Scientific Methods: Epistemological Issues in Cross-Disciplinary Science Curricula

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Abstract: We discuss the different ways of conducting scientific investigations among working scientists, and identify a small set of general categories of method. These methods amount to distinct operational definitions of "data" and consequently different epistemologies that, to some degree, are domain-specific. We also identify a set of domain-general reasoning skills for scientific analysis and use of data once it has been acquired. We consider the implications of differing domain-specific scientific epistemologies for the construction of activities and curriculum units at the middle school level. We illustrate how the construction of several of our units has been influenced, and propose a general organizing framework for larger scale curricula that may afford noticing and discussing the domain-general and domain-specific aspects of scientific reasoning.

Most attempts to create science curricula implicitly assume that there exists a set of general scientific reasoning skills that transcend domains. However, recent research (Schunn and Anderson, 1999; Hammer and Elby, in press) has called this assumption into question. In addition, our work in creating project based science curriculum units (Kolodner et. al. 1998, Kolodner et al., 2002) has naturally employed related but logically distinct methods of collecting data. A number of questions relevant to cognitive research and curriculum development immediately arise. For instance

- What are the classes of scientific investigation? What are the similarities and differences between these classes, both as perceived by experts as well as by novices? How do they affect what is perceived as evidence?
- What are the pedagogical challenges and opportunities in learning scientific methodology if it is so varied? Are there domain-general skills which can be exploited for a unified approach to curriculum development?

First, we will propose a set of domain-dependent scientific methods for data acquisition and domain-independent methods of reasoning based on data. Then we will investigate the challenges inherent for education in identifying all these very different things as “scientific,” and the opportunities that a project-based educational approach provides for addressing these challenges. We will propose a multi-tiered integrated science project framework based on subsystem modeling as a solution to these challenges.

Cognitive Issues in Scientific Methodology

Schunn and Anderson (1999) have shown that reasoning skills interact closely with domain knowledge. Even expert scientists do not consistently exhibit expert performance when designing investigations outside their knowledge domain, suggesting that "scientific reasoning" may not be a single concept. Evidently, the logic of scientific reasoning cannot be cleanly separated from domain information, and reasoning performance scales accordingly. Scientific experts reasoning outside their native domain perform somewhere between novices and domain experts.

Schunn and Anderson (1999), Hammer (in press), Kuhn (1989, 1991) and Kuhn and Pearsall (2000) have also explored how colloquial epistemologies on the uses of data differ from those of working scientists. Novices tend especially to assign greater importance to small data variations than do scientists, and to view arguments based on theoretical concepts as equivalent to and interchangeable with arguments based on observations.

Evidently, there are objectively distinguishable, domain-dependent, but overlapping, epistemological skill sets involved in *acquiring* data that transfer across domains only with difficulty. However, there are also domain-general logical skill sets involved in *using and interpreting* data that transfer more easily as they are shared by all scientists.

To some degree, these research results should be expected based on cognitive models of human learning and reasoning. For example, case-based reasoning (Kolodner, 1993) clearly implies a close linkage between reasoning skills and specific experiences. Current situations are mapped onto prior experience, and appropriate reasoning strategies are identified and transferred to the new situation. The more removed a new experience is from past experiences, the less likely it is that it will map cleanly onto indexed memories and trigger recall.

Alternatively, the ecological approach (Gibson, 1979 and Zhang, 1999) relies on the recognition of affordances that can be exploited opportunistically. However, the semiotic invariants of internal affordances require internal representations that must be learned. They do not initially provide affordances, and so one would not expect any sort of newcomer (either novice or other-domain expert) to consistently recognize and exploit them.

There also seems to be an epistemological confusion that may be related to Schunn and Anderson's results. Science is considerably less monolithic than is usually perceived. Transfer difficulty ensues when the underlying assumption is that every scientific investigation is an experimental investigation or when experiences that are not experiments are treated as if they were. But the epistemological complexity of science also offers the opportunity of focussing learning environments on the domain-general skills that are its true core -- not how data is acquired, but how data is used once it is in hand. In addition, there is the opportunity of learning how to deploy different investigation strategies contingent on the nature of the problem being addressed.

Domain-dependent Aspects of Scientific Methods

In order to fully understand the proposed solution, it is necessary to first outline the different investigational methods that are contained within the umbrella of science. All of them can be considered as specific instances of a general hypothetico-deductive methodology, in which a more or less well-formed theoretical idea about natural process is logically linked to observational consequences. The differences then lie in how nature is probed to seek evidence of those consequences. The philosophical basis of this procedure was constructed by Bacon (1620) and Galileo (1632, 1638). Essentially, each of these methods may be regarded as an operational definition of the term "data." Generally speaking, novices (and many experts) can be expected to be dimly aware of these issues, if at all.

Experimental Method – Processes Probed Directly

This is the classic "scientific method" that is on the poster in every science classroom. Experiments are conducted on the actual items of interest -- if you want to know about protons, experiment with protons -- and close attention is paid to tight variable control, multiple trials, statistical treatments, and so on. The goal is to explore hypothesized relationships within a set of variables by isolating that set as much as possible from all other variables, and reducing the room for experimental error to exclude, to the extent possible, uninteresting data. Physics is the classic domain example of a science founded on experimental methodology.

Modeling Method – Processes Probed Indirectly

Model-based[1] investigations can be thought of as an extension of experiments. The primary difference is that rather than conducting experiments on the actual objects of interest, they are conducted on designed imitations of the objects. Thus, the modeling method is the experimental method extended by model validity conditions, both for the objects and the processes in the model. Model-based investigations would be appropriate in situations where the objects themselves are too large or dangerous to work with directly, or the time scales for processes are too long for feasible experiments. The goals of a model may then be to reduce the size or complexity of the phenomenon or to compress the time scale into a reasonable period. Geology is a good example of a domain in which models can be very useful to the scientist.

Observational Method – Processes Inferred From Populations

In some domains (notably astronomy and psychology), the objects of interest are largely not susceptible to either experimental or model-based investigations (though this is becoming less of an issue with the progress in digital modeling). The phenomena are simply inaccessible to manipulation, and you must take whatever nature gives you. There is no opportunity for variable control, and the means of acquiring information may be very tightly constrained by physical or ethical limitations. In astronomy, with few exceptions, all information must be gleaned from the electromagnetic radiation that arrives at the Earth. Frequently, process is not evident as it is in experiments and models. As a result, astronomers do a lot of population and comparative studies. The idea is to exploit the vastness of the universe, and the large number of uncontrolled experiments being run by nature, to isolate the truly fundamental phenomena from those that are products of local circumstances. The nature of the data is that of a spatial series, a large collection of objects viewed simultaneously but assumed to be at various points in their life cycles. Due to the lack of control, uninteresting data cannot be excluded. Instead, the total data set must be filtered into interesting subsets. Process is inferred from those through trends and correlations in those subsets, representing similar objects at different points in their life cycle.

Historical Method – Processes Inferred From Sequence of Static Outcomes

Charles Darwin was the first scientist to explicitly identify his working method with that of the historian[2] as more than just an analogy, and evolutionary biology is the preeminent domain example. As with astronomy, the underlying process is inaccessible. Some experiments can be conducted on general features of speciation (Dobzhansky and Pavlovsky, 1971), but for the most part experiments and models are largely inapplicable due to the random nature of the process. Consequently, any results would lack predictive power. Observation is frequently an important issue, but is rendered problematic since most of the organisms and environments of interest are long dead, and those that have left traces behind were randomly sampled. Instead, the biologist must reconstruct the developmental process based on the traces of its static outcomes that were left behind in the fossil record and in currently existing organisms. The nature of the data is that of a time series, observing a population at specific sequential points in time. Uncontrolled data sets must be filtered and sifted through for trends and correlations in a manner similar to the observational method. As Darwin noted, constructing a story from this type of data is quite similar to the work of a historian attempting to reconstruct social processes based on the evidence left behind in static documents. As with history, and because of the large element of chance involved, the result is usually a retrodictive rather than predictive theory, in contrast to the other methods.

General Comments on Method

While I have associated each of these methods with a particular domain example, it is important to note the obvious -- no science is exclusively tied to any one method. Biologists do experiments and observations in addition to historical analysis, and psychologists use experiments and cognitive models in addition to observations. The associations above are simply comments about relative importance.

More seriously, each of these methods is primarily about data acquisition and interpretation. They say very little about theoretical generalization from that data. However, it is through the construction of theories that science acquires its predictive power, and much of its beauty. There has been some investigation of this aspect of science through the use of rules of thumb as intermediate generalizations (e.g. Ryan et. al. 2001), but most presentations simply assume a theory exists and concentrate on data collection procedures to test it. Such procedures are easier to define and carry out, but are of a great deal less interest to working scientists.

Domain-general Aspects of Scientific Methods

How do we justify identifying all these logically very different things as examples of the same thing, namely science? Though there is a great deal of variety within science in the acquisition of data, there is broad general agreement on its uses. I call this understanding the Eco Conundrum.[3] In a learning environment, it implies the need for a tighter and more consistent focus not only on the mapping between various domain-specific data acquisition methods and problem classes, but also on the unifying domain-general methods common to all sciences. We briefly describe some of these, as viewed by experts and by novices.

Discriminating Between Theories

Why collect data at all? The views of scientists and novices on the reasons for conducting an investigation are significantly at variance, as noted by Schunn and Anderson (1999). Scientists use evidence for the purpose of validating models and discriminating between alternative theories. This means that, to a scientists, theories inform and partially dictate observational strategies -- what you investigate depends to some degree on what you expect to find. There are no theory-free observations.

Novices, on the other hand, do not typically see experiments and observations as discriminators. Generally, if they conceive a linkage with theory at all, it is in terms of validating a specific theory (Kuhn, 1989, 1991; Kuhn and Pearsall, 2000) rather than dividing the universe of theories into those that are possibly true and those that are possibly untrue.

Constructing Arguments

What does one do with data when it is in hand? Scientists construct pro/contra arguments based on evidence, systematically examining theoretical arguments for the extent to which they account for the data. Novices, on the other hand, have difficulty distinguishing evidence from theory and typically view them as interchangeable (Schunn and Anderson, 1999; Kuhn, 1989, 1991; Kuhn and Pearsall 2000). Theoretical arguments can be presented as if they were established, evidentiary facts. For example, in an investigation of friction used for performance assessment, students collect some experimental data on sliding friction for different types of rubber, and are then asked a series of questions. The first question attempts to elicit a data driven response: "What were the differences, both measured and observed, between the two types of rubber?" Many students do in fact give a data-driven answer, such as this one:

> "They were all about 50 g apart. Soft rubber was harder to pull than the hard rubber. The soft rubber with 400 g went over the highest # on the scale."

However, many others rely on a microscopic theory of friction as an equivalent answer, such as these two:

> "The softer rubber gets more traction because of the rougher surface."
>
> "The soft rubber acted like a spong [sic] and the tiny groves [sic] in the rubber grabbed on the gravel."

Identifying Relevant Data

How do you distinguish the forest from the trees, and when is it appropriate to pay attention to each? Working scientists of whatever discipline have well developed filters to distinguish signal from noise in data. They ignore small fluctuations as simply random variations of no significance, while being on the lookout for aberrant events[4]. Novices typically assign much greater importance to noise, and exhibit an inability to consistently distinguish such noise from actual unexpected events (Schunn and Anderson, 1999).

Refining Generalizations

Einstein (1956) argued that "The whole of science is nothing more than a refinement of everyday thinking." Some evidence has been found to support this point of view in cognitive studies of the relationship between novice and expert reasoning. Becoming expert involves at least two important cognitive refinements. One is the progressive refinement of primitive phenomenological concepts into more broadly applicable, consistent and well-specified predictive axioms (diSessa 1988, 1993; Smith et. al., 1993). This comes about largely through reflection on the common features of varied experiences. Another refinement is the complex process of learning how to map a relatively sparse set of theoretical concepts to the rich set of data available from physical situations (Chi et al, 1981; Reif, 1985). This seems to be based at least in part on a continued, but controlled, use of naive conceptions in expert reasoning (Smith, diSessa and Roschelle 1993).

Challenges and Opportunities Afforded by Varied Scientific Methods

The core challenge, then, is to help students see that there are many different scientific methods for collecting data, each mapping to a particular class of problems, and that there is broad agreement across disciplines on the use of that data and the purpose for collecting it. Every challenge is an opportunity waiting to happen. Here, the opportunity is to consciously design a learning environment such that it affords noticing and talking about both the domain-dependent and domain-general skills of science. Development of scientific epistemologies has been of some considerable interest to a number of researchers (see e.g. Hammer and Elby in press; Sandoval in press). These efforts are of limited use here in that they typically do not explicitly recognize the existence of scientific methods other than experimental. What we have in mind is more fundamental: identifying the different epistemological goal states in science, exploring how project-based curricula can be adapted to accommodate that set of goals. This would provide environments within which developmental aspects could be explored.

An essential component of any solution to this challenge is for curriculum designers to construct sequences, within or across project challenges, that afford the opportunity to notice similarities and differences between the scientific approaches they take, to reflect on those comparisons, and to adapt old skills to new contexts. Table 1 (following page) summarizes the set of activities in three LBD launcher units (Camp et. al. 2000; Holbrook et. al. 2001). Each centers on a different scientific method.

As indicated, *Apollo 13* is in the physical science domain, and its design is dictated by the requirements of experimental methodology. *Digging In* is shaped by the requirements of modeling methodology, an extension of experimental, and so the activities are quite similar *Struggle for Survival* is very different, the activity structures and epistemological viewpoint deriving from historical methodology and so radically different from the more experimental units.

All three begin with a simple design activity, either a book support or a boat, to highlight basic collaboration, iteration and knowledge-based design skills. The Oreo Cookie challenge has two versions which are determined by the relevant scientific method. The activity involves finding the number of drops of water that will fit on a penny without falling off. Version 1 treats this as an experimental method problem in which students must standardize the height, counting method and dropper size to narrow the range of error in the data and create a fair test. This is obviously appropriate for experimental design (*Apollo 13*) as well as for model testing (*Digging In*). Version 2 has been recast to suit the inherently uncontrollable observations of ecological biology. Instead of refining the procedure, they collect a large amount of data and then learn how to filter it into subsets based on the independent variable they are interested in investigating. The Tape and Keep it Hot activities are each about designing experimental procedures to answer a particular question (what is the best kind of tape for a task, and what is the best thermal insulation). Again, due to the close relationship between the experimental and modeling methods, this is appropriate for both. However, it is inappropriate for the life science unit which involves a domain in which experiments are not useful (evolution is not predictive). Instead, through the epidemiology activity, students use retrodictive observations as evidence to justify a written natural history of disease spread (the goal is to trace a simulated infection back to the original source and construct an evidence-based history of its propagation through a population). The Design an Animal activity has no parallel in the other two units. It is a simple, case-based activity to introduce the idea of adaptation of organic structures to environmental pressures, a domain-specific issue that will be important in understanding the finch problem.

Table 1: Major LBD Launcher Unit Activities

Apollo 13 (Physical Science/Experimental)		**Digging In (Earth Science/Modeling)**		**Struggle for Survival[5] (Life Science/Historical)**	
Challenge	*Goal*	*Challenge*	*Goal*	*Challenge*	*Goal*
Book Support	Collaboration, iteration	Key Relay	Collaboration, iteration	Book Support	Collaboration, iteration
Oreo Cookie 1	Fair testing	Oreo Cookie 1	Fair testing	Oreo Cookie 2	Fair Selection, trend analysis
Tape	Experiments	Keep it Hot	Experiments	Epidemiology	Observation, Natural History
Parachute	Complex experimental design challenge	Erosion	Complex model design challenge	Design Animal	Adaptation, form and function
				Finches	Complex observational natural history challenge

The final activity in each unit is a complex investigation that ties together all the preceding experiences into a unified, iterative solution of a problem. In *Apollo 13*, students design experiments to test all the variables that affect the fall of a parachute. After presenting their results to each other, they use the information obtained to create their own designs for a parachute that will fall as slowly as possible.

The *Digging In* unit culminates in an erosion management challenge. Students design models on which they can perform experimental investigations to find the best way for managing erosion on a specified site. Using the results of models to inform real-world designs imposes interpretive issues which students find they must confront: some things must be left out of a model so is it still similar enough to the real world to trust? Scale must be attended to so that they know how to translate the model results into real world designs. And since it is a process that is being modeled, both of these points are important for the procedure of running the model as well -- scale must be imposed on the experimental design by which the model is tested. It is in this activity that *Diggin In* diverges from *Apollo 13* as similarity and scale issues are laid on top of experimental design.

The *Struggle for Survival* unit diverges from *Apollo 13* even further, as dictated by the methodological differences in the sciences. Experiments are not possible, and neither are predictions. Instead, observations must be relied on to explain the process of a historical event. The event in question is a microevolutionary study of morphological changes in a group of Galapagos finches during a drought. Students have a large data set that records many characteristics of the finches as well as various aspects of their environmental conditions. They must filter that data into subsets appropriate for finding trends within and correlations between different variables. Using those trends and correlations as evidence, they construct a natural history that explains the process by which the finches changed and the likely cause.

A System/Subsystem Approach to Integration

Though the launcher units are crafted to afford use of specific scientific methods in a natural way, in most school systems they would not be used together. For the most part, we could expect them to be used in different years altogether. This seriously impedes any effort to metacognitively reflect on similarities and differences in investigation strategies and their relationship to the domain. We cannot even count on having the same students or the same teachers in successive years.

We are in the early stages of exploring a project approach based on system/subsystem modeling that might provide a general framework for addressing the different methods of science in a way that might afford such comparisons. The fact that there are both domain-dependent and domain-general skills to be learned suggests the use of multi-tiered interdisciplinary projects – small projects emphasizing domain-dependent skills, tied together by a larger project emphasizing domain-general skills and cross-domain comparisons. The general idea is to have a large project based on a complex system within which smaller projects may function as models of subsystems.

For example, in Learning by Design (Kolodner et. al. 1998, Kolodner et al., 2002), force and motion concepts are explored in the context of designing a powered vehicle that must traverse a specified test track. In LeTUS (Singer, et. al. 2000), the same issues are explored in the context of designing a bicycle helmet. However, suppose we reimagine both of the projects from a more abstract point of view. The LBD car design project concerns continuous forces that operate for extended times. The LeTUS helmet design project concerns impulsive forces that operate almost instantaneously. We might, then, imagine a design project that encompasses both, and more besides, by expanding the car design project into a car *system* design project. We design the overall system by modeling its various subsystems in smaller design projects. The LeTUS project can be reinterpreted as a model of crash protection subsystems in a car, which reapplies Newton's Laws in a new context, brings up the idea of crumple zones and the like, and also provides a link to momentum concepts. We can then imagine plugging other subsystem model design problems into the overarching car design project, such as electrical circuits -- how do you design a circuit that will still allow you to start the car even when the dome light is burned out? Or how do you dissipate heat from the engine most efficiently? In the process of combining these disparate projects, we bring in both experimental issues for the subsystem design projects, as well as model validity issues when integrating them into the overall car system design. This provides an opportunity to think about the situations suitable for each method in the context of a single-domain (physics) set of problems.

To understand the true power of this approach, however, we must think of systems and subsystems on a more abstract level. For example, think of a bird as a system of subsystems. The LeTUS finch unit (Reiser et. al. 2001), which was used as part of the *Struggle for Survival* launcher, is a good example of historical method, though LeTUS does not identify it as such explicitly. The overall lesson from the finch problem is that the biomechanical constraints of the birds, and variations therein, cause a survival differential in the population. Over time, the characteristics of the birds change. This linkage to historical method was the foundation of the launcher, and can also be linked to Darwin's original investigation of changes in bird morphology. Darwin's hypothesis was that all the Galapagos finches radiated from the same original population, with consequent reconstruction of their natural histories. However, there is a larger lesson: biomechanical constraints are a profound influence on bird survival. Considering a bird as a system containing subsystems, there are necessary requirements for the strength of bones, power production from muscles, flow rate of blood vessels, etc. Each of these links directly to fundamental physics principles, and experiments can be performed on carefully designed model subsystems. These models would establish physical constraints on the birds, imposed by their environments as well as by the necessities of their lifestyles, which can then be used to reconstruct the natural history of bird evolution Such a set of units would allow all four scientific methods to be used when appropriate within the context of a single investigation, naturally affording the opportunity to think about how they are different and why, in addition to integrating the domains of biology and physics.

Advantages

These examples show how cleverly chosen projects, based on a subsystem approach exploiting abstraction of complementary features, can highlight both domain-general and domain-specific features of scientific methodologies. By juxtaposing subsystem projects based on different investigation methods, an opportunity is created to discuss both the differences in how data is acquired, and the similarities in the uses that are made of that data.

In addition, the infusion of additional content can make the projects more valuable to stakeholders and alleviate some of the time concerns that are endemic to project-based curricula. The learning curve within the unit might also be lessened by allowing the acquisition of both content and process skills to be stretched out over a larger unit (i.e., you could have a year to get them up to a specified level of performance rather than eight weeks). Finally, many students and teachers express boredom concerns by having to return to the same project day after day. If we conceive of a variety of subsystem projects, with return to the overarching project say every month or so, then perhaps this concern would be significantly abated as well.

Opportunities Beyond Design Projects

Some domains (for example, astronomy) are simply not easily amenable to the design project curriculum model. It may be that "Big Question" projects could serve as an adequate substitute both for generating student engagement (because they are profound questions) and providing opportunities for iteration (since there are many ways to approach the questions).

For example, one Big Question might be "How old is the universe?" Consideration of the vastness and antiquity of the place we live is intrinsically interesting to many people, and it may be addressed in a variety of ways. Geology and comparative planetology address the age of the Earth and the solar system, which places one constraint. Stellar evolution places another constraint, as does galactic evolution and cosmology. All of these constraints must be consistent to give a scientific answer to the question. There are examples from the past when, for example, due to experimental subtleties with variable stars that took some time to resolve, there were stars whose apparent age seemed to be older than the apparent age of the universe that contained them. Thematic consistency and feedback management would be a significant issue with Big Question projects since they are not centered on physical artifacts.

Endnotes

[1] There is an important distinction that must be made here since there appear to be at least two different meanings of the word "model" in common usage. Much research has been conducted on development of the use of models. However, that research does not always clearly distinguish between mental models (how knowledge is represented) and scientific, exploratory models (used for scientific discovery). Sometimes, the former is presented as if it were the latter. To a scientist, a model is a tool for investigating natural processes, so it is really the process that is being modeled. Physical objects are modeled only to the extent that they play a role in the process. This means that a scientific model must be "runnable," not static, which distinguishes it from other types of model. In many investigations, a "model" is conceived of as simply a tool for representing knowledge acquired by other means. This is certainly a legitimate concern for cognitive research, but it should not be confused with a scientific model.

[2] E.g. “I look at the natural geological record, as a history of the world imperfectly kept, and written in a changing dialect. . .” (Darwin ref)

[3] "The beauty of the universe consists not only of unity in variety, but also of variety in unity." Umberto Eco, *The Name of the Rose*

[4] A good example of this is the unexpected discovery of the charm quark in the mid-70's from an unusual bump in the energy distribution of a scattering experiment (Coughlan and Dodd ref).

[5] Portions of this unit are adapted from the LeTUS *Struggle for Survival* unit (Reiser et. al., 2001).

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