents the target instructional materials (IM). (VFTE = Validated and Field-Tested for Effectiveness; CHQKB = Critical High Quality Knowledge Base; ARCs = Appropriate Representations and Communications).

c. Overview of Theoretical Frameworks

As can be seen in Figure 1, there are macro and micro frameworks and theories for this work (see Carifio 1975 for details). The macro instructional framework is the theory, process and model by which the relevant scholarly and non scholarly literature for an area, topic or discipline is established, screened, weeded and refined into a Critical and High Quality Knowledge Base (CHQKB). Figure 3 depicts in detail the CHQKB for the Nature of Science (NOS) domain and knowledge base for this research. The CHQKB is derived from four primary sources including a review of (a) the science education literature, (b) primary sources in the history and philosophy of science, (c) materials from leading

history and philosophy of science centres, institutes universities and groups, and (d) science education standards documents in the United States. The CHQKB is then translated into Appropriate Representations and Communications (ARCs) for a particular audience or set of audiences, which are then validated and Field-Tested for Effectiveness (VFTE). One instantiation of ARC's is written instructional materials, which is the focus of this research. What constitutes appropriate and high quality instructional materials and their testing is micro theories in this macro model and these theories are briefly described below. The macro and micro theory and frameworks are summarized in Figure 1. The next section of this paper more specifically addresses (1) the Critical and High Quality

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Knowledge Base (CHQKB) that led to the development of the KCCM, (2) the Appropriate Representations and Communications (ARCs) that led to the KCCM derived instructional materials and activities and (3) the psychometric theories and processes that will subsequently be used to validate and field test these materials for effectiveness (VFTE). Formal definitions for each of the three macro-model elements are provided in Appendix A.

d. Critical and High Quality Knowledge Base

Critical and High Quality Knowledge Bases are part of any macro instructional model and represent the content that will be translated into instructional materials and activities. The first step in any macro instructional model is developing this type of knowledge base, which in many instructional milieus is a tacit and implicit function and something Carifio's model looks to make explicit. As mentioned above, the specific CHQKB used in this research (see Figure 3) is derived from four primary sources including a review of (a) the science education literature, (b) primary sources in the history and philosophy of science, (c) materials from leading history and philosophy of science centers, institutes universities and groups, and (d) science education standards documents in the United States. One of the main themes that emerged from the analysis of these four sources was the importance and centrality of understanding the dynamic nature of scientific knowledge, and, in particular, scientific change and progress. A brief summary of this analysis is given below, which also provided justification for the KCCM. A more complete and comprehensive description of this analysis is provided in Perla & Carifio (2004) and a more complete description of the KCCM and its theoretical referents are provided in Perla & Carifio (2003).

The delphi study by Osborne, Collins, Ratcliffe, Millar and Duschl (2003), which sought to develop an expert consensus about what 'ideas about science' should be taught in the classroom, is an excellent example of the systematic and logical construction of a CHQKB in nature of science related studies, and the only such study of which we are aware. However, the themes identified by the experts

in this study (including philosophers, historians, and sociologists of science, science educators and science teachers) were summarized using language that was admittedly 'academic' in nature—a language that would need 'to be unpacked and elaborated for a practitioner audience' (Osborne et al. 2003, p. 699). This 'second step' of linguistic and conceptual 'unpacking' and 'elaboration' for a particular instructional audience is a process that requires just as much (if not more) consideration, skill, structure and theoretical organization as the development and validation of the CHQKB. The process of unpacking, elaborating and translating this content base into appropriate instructional materials and then field testing and validating these materials is what defines the scope and essence of the ARC and VFTE elements of the macro model (described below).

2. UNDERSTANDING AND MODELING CHANGE IN SCIENCE

In contrast to the 'linear' and accretive view of knowledge explicated by logical positivists—which dominated the early science curriculum and continues to inform science education in recent times (see DeBoer 1991)—contemporary philosophers of science and science educators generally believe that scientific knowledge is best described as a dynamic and at times discontinuous process involving a number of complex factors (Duschl 1994; Losee 2004). Understanding and having a formal and interactive model of the nature of scientific change as well as the factors and dynamics that bring about scientific change is important in a globally competitive economy and society that is driven by scientific discovery, change and the applications of discoveries and changes rapidly in the market place (Burrus 1993). Despite the fact that an understanding of the nature of science has become a perennial goal of the current science education reform movement, there are no formal, nonlinear and 'real-time' models of scientific change available for educators that dynamically depict theory change and progress in science. Having validated formal models of these phenomena and related instructional materials will facilitate both the teaching and achieving of these relatively new and critically important goals.

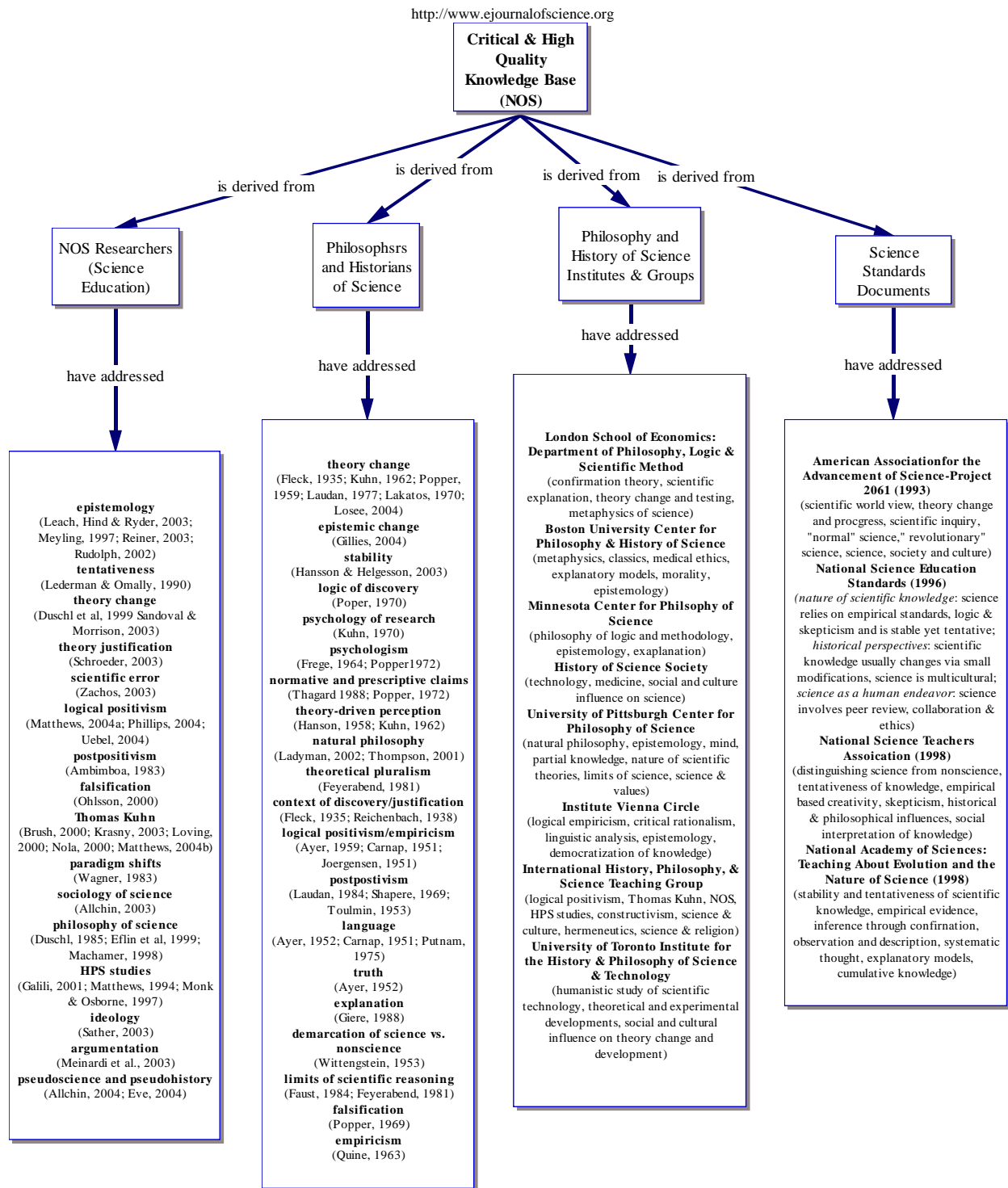


Figure 3. Critical and high quality knowledge base for nature of science.

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Although no standard definition of the nature of science exists, the educational literature generally associates this concept with the epistemology of science, or the values and assumptions inherent in the development of scientific knowledge (Lederman 1992). Specifically, this epistemological view among science educators emphasizes the idea that scientific knowledge is stable yet tentative, empirically based, inferential, subjective, theory-laden, and influenced by the social and cultural milieu (American Association for the Advancement of Science 1993; Lederman, Abd-El-Khalick, Bell, & Schwartz 2002; NRC 1996). Many of these epistemic features of the nature of science identified by educators have been substantiated by professional philosophers of science (Eflin, Glennan, & Reisch 1999) and empirically validated by a wide range of nature of science experts (Osborne et al. 2003).

Of these epistemological features, the tentative and revisionary character of science is believed to play a central role in nature of science studies by teachers, researchers, and curriculum developers. As Lederman and O'Malley point out, much of the research regarding the nature of science in an instructional context has been based on the belief that 'tentativeness is the primary attribute of scientific knowledge...' (Lederman & O'Malley 1990, p. 225). Indeed, for the past six decades instruments designed to gauge student understanding of the nature of science have to some degree and at varying levels of sophistication involved measures of tentativeness and change (Lederman, Abd-El-Khalick, Bell, & Schwartz 2002; Aikenhead 1987; Lederman & O'Malley 1990; Ruba & Anderson 1978; Vitrogon 1967; Wilson 1954). This priority focused on the tentative, dynamic and changing nature of scientific knowledge has developed gradually over the past fifty years following developments in the history and philosophy of science and it has played an increasingly important role in science education (Duschl 1994).

The transition to a more dynamic view of scientific knowledge has largely been influenced by and associated with the work of Thomas Kuhn (1962/1996). In sharp contrast to the early positivist view of the nature of science and scientific knowledge, Kuhn argues that the scientific enterprise involves states of continuous, gradual development ('normal' science) punctuated by comparatively rare instances of turmoil and change ('extraordinary' science), which ultimately brings about a new

stability and a qualitatively changed knowledge base in a rather abrupt and discontinuous way ('revolutionary' science). What Kuhn (and other historians and philosophers of science) was arguing for and attempting to model was a differentiated view of theory change. A differentiated view of theory change is one that explicitly involves and addresses both local (theory sustaining) and global (theory busting) forms of change and their interrelation. The term differentiated refers to the idea that local and global varieties of change are qualitatively different; that is, local change in science is associated with the acceptance of a fundamental or core theory, whereas global change in science is associated with the rejection of a fundamental or core theory—two qualitatively different states (see Appendix A for definitions).

Implicit in Kuhn's view of theory change is the idea that over time local changes may eventually lead to a global change in a theoretical system that is relatively sudden and unpredictable, thereby suggesting a link or interrelation between the two qualitatively different forms of theory change. This view of change is a central feature of chaos theory, which addresses the extreme sensitivity of a system to its initial conditions where organized 'inputs' lead to unpredictable and random 'outputs' over time. Similarly, catastrophe theory (a branch of chaos theory) has been used to qualitatively model and understand the problem of succession of form where continuous causes lead to discontinuous effects (Thom 1989). Combining the ideas of Thom and Kuhn gives rise to a qualitative mathematical model of scientific change and progress referred to as the Kuhn Cusp Catastrophe Model (KCCM), which is developed in detail in Perla & Carifio (2003).

Table I provides a mapping of the five qualitative properties of a cusp catastrophe to the key features in Kuhn's model of scientific change. Christopher Zeeman, a disciple of Rene Thom and prolific catastrophe theory modeler, states that 'If any one of them [the qualitative properties] is apparent in a process, the other four should be looked for, and if more than one is found, then the process should be considered a candidate for description as a cusp catastrophe' (Zeeman 1976, p. 76). Following Zeeman's maxim, we can establish ex post facto correspondences between the qualitative properties of the cusp and Kuhn's description of the scientific enterprise.

Table I: Correspondence between the five qualitative properties of the cusp catastrophe and Kuhn's model of scientific change.

Qualitative Property	Catastrophe Theory Definition	Kuhnian Correspondence
Inaccessibility	refers to an area in the system that is not capable of being occupied	the idea that scientists are never without a guiding theoretical commitment (i.e., scientists are never theoretically neutral)
Divergence	involves different behaviors that start in a similar position, but end up far apart	involves competing paradigms which initially experience similar success predicting natural phenomena, but experience different outcomes over time (i.e., acceptance or rejection)
Hysteresis	characterizes the delay associated with cyclic transitions in behavior	is evident in the historical observation that paradigms are not immediately rejected even in the face of major anomalies and alternate views
Bimodality	defines an area in the system where two distinctly different behaviors may occur	results in the presence of a competing paradigm
Sudden Transition	is the abrupt transition or change from one behavior or state to its polar opposite	represents the gestalt-like 'switch' in paradigm commitments

The KCCM is actually a meta-model of scientific change and progress that incorporates a number of post positivist views and theories of scientific change explicated by different historians and philosophers of science each advancing their own brand of theoretical pluralism and a differentiated and dynamic view of theory change (e.g., Fleck 1935/1976; Kuhn 1996; Lakatos 1970; Laudan 1977). Since understanding change and the succession of form is the primary aim of catastrophe theory and also represents a longstanding and fundamental problem in the philosophy of science—especially as the latter relates to changing theoretical commitments—it is quite logical to frame aspects of the epistemology of science using the formalism and lexical precision of catastrophe theory with the expectation that this formalism will provide the basis for a systematic and meaningful interpretation of the scientific enterprise, and one that may have instructional value particularly at the high school level and beyond if is effectively translated into instructionally valid materials and activities.

The importance in understanding the dynamic and differentiated view of theory change outlined by Kuhn (and others) is also recognized by the science education community at large as is evidenced by various international science education standards documents (McComas & Olsen 1998), many of which make reference to Kuhn's periods of 'normal' science and 'revolutionary' science,

respectively. Although this discontinuous and nonlinear view of scientific knowledge is shared by a number of philosophers of science and science educators currently, Kuhn's description of how progress in science occurs has never been formally modelled from a nonlinear and 'chaotic' mathematical perspective, despite the fact that such models are capable of representing exactly this type of phenomena. Notwithstanding the advantages of nonlinear mathematical models when dealing with complex phenomena—particularly their formal structure and precision, their ability to handle multiple representations and factor structures and their clear link to the philosophy of science—they remain a largely unexploited resource in philosophy and nature of science studies hitherto.

The work we are presenting here outlines a process whereby macro and micro models of instruction can be used to logically translate the KCCM (and its associated content) into a module (or mini-course) on theory change including four instructional units (described below). This instructional model and its related activities explores the influence and effectiveness of using a qualitative mathematical model of theory change to analyze and depict an actual case of theory change in science by students and experts who have been introduced to key and critical NOS concepts (describe below) that serve as epistemic scaffolds or cognitive primers before the modelling activities.

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One last point needs to be made here regarding the instructional assumptions implied in the KCCM. The view presented here argues that it is possible to develop and validate a nonlinear (catastrophe theory) model of scientific change and to translate this type of model into instructional materials, activities and units that will actively engage undergraduate students and teachers. By developing a general and formal model around a central epistemic feature of science (i.e., tentativeness and change), other important features and concepts of science (such as parsimony, falsification, reproducibility, exemplars and methods of inquiry) can be incorporated into the model and its related instructional materials. This central features-based instructional approach is an important consideration of cognitive psychologists and contemporary learning theorists (Aschraft 2002).

This strategy and approach of developing a general model (or models) of the nature of science and scientific change, it should be noted, contrasts the ‘particularise’ view of the nature of science currently espoused by some science educators (e.g., Rudolph 2000). The particularise approach argues that there is no single (or universal) nature of science and that the science curriculum should focus on helping students learn about the proximate goals of science and ‘the diverse, local practices that are found within and across scientific disciplines’ (Rudolph 2000, p. 403). Although this is certainly a laudable instructional aim, the absence of a general and ‘standard’ epistemic model or normative prototype of the nature of science, which is not a concern of the particularise approach, fails to consider how these particular instances are being organized conceptually by the student on the larger scale and provides very little guidance or structure for teachers—many of whom have little experience, training and competence in philosophy and epistemology.

The view constructed here contends that the ‘particulars’ without the ‘universals’ (or vice-versa) is an impoverished and incomplete approach to teaching aspects of the nature of science and that both perspectives are necessary to optimize science instruction that aims to help students develop a sophisticated view of the nature of scientific knowledge, progress and change. We believe that each of these perspectives can effectively be operationalized via the KCCM. Nevertheless, operationalizing and concretizing the catastrophe theory model of scientific change via instructional

materials (i.e., going from theory to practice) requires a logical translation process, and developing and field-testing this logical translation process represents a critical dimension of the research outlined here.

Lastly, although it may seem odd and a contradiction to use a formal mathematical model to represent the ‘postpositivist’ view of scientific progress and change, the KCCM, it should be emphasized, is not an ‘anti-positivist’ model. Theoretically, the KCCM can effectively model the views of theory change and development explicated by positivists and postpositivists alike. As the science education community has recently emphasized, there are strong virtues of positivism (instructional and purely philosophical), which center on a formal, rigorous and precise use of language and logic in developing a knowledge base (Matthews 2004; Phillips 2004). Any model of scientific progress and change needs to demonstrate the capacity to model such concepts, and the KCCM certainly accommodates this requirement.

a. Appropriate Representations and Communications (Arcs)

Appropriate Representations and Communications include instructional materials such as written instructional texts, instructor’s manuals, laboratory exercises, charts and diagrams. The word ‘appropriate’ refers to theoretical appropriateness or justification, as the initial selection of the representations and communications is required to be justified (logically and empirically) by the theories that will inform the selection process. These theories include but are not limited to theories of learning, instruction, information processing as well as philosophical considerations related to the nature of the material (i.e., what is the representation at the most fundamental level and how is that justified). The word appropriate is an anticipatory, predictive and probabilistic word as one assumes a direct proportional relation between theoretical appropriateness and actual appropriateness as determined by validation and field-testing procedures (see below). A description of the main ARC referents is provided in Figure 1. Some of the more important (and often ignored) considerations of ARCs include whether the researcher and/or instructional materials developer has:

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- a. A basic understanding of the learner (e.g., development, aptitude and ability level of the learner);
- b. A 'theory of the responder'; and
- c. A "theory of information processing."

In addition to these three concerns, the specific nature of the learning and 'processing' task needs to be understood. For example, despite the fact that this research looks to translate a 'graphic' model of scientific change, this translation process is text mediated requiring the instructional materials developer to understand, conceptualize and define the:

- a. Text processing and reading comprehension model(s) adopted for the specific ARC;
- b. Semantic structure and presentation structure of the ARCs;
- c. Instructional sequencing and content structure of the ARCs; and,
- d. Key and critical features to be taught and emphasized.

Additionally, because 'graphs' and 'models' are being used as ARCs, one would need to conceptualize and define:

- a. What a 'graph' and 'model' are and how they are distinguished from 'text';
- b. How a 'graphic model' supports (or subverts) the 'text' and vice-versa; and,
- c. The best method of translating key KCCM concepts to the learner

To discuss the ARC theoretical referents in detail would take up far too much space and time and goes beyond the scope of the present paper which is to provide a general description of the instructional materials development model. The theoretical referents associated with these and related ARCs are provided in Figure 1. It should be clearly stated that there are multiple instructional referents, views, priorities, preferences and perspectives that could be used in this model. The point of this model is to make these referents explicit and to codify them into

a system of instructional materials development that can be used to refine and modify the materials.

Clearly, in the absence of proper contextualization and instruction, the KCCM will be far too complex and abstract to be understood by most undergraduate science students and many science teachers. Further, many of the ideas, concepts and terms associated with the model are philosophical in nature and are likely to be unfamiliar to students and teachers with little exposure to philosophy and philosophical discourse, and particularly the philosophy of science and its subtle yet critically important nuances. For this reason, the ARCs we are currently developing will include four instructional units that address these points and problems and build on one another. Following the guidelines stated above, these four instructional units can be described as follows:

Unit 1: A definition and overview of the aims and scopes of the history and philosophy of science including key terms and concepts as well as an overview of scientific knowledge and the two modes of scientific (theory) change outlined in the KCCM;

Unit 2: A basic introduction and overview of the philosophical tradition known as logical positivism and post positivism and their views of theoretical change, stability and progress in science;

Unit 3: An overview of nonlinear models (including the KCCM), and the link between the KCCM and the contemporary views of theory change and progress in science explicated by Kuhn and other post positivist philosophers of science; and

Unit4: An expository and didactic instantiation of the general KCCM in the form of a case study of an episode of theory change in science where respondents are asked to read a series of narrative excerpts and then to graphically model and represent theory change using the KCCM. The actual KCCM graphics and mathematics used in unit 4 will be modified to provide the most basic representation possible.

Each of the individual units will focus on key and critical features relative to their specific subject matter (see Table II). Each of the units are

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necessarily linked to one another with the first unit providing the conceptual foundation for the second unit and so on. The intent of the final unit (unit 4) is to have respondents' use and incorporate key elements from each of the units to critically examine and graphically represent theory change and progress in relation to the quasi case study using the KCCM and model related aides. The emphasis will be on

recognizing and modeling the dynamic nature of science (i.e., both stability and instability).

Of course the content in each of these units is rich and densely packed and could, at a later date, be blown out and separated into multiple additional units as well as additional modules. However, the purpose of this research is to cover key issues and topics that help students develop the requisite or

Table 2: List of critical and key feature strands and exemplars extracted from the Critical and High Quality Knowledge Base (CHQKB).

Critical Feature Strand	Exemplar	Units Present	Degree of Recursion*
Discipline strand..... (Derivatative)	philosophy, philosophy of science, history of science, epistemology, Science, metaphysics, natural Philosophy	1	Low
Change strand..... (Generative)	theory change/progress, tentativeness, stability, differentiated change, local Change, global change, normal science, Revolutionary science, competing views, Falsification, theoretical pluralism	1,2,3,4	High
Historical figures/ Groups strand..... (Derivatative)	Aristotle, Plato, Bacon, logical positivism, postpositivism, Thomas Kuhn, Karl Popper, Vienna Circle, Rudolph Carnap	1,2	Moderate
Analytical strand..... (Generative)	justification, discovery, analogical reasoning, mathematical modeling, Language, logic, nonlinearity, prescriptive Claims, descriptive claims, psychologism	1,2,3,4	High

*anticipated degree of recursion based on the following criteria:

High = focus of each unit (n = 4); Moderate = focus of 2-3 units; Low = focus of 1 unit

background schemata necessary to successfully and meaningfully execute the final (modelling) unit that incorporates a number of key concepts from the previous three units in the sequence. Certain aspects of each unit may be eliminated, elaborated and streamlined on various grounds, and the process of logically modifying and reconstructing the individual units is a critical part of the Validation and Field Testing for Effectiveness process described below.

3. KEY AND CRITICAL FEATURES

An important aspect of this research involves the filtering and selection of information and

knowledge from the CHQKB (universe of content) to be translated into the instructional units (ARCs). The decision to select certain elements and relations between elements from this theoretical universe of content—and to characterize them as key and critical—is somewhat subjective and requires validation to ensure that the content and conceptual (semantic) structure of any activity (e.g., the units) is fairly representative of and consistent with the existing body of knowledge from which the content was selected. Because the universe of content is theoretical, content validity is basically a matter of judgment by experts in a specific field or fields of study (Kerlinger & Lee 2000). Table II shows the key and critical feature strands and their exemplars

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that have been extracted from the CHQKB and that will need to be operationalized, validated and field-tested vis-à-vis the instructional units. Additionally, the relation between each of these key and critical features (or concepts) is presented in the form of a concept map that depicts the semantic structure of the complete module (see Figure 4).

As can be seen in Table II, each of the critical feature strands are characterized as either generative (ability to originate further ideas) or derivatative (extended or adapted from other ideas). In addition, Table II includes a description of which critical feature strands will be focused on during specific units and a corresponding weighting of the degree of recursion (i.e., the degree to which a strand is focused on across each unit). For example, the critical feature strand referred to as the discipline strand and its associated exemplars are only focused on during a single unit (Unit 1), and this frequency corresponds to a Low degree of recursion. The system in Table II provides a fuzzy heuristic and matrix that can organize some of the cognitive aspects of the unit development process and was used as a guide during the actual construction and writing of the units.

It should be pointed out that during the validation phase of the research (VFTE), these key and critical features are subject to change and therefore shifting weights. It should also be pointed out that these critical feature strands and their exemplars are not mutually exclusive, but rather are interrelated and conceptually linked. For example, philosophers of science (discipline strand) such as Kuhn (historical figure strand) study theory change

and progress (change strand) by examining the justification of knowledge claims (analytical strand).

a. Validation and Field Testing For Effectiveness

The process of ‘validating and field-testing for effectiveness’ involves psychometric procedures and principles used to generate information and data that address the actual appropriateness of a selected instructional representation and communication for a stipulated group. These include procedures and principles such as those associated with measures of content and construct validity, logical validity, ecological validity, internal and external validity and instrument or treatment reliability. These procedures include both qualitative and quantitative methods and the admixture of the two (what could be called a ‘qual-quantitative’ or ‘quant-qualitative’ approach and design). It is the absence of a systematic, rigorous and theory-based VFTE process and program that is causing such concern in the current educational climate (Shavelson & Towne 2002), and we believe much of the problem is the lack of macro models of instructional design that incorporate this critical and scientific element of rigorous assessment and revision. We are not suggesting that our VFTE method is ideal for all situations (since all instructional milieus are certainly different), but only that curriculum developers and researchers explicitly conceptualize and incorporate a macro structure that includes the VFTE element. With that qualification, we briefly describe our VFTE approach below.

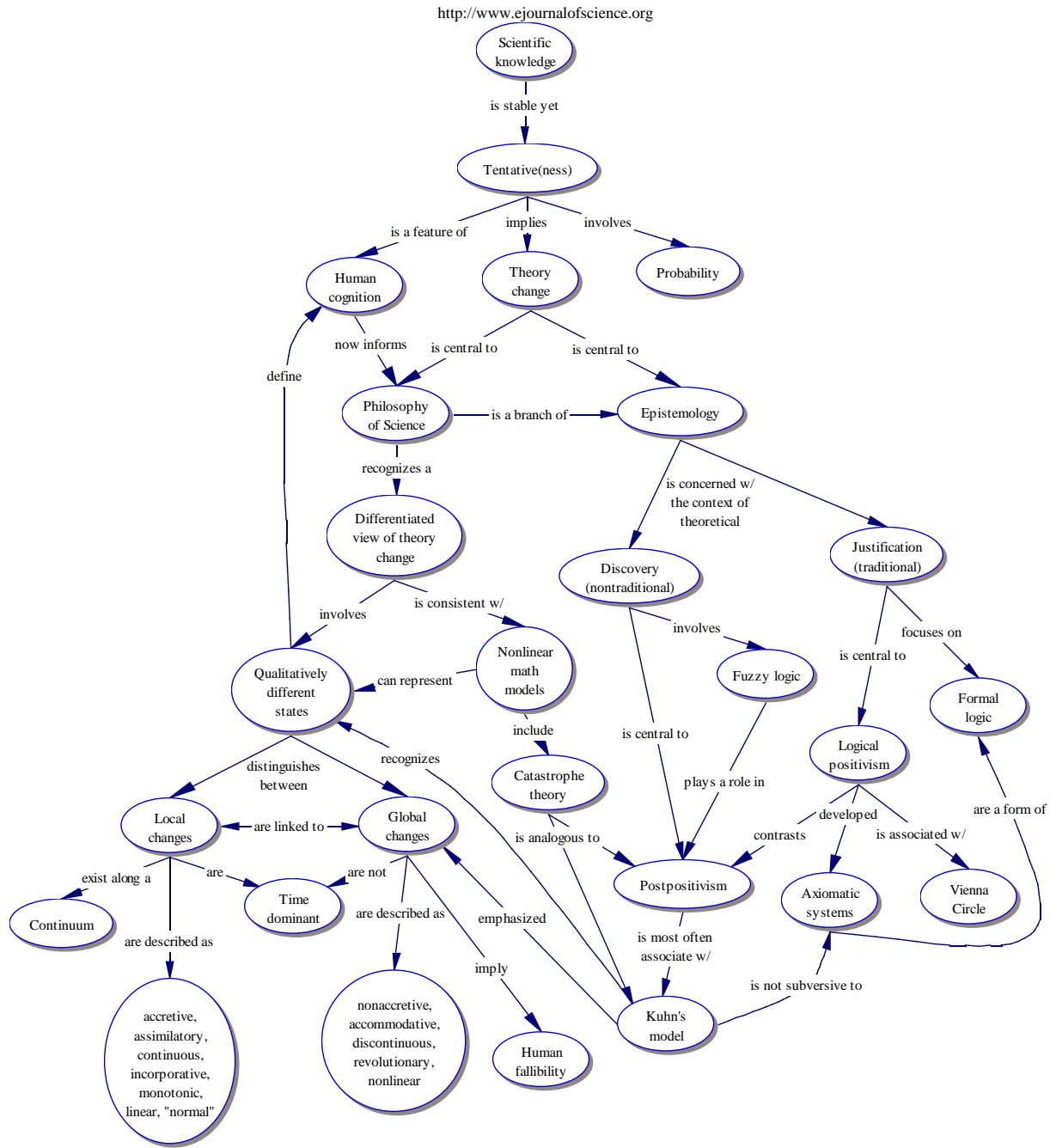


Fig 4: Concept map and semantic structure for the module.

The general research design that is being used in the study we are developing along with the different groups of respondents required (described below) is an adaptation of the convergent and discriminant design of Campbell and Fiske (1959), and the expert panel validation design of Lanza and Carifio (1992) which has been used by others to establish the logical validity of instructional materials

(Dagostino & Carifio 1994a, Nasser & Carifio 1993). Convergence refers to evidence that different sources (observers or modes of observation) used to measure a construct or 'traits' produce similar results, whereas discriminability refers to similar traits that can be empirically differentiated from one another or identifying traits that are not correlated or negatively correlated with each other or the construct (Kerlinger

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& Lee 2000). After the instructional materials (i.e., units) have been created and then reviewed by a panel of three learning theory and reading comprehension experts, two 3-person panels (NOS experts and undergraduate science faculty) will complete a standardized text evaluation protocol developed by the authors for each unit. The intent of the evaluation form is to gauge whether the units (and their associated traits) as constructed and operationalized actually reflect and represent what they purport to represent (i.e., the specifications of the units). If the judges agree that the units represent the specifications, then their judgments are said to have 'converged' on the construct and are evidence of the units logical validity or what can be referred to as theoretical or construct validity, which is defined by Kerlinger and Lee as 'one of the most significant scientific advances of modern measurement theory and practice' (Kerlinger & Lee 2000, p. 670). The significance of construct validity lies with the link it looks to establish between psychometric notions and theoretical notions (Kerlinger & Lee 2000).

The instructional text evaluation protocol we will be using here is an adaptation and elaboration of a standardized and already field tested instructional text evaluation protocol (see Carifio 2003; Dagostino & Carifio 1994a). The modified version of this protocol is a 36-item open-ended survey protocol that includes forced-choice items and open-ended responses. Dagostino and Carifio (1994a) were looking to determine if a theoretical model and construct (i.e., evaluative reading) could be logically translated into meaningful instructional material. Using a convergent and discriminant design, they demonstrated that this translation of theory into instructional materials could be done, which is a very critical and hopeful finding. Having 16 judges rate evaluative reading instructional activities using their standardized text evaluation protocol, Dagostino and Carifio performed a one-way repeated measures ANOVA with F-ratios for the judges that converted into an inter-rater agreement coefficient of $r = +.94$. This high level of agreement demonstrates that the judges were able to effectively recognize the theoretical construct of evaluative reading in an instructional context. Using a similar but more elaborate instructional text evaluation protocol, this research will look to establish the logical validity of the units developed using a panel validation process described below.

Two forms of this protocol are being used in our current work. The first form will be used with

the NOS experts and science faculty and will focus on the specific content of the units, the presentation and semantic structure and the teach ability of the unit materials. Areas of disagreement between judges will be analyzed and reported and all necessary and reasonable revisions made to the units based on this feedback and the feedback described below. Additionally, the standardized text evaluation protocol will ask the expert reviewers to judge the stability of each unit, where stability refers to the likelihood that a particular unit under review would be subject to changes (and the degree of these changes) if they were reviewed by a larger group of fellow experts in that particular field. From this data, a stability index will be calculated for each unit. After the NOS experts and science faculty panels have reviewed all four units, 25 sophomore science majors with little to no explicit or formal NOS exposure (as measured using an instrument developed by the authors) will be asked to read and review the units using the second form of the standardized instructional text evaluation protocol, which is similar to the text evaluation form used by the experts but excludes questions focused on the accuracy of the content and the mechanical quality of the units. Similar forms of analysis as described above for the expert text evaluation process will be used to determine the consistency of response among students as well as to identify areas of misunderstanding and confusion in the units.

The final versions of the instructional units we are developing will be ready for confirmatory effectiveness testing after the formative field-testing processes described here. This formative field-testing process has been described in some detail here so that this field-testing process may become a standard step and protocol in the development of instructional materials (ARCs) in the future.

The shift toward a more sophisticated and differentiated view of scientific knowledge and theory change in science and science education (e.g., Cotham & Smith 1981), and the recognition that student understanding of such epistemic and philosophic constructs and related terms is complex and difficult to measure, particularly with standardized Likert-like scales exclusively. This problem and difficulty has necessitated the use of more detailed, thorough and probing (qualitative) assessment measures such as open-ended questions and interviews, post-questionnaire interviews, tape recordings and student elaboration and defense of a particular view, statement or position (Aikenhead

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1987; Lederman, Abd-El-Khalick, Bell, & Schwartz 2002; Lederman & O'Malley 1990). This 'fuzzier' and less targeted (and to many less scientific) approach is certainly a logical strategy if one adopts a cognitive view of learning and memory, since standardized 'paper and pencil' NOS tests and instruments alone are unlikely to capture a respondents schemata or conceptual networks in a valid and meaningful way, but are more likely to capture a decontextualized, distorted and isolated 'part' of a schema, which may lead researchers to dubious conclusions, particularly with regard to the use of language in philosophic and epistemic contexts (see Lederman & O'Malley 1990).

However, it should be pointed out that this important assessment concern and issue of probing deeply into student understanding of assessment questions and concepts can and should be reflected back on the initial development of the instructional and assessment materials themselves, which is basically an issue of construct validity, which is not addressed and dubious at best in most of the aforementioned 'qualitative' efforts. For example, educational researchers must not only assess how well students or respondents understand a particular treatment or assessment, but they should then use this information to further develop, refine and optimize the treatment. This is a major reason why student follow-up interviews, elaboration, arguments, and justificatory models are central to the unit refinement, validation and assessment strategies if they are well connected to both a CHQKB and an integrated information processing theory of learning.

b. Limitations

There are two primary limitations to our work and process. First, it is important to emphasize that the purpose of our work is to test and assess the model for developing specialized instructional materials as opposed to the effectiveness of those materials once developed and in final form. This fact alters and modifies the usual criteria for internal and external validity (Moss 1992). Because our work is concerned with the initial development, validation and translation of the KCCM and its corresponding instructional materials, the translation results and effects obtained using these materials may not be generalize able across a wide range of settings and student and teacher populations. Although future studies we will conduct will address the general or broader effectiveness of these instructional materials with students and teachers, the reliability and internal validity (or meaningfulness of the results obtained) of

the macro model guided instructional materials (instantiation) is the logical first order of business and a necessary pre-cursor to confirmation effectiveness studies with a broader range and larger number of students and teachers.

Second, as Eflin, Glennan and Reisch (1999) point out, the nature of science concept in education (and elsewhere) seems to presuppose an essentialist view of science. That is, nature of science instruction assumes: (a) that there is a nature of science that can be discovered and taught to students; (b) that there exist tenets that describe the nature of science; and (c) for a discipline to count as science these tenets must be met to some degree. Eflin et al note that these assumptions are untenable in a pure philosophical sense and that most philosophers of science accept Ludwig Wittgenstein's view of science as a family resemblance concept, where science 'is not a sharply circumscribed concept' (Eflin et al 1999, p. 108), but a 'fuzzy' concept where the rules of inclusion are based on paradigmatic examples and other similar activities.

Despite this philosophical transgression, Eflin et al agree that this essentialist view of the nature of science may be appropriate and quite necessary for instructional purposes. Indeed, science educators seem also to agree that a vulgarized or simplified version of the nature of science concept is a necessary point of departure for such instruction (Osborne, Collins, Ratcliffe, Millar & Duschl 2003). The research and model outlined in this work recognizes this limitation, and believes that it makes the reliability and validity issues that much more crucial for a new instructional approach to the nature of science.

c. Conclusion

Concluding points can be made regarding (1) the virtue of nonlinear, dynamic models of scientific change and (2) the use of macro models of instructional materials development that can be used to translate, operationalize and validate such models of scientific change and their related content.

4. NONLINEAR MODELS OF SCIENTIFIC CHANGE

Once thought to be the 'exceptional case', nonlinear and chaotic phenomena are being identified wherever prepared minds care to look (Gleick 1987; Hofstadter 1999). The deterministic, rigid, and idealized 'black box' world of Laplace has given way

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to a more 'fuzzy', 'kinky' and dynamic reality. And for almost a decade educationalists have anticipated the use of chaos (and catastrophe) theory both in the classroom and in educational research (MacPherson 1995). However, there are relatively few research based and field tested applications of chaos theory in the curriculum today and none in science education. The striking similarity between contemporary philosophic views of scientific progress and change and the qualitative properties of catastrophe theory make this an ideal testing ground for chaos in the classroom, which may certainly be extended to countless other instructional milieus. Because the principles of catastrophe theory are expressed in graphic form, they may serve as a compensatory cognitive and instruction device. This hypothesis will also be tested in our work.

From an instructional perspective, it may be argued that the nature of change is the very thing students learn in and through the science classroom and that educators are obligated to provide students with a formal general model (or models) that will help them understand the revisionary character of scientific knowledge on both the local and global scale. Despite the fact that mathematical models play an important role in science, no formal models of scientific change exist in science education. In this sense, then, the approach suggested here is, in some ways, an attempt to make the study of the nature of change in science more scientific by using models that are systematic, precise, rigorous, and which also require elaboration and justification. It is also an attempt to apply mathematics (and mathematical models and representations) in contexts outside the area of mathematics, which also is a standards-based recommendation from the National Council of Teachers of Mathematics for grades 9-12 (NCTM 2000).

Because the nature of science involves highly abstract concepts and meta-cognitive skills, the use of text-based instruction alone, in the absence of formal models or systems, may facilitate misconceptions (or alternative conceptions) due to the vagaries of human language and the absence of graphic (visual-spatial) models (see Sandoval & Reiser 2003). The virtue and advantage of formal mathematical models and systems is that they not only require the precise use of terms, concepts, relationships and justification of ideas, but at the same time they also allow for different and often competing representations of phenomena. As such, formal models can, when administered thoughtfully,

act as global structures to introduce a wide range of learners to very complex and sophisticated ideas and concepts, as well as the basics and advantages of modeling phenomena, which are highly generic and valuable higher order cognitive skills (Latour 1988; Polya 1981; Thom 1989). These fundamental facts are why the KCCM and its associated instructional units are so critically important not only to science education, but to our society and its success in the modern, highly competitive global economy. Developing instructional materials to teach undergraduate (and even high school) students and professors the KCCM and all of its associated content will not only begin to achieve a 70 year goal of science education, but will do so in a way that teaches and integrates modern mathematics, the philosophy of science, and the nature of scientific knowledge and scientific thinking. Although the KCCM is by no means a definitive model of change in science and is subject to revision and different representations, it suggests the possibility of a new approach to both formally modeling and teaching the nature of scientific knowledge and scientific change in the classroom.

5. GENERAL MACRO MODELS OF INSTRUCTIONAL MATERIALS DEVELOPMENT

Many educators and educational researchers may not immediately recognize that the process and activity of examining a knowledge base for patterns and relationships between elements in the data and then extracting certain (useful) elements from this knowledge base for instructional purposes is quintessentially a data mining procedure (which is a procedure that represents the very heart of science and scientific endeavours). Although there are many different definitions of data mining available, data mining can be thought of a systematic and exploratory process of analysing large amounts of data to identify patterns and relations among the data that are nontrivial, perhaps novel and useful for the user (or data retriever) (Fayyad 1996). Over the past decade there has been a proliferation of highly sophisticated (algorithmic and statistical) data mining techniques and strategies developed to process and make sense of the incredible increase in knowledge products and the communication of these knowledge products globally. This knowledge explosion tremendously impacts educators and curriculum developers as the decision to select or omit certain elements from a dataset or knowledge base for instructional purposes becomes more difficult as the

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knowledge bases become larger, more extensive and subsumed by other knowledge bases. This type and degree of knowledge proliferation is certainly the rule in the sciences.

As mentioned earlier in the paper, there is a push to have science teachers at all levels become proficient not only in the content they teach, but also in the history, philosophy and epistemology of their respective discipline (referred to as nature of science studies or history and philosophy of science studies). The latter requirement and emphasis is relatively new and the content that defines this area in an educational context is only now resulting in an extensive and valid knowledge base (see Eflin et al. 1999; Osborne et al. 2003). However, this knowledge base is large and complex and educators and curriculum developers still need logical methods that can be used to extract information from this knowledge base in an instructionally appropriate and useful way. The sampling methods used with these large, complex and relational 'databases' (or knowledge 'warehouses'), moreover, are also somewhat counter-intuitive and different from classical methods but consonant with chaos theory (see Carifio, Schwedel, & Kermis 1990).

For these reasons, it is important to point out that the macro and micro models described in this chapter can be considered a data mining system that can help in the process of making sense of the large and complex knowledge base that defines nature of science studies by focusing on key and critical issues in this knowledge base and developing a systematic way to create appropriate and valid representations of this knowledge and then translate these representations into the classroom. This type of systematic strategy and approach in education will become increasingly important and necessary as technology and information capabilities continue to increase in society at an exponential rate. It also provides an internal check and balance (or quality control) system that can be used to periodically 'QC' ones instructional materials, much the same way proficiency testing is done in the 'hard' scientific

disciplines. Part of the significance of the approach and models outlined here, it should be emphasized, is

- a. having a highly explicit explicated and formal model of instructional materials development for science (and mathematics) education to both guide and evaluate past, present and future activities in these areas; and
- b. field-testing this formal model of instructional materials development that addresses highly abstract, complex and sophisticated content and reporting the results of these field tests relative to confirming or disconfirming this formal model or aspects of it

The use of this highly generic and functional model may help researchers in other fields or areas of instruction attempt to make the critical transition from theory to practice in an organized, systematic and logical way.

Lastly, having a formal and explicit instructional development model such as the one presented here allows one of the key and defining criteria of science and scientific knowledge to be employed in the development of instructional materials in science. This principle is the principle of independent replication. Two different development teams using the model to develop instructional materials to a given set of specifications should develop fairly similar materials (as opposed to the strikingly wide and heterogeneous variety of materials we see across various textbooks today). This 'Turing Test' for this model would not only validate the model but give us much higher confidence about the nature of instructional materials developed in science and used in science education research. As getting someone to fund such a study would be problematic we will have to use this study's 'poor cousin' and 'fuzzy approximator', the 'case study' and decide the models by 'weight of evidence'. The weight of evidence to support this model and its validity has been strong to date.

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inform the selection process. These theories include but are not limited to theories of learning, instruction, information processing as well as philosophical considerations related to the nature of the material (i.e., what is the representation at the most fundamental level and how is that justified). The word appropriate is an anticipatory, predictive and probabilistic word as one assumes a direct proportional relation between theoretical appropriateness and actual appropriateness as determined by validation and field-testing procedures (see below).

APPENDIX - A

Definitions of Key Terms

1. INSTRUCTIONAL MODELING TERMS

a. Appropriate Representations and Communications (ARCs)

Instructional materials such as written instructional texts, instructor's manuals, laboratory exercises, charts and diagrams. The word "appropriate" refers to theoretical appropriateness or justification, as the initial selection of the representations and communications is required to be justified (logically and empirically) by the theories that will

b. Critical & High Quality Knowledge Base (CHQKB).

A base of knowledge derived from the universe of content it represents that is selected based on a critical selection criterion. This base of knowledge is the result of intense and exhaustive reviews of the scholarly (e.g., peer reviewed journal articles, texts, monographs, books, proceedings and conference papers) and nonscholarly (e.g., websites, popular sources, curriculum materials and professional development materials) literature recovered from a number of different domains such as standards

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documents, professional affiliations, primary sources and secondary sources. Critical and High Quality Knowledge Bases are part of a macro instructional model and represent the content that will be translated into instructional materials. The first step in any macro instructional model is developing this type of knowledge base.

c. Macro model/theory.

A model or theory that is broader in scope and application relative to micro models (i.e., the big picture or “frame”), and its variables tend to be “indices,” or collections of variables at the micro level. In other words, macro models or theories address the aggregate units (i.e., the “whole”) in a specified field or area of study and subsume “smaller” conceptual units sometimes referred to as sectors.

d. Micro model/theory.

A model or theory that is nested in or subsumed by a larger, broader and more encompassing model or theory within a stipulated area or field of study. Micro models (sometimes referred to as sectors) have a truncating effect as they focus on only some of the relationships and variables in a system in greater detail and specificity compared to macro models (Fisher 1992).

e. Validated and Field Testing for Effectiveness (VFTE).

Psychometric procedures and principles used to generate information and data that address the actual appropriateness of a selected instructional representation and communication for a stipulated group. These include procedures and principles such as those associated with measures of content and construct validity, logical validity, internal and external validity and instrument or treatment reliability. These procedures include both qualitative and quantitative methods and the admixture of the two.

2. KUHN CUSP CATASTROPHE MODEL TERMS

a. Catastrophe theory.

An extension or branch of chaos theory developed by the mathematician Rene Thom during the 1960's, catastrophe theory is a ‘purely mathematical theory of singularities of smooth maps’ (Thom 1989, p. xi) that can be used to qualitatively model and understand the problem of

the succession of form where continuous causes lead to discontinuous effects.

b. Chaos theory.

First recognized by Poincare (1854-1912), chaos theory addresses the extreme sensitivity of a system to its initial conditions where organized ‘inputs’ lead to unpredictable and random ‘outputs’ over time.

c. Change.

The word change is used to imply an action that reflects the alteration of form, specifically as it relates to guiding theoretical commitments in science. Whereas tentativeness is mostly a denotative concept, change is a relational concept. A key assumption in this research is that knowledge that is tentative is always changing form, but that this change in form can be of two qualitatively different yet related types, referred to as local and global change (see below).

d. Differentiated change.

A conception of change that explicitly involves and/or addresses both local and global forms of change and their interrelation. The term differentiated refers to the idea that local and global varieties of change are qualitatively different; that is, local change is associated with the acceptance of a theory, whereas global change is associated with the rejection of a theory—two qualitatively different states. Over time local changes may eventually lead to global changes in a system.

e. Discontinuity.

As in catastrophe theory, discontinuity is a condition or situation where continuous causes (or inputs) lead to a qualitative state change (or output) in a system or model. Discontinuity is both a quantitative and qualitative concept used by mathematicians and psychologists, respectively. By this definition, a global change is discontinuous.

f. Dynamic.

Broad concept referring to a phenomenon marked by continuous change (local or global), activity and progress at varying levels of intensity and force.

g. Formal model.

A quantitative or qualitative mathematical model which implies the careful, moderated and precise use of

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terms and concepts that serve to clarify the understanding of a phenomena or problem.

h. Fuzzy.

Used in reference to Zadeh's fuzzy set theory, which departed from classical set theory inasmuch as it associates a class with 'a continuum of grades of membership' (Zadeh 1965 p.339)? The virtue of Zadeh's 'fuzzy logic' is that it provides a way of 'dealing with problems in which the source of imprecision is the absence of sharply defined criteria of class membership rather than the presence of random variables' (Zadeh 1965, p.339). In this sense, fuzzy logic provides a strategy (and also a heuristic) for dealing with the demarcation problem that plagues a number of academic disciplines including the philosophy of science, which looks to distinguish science from nonscience. Fuzzy logic has been successfully applied to a large number of diverse fields including, electronics, robotics, artificial intelligence, medicine technology, cognitive psychology, and software design.

i. Global change.

A global change is characterized by the rejection of a theoretical commitment in favor of a competing and incompatible commitment. Global change does not exist along a continuum and is consistent with what Kuhn (1996) terms a 'revolutionary change'. Global change episodes are represented in this study using the following heuristic:

accept paradigm (a)→change episode(s)→reject paradigm (a) and accept paradigm (b)
or in the abbreviated form: $AP_a \rightarrow \Delta \rightarrow RP_a/AP_b$

j. Local change.

A form of change that leaves a theory functional and does not immediately lead to its rejection. Local changes exist along a continuum from very minor to major. Despite this continuum, a change or modification to an existing theory is defined as local if it leaves the fundamental features of the theory intact. A local change is consistent with what Kuhn (2000) refers to as 'normal change'. The philosopher of science Losee (2004) has recently characterized this variety of change in science as 'progress by incorporation'. Local change episodes are represented in this study using the following heuristic:

Accept paradigm (a)→change episode(s)→accept paradigm (a)

Or in the abbreviated form: $AP_A \rightarrow \Delta \rightarrow AP_A$

k. Quantitative and Qualitative mathematics.

As Isnard & Zeeman (1977) point out, mathematics has three levels or types of structure: order, topological, and algebraic. Order structure involves ordinal-level measurements, which satisfy the transitivity postulate: If x is greater than y, and y is greater than z, then x is greater than z. Comparisons like 'greater than' and 'less than' are order concepts. Topological structure is measured using a continuous scale. The assumption of continuity allows for the moderated and careful use of some calculus concepts, such as smoothness. Smooth means that a function or relation is differentiable to all orders. Differentiable means that a function or relation is continuous (it can be drawn without picking up your pencil) and does not have any hard corners, cusps or vertical tangents. Algebraic structure involves operations such as addition and multiplication, which have little value in measuring sociological phenomena. As Isnard and Zeeman point out in their sociological model of the causes and tolls of war, 'one cannot "add" two senses of threat to get a third, and even twice the cost can become meaningless if one tries to include in the cost of a war the measure of human suffering' (Isnard & Zeeman 1977, p. 321). Hence properties involving order structure and topological structure are defined as qualitative, while properties that rely on algebraic structure are defined as quantitative. This distinction is critically important because it implies that as long as changes between different scales are 'smooth and order-preserving' (Isnard & Zeeman 1977, p. 321) they are considered qualitatively similar, even if the algebraic structure is not preserved. This qualitative perspective allows for non-linear variations of scale, which are the type of variations that are recoverable from the theses of post-positivist philosophers of science such as Kuhn, Laudan, and Lakatos, among others. For an example of qualitative mathematics see Perla & Cross (2005).

l. Tentativeness.

In this study, tentativeness is basically a state or status used to represent the idea that scientific knowledge (i.e., theories and facts) is provisional, inconclusive, and not completely worked out or established, and is at best probabilistic.